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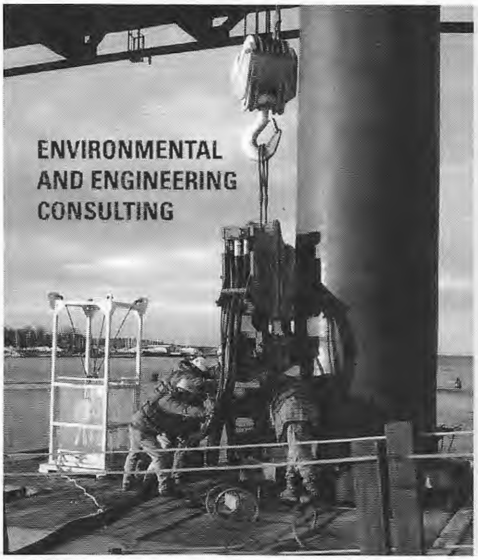
A CITY UPON A HILL:
The Geology of the City of Boston & Surrounding Region



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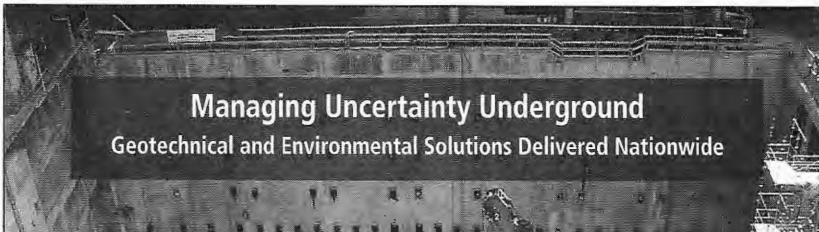

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A CITY UPON A HILL: The Geology of the City of Boston & Surrounding Region

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The Geology of Boston & the Surrounding Region

Who but geologists and a few civil engineers would look at New Old South Church on Bolyston Street in Copley Square and think that a mere 600 million years ago, the conglomerate stone of its walls was being formed as accumulating sediment along the shore of a volcanic island just off the coast of the continent of Gondwana, the forefather of present-day Africa. Or you might ponder as you gaze across Copley Square that only 22,000 years ago, the glacial ice thickness over Boston was twice as thick as the John Hancock Tower is tall. About 3,500 years ago, Native Americans were harvesting fish using an ingenious weir at the site of 500 Boylston Street in the tidal embayment and mud flats of the Back Bay. Less than four hundred years ago in 1630, geology beckoned the 1,000 or so people to settle on the hills of the Shawmut Peninsula, the peculiar layering of soils providing many fresh, free-flowing springs, with the geography providing defensible high ground and an adequate harbor for ships of the day. It was just one hundred and fifty years ago that the state of Massachusetts was in the midst of the world's greatest land-moving operation ever to import sand and gravel fill from the glacial kames and eskers in Needham and Dedham to fill the Back Bay. Our history is founded on geology, as are our buildings. Our tunnels are bored through very interesting accumulations of rock and soils. It is therefore with great pleasure and excitement that the Editorial Board presents this special combined edition of your BSCES Journal, *Civil Engineering Practice,* on "The Geology of the City of Boston & Surrounding Region."

The opportunity to publish this major work on the geology of Boston came to BSCES from two well-known geologists, Dave Woodhouse and Pat Barosh. Their work has appeared before in the Journal in 1989, along with other notable geotechnical engineers and engineering geologists. However, the current 2011/2012 combined edition of the Journal puts a plethora of geologic information and nearly a century of the authors' research, practice and expertise in one bound volume. The bibliography contains well over eight hundred references. The authors are to be congratulated on such a significant undertaking and I personally thank them for the opportunity that BSCES now has to present this work to our members, as well as to the geological and civil engineering community. The first three papers present details of the geologic setting of Massachusetts, and in particular the Boston Basin. The geologic factors of soil and rock conditions and the impact of these conditions on building foundation requirements are described in two papers. The impacts of geology on tunnel construction and the details of the geology discovered along the routes of tunnels for transportation projects and for water and wastewater conveyance are described in the final two papers. As much as these papers are about the geology of Boston and surrounding region, they are also a history — a history of ground's formation and man's interaction with it. Every engineer should find something of interest in the majority of the papers.

Special thanks are also given to the eleven firms and individuals who have contributed at various levels of support to sponsor this special edition of the journal. These firms and individuals are acknowledged on the sponsorship page that preceeds this editorial. Their sponsorship shows a keen interest in the Journal and the geology of Boston, and of course greatly helps to defray the cost of editing and printing production of this nearly five-hundred-page edition.

In order to accommodate this extraordinary undertaking of this focus on Boston's geology, we have altered some of our usual practices in presenting papers. Since all papers have common authors, we have printed their biographies once (on page 410). In addition, since the papers share many of the same references, we have collated references for all of the papers at the end (on pages 411-442), and in text instead of using superscripts to note a reference, we use APA style. Also, since papers do refer to figures in other, preceeding papers, we adopted a two-number system to make it easier to identify and locate figures across papers (for example, Figure 3-12 refers to the twelfth figure in the third paper in this issue). Last, since color is key in conveying information for some of the figures (especially photos of rock samples), we have included a special color insert (on pages 449-480).

For the next edition of *Civil Engineering Practice* — for the year 2013 (Volume 28) — we will examine issues of seismicity in the Boston Basin. However, our ongoing quandary is what will we publish in subsequent editions of the Journal. The Editorial Board continues to face a dearth of professional papers on the practice of civil engineering. One previous source of papers to publish has essentially done dry because it used to be that the different BSCES seminar series required submittal of formal papers from every guest speaker. These provided several papers each year for the Journal. Unfortunately, printed PowerPoint slides have become a substitute means of disseminating the information presented in these lectures. Although a picture might be worth a thousand words, words are needed to tie pictures together! We are investigating possible means of capturing these presentations in a format that could be turned into ready material for publishing in the Journal, perhaps by capturing the spoken words at a technical presentation, coupled with some of the PowerPoint images.

However, we are still a journal for our members. Therefore, we would really like to publish a paper on professional practice that you would write. Got an idea about an interesting project you worked on some time in the past? Want to write about it? Or maybe one of the young engineers in your firm could be encouraged to write about that project? If you have ideas for possible papers, please get in touch with me or other members of the Editorial Board.

Sincerely yours,

Jim Lambrechts

Professor Jim Lambrechts, P.E.
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Directing Our Gaze Toward the City Upon a Hill

"For we must consider that we shall be as a City Upon A Hill.
The eyes of all people are upon us."
— Governor John Winthrop, June 12, 1630, aboard the *Arbella*

**Trimountain, view south from Charlestown.
From J. Winsor's (1880-1882) history of Boston.**

Boston, Massachusetts is considered — by many who have worked to understand its complex sequence of deformed unconsolidated material and bedrock — to be unlike any other city in the world and geologically unique. The same series of geologic events responsible for its founding have conspired to make foundation design a serious challenge to the engineering community. Boston's soils range from the softest compressible organic material to very dense glacial till (as well as an extreme variety of fill). Their complexity and unorthodox behavior gave rise to the sciences of engineering geology and soil mechanics at the Massachusetts Institute of Technology and Harvard University starting in the late nineteenth and early twentieth centuries, respectively. The variation in potential response to earthquakes of this material and the memory of the 1755 earthquake also led to the development of the first seismic hazard studies for insurance purposes. The bedrock is equally complex, and unravelling its variable rock types and myriad faults has further challenged those who work in the region.

When the Puritans first surveyed the site that would be Boston, they could not have conceived that it was a gift from plate tectonic movement: a remnant of ancient Africa that had smashed against the old North American continent and was then left dangling as the Atlantic Basin later broke open. The more recent repeated gouging by glaciers and burying by their debris would have been easier for the Puritans to fathom as God-given plagues for the sins of a wayward lost tribe of Israel. These events, however, created a favored place for their "City Upon a Hill," but one that stretched their ability to build upon it. The unique geologic conditions around Boston brought out the remarkable ingenuity of their descendants in overcoming obstacles to create a remarkable list of engineering firsts. The unraveling of this geologic history and construction on the unstable ground over the past two hundred years chronicles a remarkable achievement. The following is a story of this geologic framework, how it affected settlement and the struggle to overcome the limitations it imposed and difficulties in construction.

This special issue is a revised and greatly expanded version of our paper, "Boston Geology: A Survey of Engineering Impacts," published in *Civil Engineering Practice* in 1989 and our paper, "Geology of Boston, Massachusetts," published in 1991 by the Association of Engineering Geologists. We acknowledge the late Clifford A. Kaye of the USGS, Henry Russell of PBQ&D, William E. Pitt of GEI, the late Stephen A. Alsup and K.E. Franz of S.A. Alsup Associates, and the late Edmund G. Johnson of Haley & Aldrich, Inc., who contributed to those publications. The descriptions of the bedrock geology of Boston were compiled in large part from the work of Kenneth G. Bell and Clifford A. Kaye.

We gratefully acknowledge our indebtedness to Clifford A. Kaye and Kenneth G. Bell for their many years of work to understand the geology of the Boston Basin. The papers presented here were prepared by us with the aid of many from Boston's geotechnical and geologic community whose contributions are appreciated. These persons include Brad Miller and Damian Seibert of Haley & Aldrich, Chris Erikson of McPhail Associates, Matthew Barvenik of GZA, Jutta Hager and Mario Carnevale of Hager Geosciences, Leo Martin of AECOM, Richard Sherman of Metcalf & Eddy, Jean Carroon of Good Clancy, Frank Leathers of GEI, John Kaplan of Gilbane, John Roma of Weeks Marine, Andy McKown of McKown Associates, Margaret Thompson of Wellesley College, Dorothy Richter of Hager-Richter, Christine Keville of Keville Enterprises, Thomas Annaratone, Ann Leifer, William Levy and Rebecca Kennedy. We also thank Brian Boisvert of Roger Williams University for the preparation of the figures, Donald Call for his IT expertise, Deborah Cooper for word processing and the following technical reviewers of the various sections in these and previous papers: A.W. Hatheway, the late M.H. Pease, Jr., the late W.H. Dennen, Harl P. Aldrich, Jr., the late Ronald Hirschfield, E.L. Krinitzsky, the late Dorothy Brownlee, the late William A. Weiler, Joe Engels and James Lambrechts. We gratefully acknowledge their efforts, time and useful comments. Finally, we gratefully thank our wives, Sandra Maxwell and Jeanne Woodhouse, for their support and patience over the many years it took to write these papers.

We extend our appreciation to BSCES for publishing these papers, to Gian Lombardo for his professional editorial and production work, and to James Lambrechts, Chair of *Civil Engineering Practice*'s Editorial Board and of the Wentworth Institute of Technology, for his tireless efforts in editing these papers and for his technical contributions to various sections.

Many remarkable achievements have been made in the fields of classical and engineering geology in the Boston metropolitan region over the past two hundred years that have resulted in a long list of engineering firsts for the nation. The challenge of the extremely complex geology beneath the city has been met in many original and innovative ways as Boston expanded. The success rests on careful field observations and adherence to disciplined scientific and engineering practices. The scientific and practical value of good geology has been shown time and again. Departures from this have led to setbacks, delays and unnecessary costs. Continuing success rests on maintaining highly qualified geologists and engineering geologists, and having access to the previous work in the area. A solution for the decline in field-based geology in New England schools has not been found, nor has maintaining the availability of reports on the work done in metropolitan Boston. The latter is urgent as valuable information is being continuously lost. The proper archiving and cataloging of this information would result in significant savings in planning, avoiding problems and preventing duplication of effort.

The future for building development in Boston and attendant supporting infrastructure is promising in spite of periodic economic slowdowns. The great past accomplishments in engineering geology, as in the Big Dig, will occur again. Each project will offer new challenges to engineering geologists and geotechnical engineers, but they will have a proud history of experience and achievements to draw upon.

—PATRICK J. BAROSH & DAVID WOODHOUSE

Settlement, Topography & Geologic Studies of Boston

A review of the important studies from the last two centuries is key in understanding Boston's complex geology.

PATRICK J. BAROSH & DAVID WOODHOUSE

In 1630, John Winthrop and his fellow Puritans set sail from their native England to "found a city upon a hill" — a city that cannot be hid. This effort was unhindered by Native Americans because roughly ninety percent of them had died from disease just before founding this city. As Winthrop unfeelingly put it, by this misfortune "God hath thereby cleared our title to the place." What Winthrop termed "the Lord's Waste" was quickly transformed into a second England. The endeavor was aided by a fortuitous sequence of geologic events that produced a safe harbor, bountiful spring water and good natural sites for fortifications for the new settlers and Winthrop's dream was fulfilled (see Figure 1-1). However, the early settlers gave scant thought to the extremely complex and unusual geology of the region other than curse, under their breath, the stones that grew in the fields each spring. Anyone trying to explain that one of the greatest structural zones of North America passes just west of Boston and that the city now rests on a fragment torn from ancient Africa would have been expelled from the colony, if not hung as a heretic (see Figure 1-2).

The ancient North American and African plates — referred to as Laurentia and Gondwana, respectively — collided in a zone just west of Boston about 650 to 620 million years ago (see Figure 1-3). The geologic character of this margin and the structure to the east of this belt are not seen elsewhere on the Atlantic coast of the United States. When the much later rifting of about 225 million years ago began to form the present North Atlantic Basin, the split left a piece of northwest Africa clinging to North America. This fragment became the foundation upon which Boston was built. The city and its harbor lie in their own much smaller rift basin formed during a pause in the collision at the very end of the Proterozoic (pre-Cambrian) about 600 million years ago. An array of volcanic debris, gravel, sand and mud gradually filled and overflowed the rift. As the collision ended in the late Ordovician about 440 million years ago,

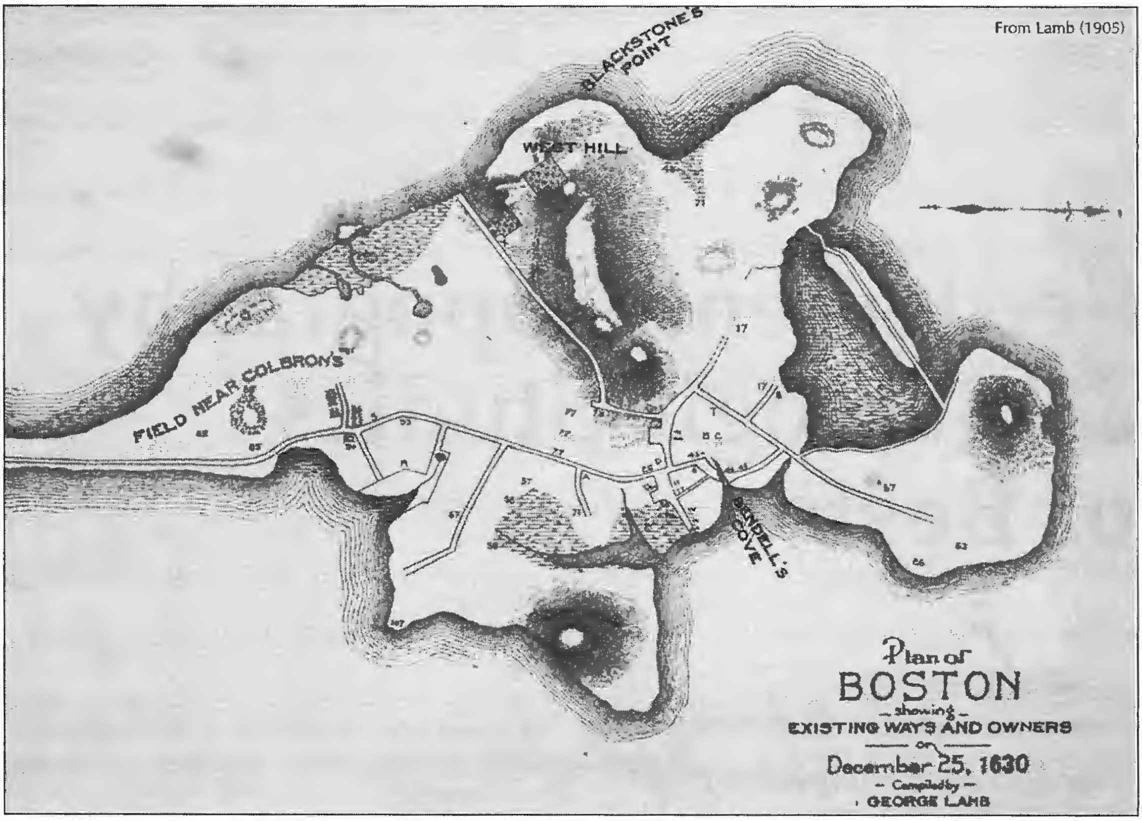


FIGURE 1-1. Plan of Boston from 1630 showing the existing ways on the Shawmut Peninsula.

volcanic upheavals formed masses of granite on both sides of the rift to give added character. These and subsequent events produced numerous kinds of structures and rock representing almost all later geologic periods. The region remains active, with earthquake activity and other indications of crustal movement, and is not at all passive. Repeated glaciations during the Pleistocene stripped off the overburden from the bedrock and then haphazardly re-covered it with a wide variety of deposits that were locally deformed by glacial re-advances. The wide fluctuations in sea level as the ice advanced and retreated along the coast left behind a confusing array of terrestrial and marine debris. The last retreat of the ice left high drumlins and hollows that have filled with water, soft sediment and peat as the sea level rose from the melting ice to create coastal marshes and beaches. The land also suffered a tilt to the south when it rebounded from the ice removal, which, combined with tectonic subsidence and a vast leveling and infilling by man, created a varied, interesting and complex coastal environment. All of these features make the Boston area one of the most challenging anywhere since nearly every site is different. The challenge in overcoming the attendant problems resulted in achieving a remarkable number of engineering firsts.

Boston's Firsts

Both the city of Boston and the state of Massachusetts contributed much to the development of the study of the area's geology and its application to the extensive underground work on water, sewer and subway tunnels, and especially the recently completed Central Artery/Tunnel Project. This endeavor had many forbearers, including: Mother Brook, the first American canal built by Europeans in 1639; the tall 1716 Boston Light that was the first American lighthouse; and the bridge to Charlestown in 1785, which was considered at that time to be the greatest engineering enterprise ever undertaken in America. The bridge

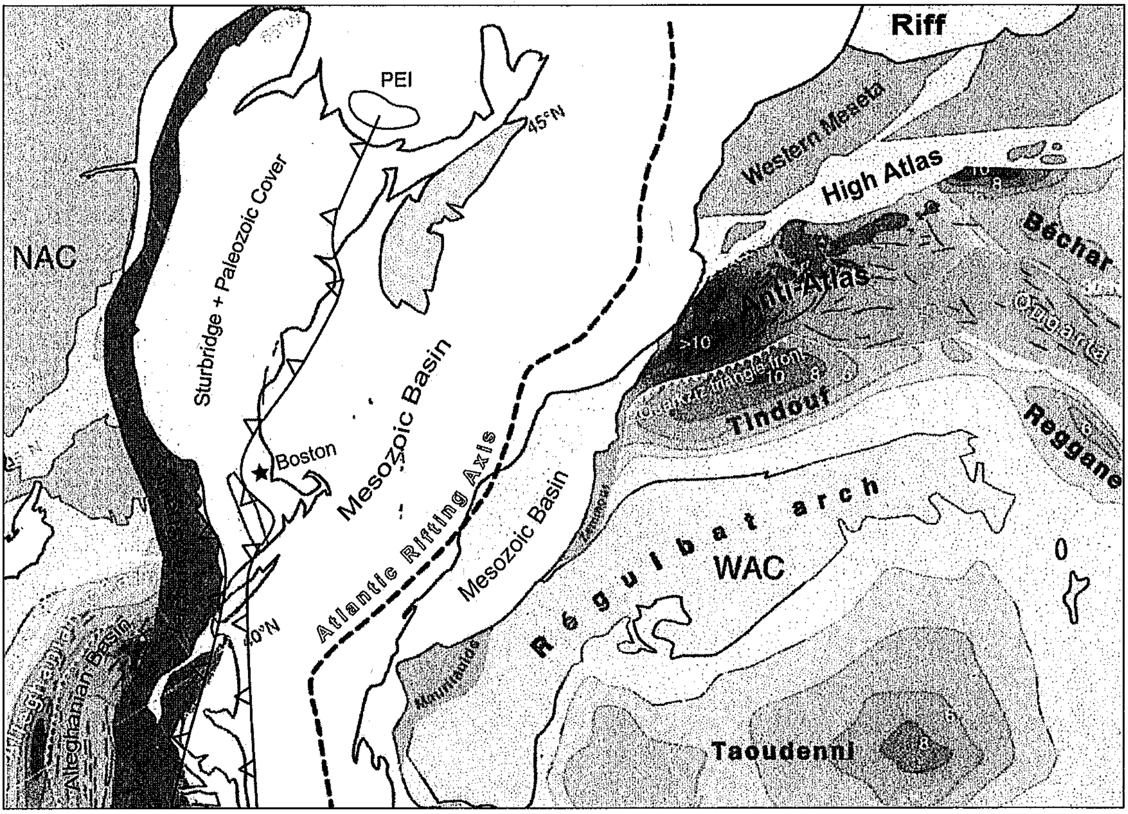


FIGURE 1-2. Map showing the New England/Morocco connection prior to the opening of the North Atlantic Basin.

was soon to be followed by the second greatest work, the Middlesex Canal, which was started in 1795, completed in 1803 and served as the prototype for the Erie Canal and the boom in canal construction. These achievements were joined by the first sewer system built from 1787 to 1834, the first gravity railway near Boston Common in 1805, the first chartered railway in 1826 and the longest bridge in North America in 1835 — the Canton Viaduct — for the Boston-Providence railway (still in use by Amtrak). The first subway was built in 1897, followed by the first extensive city water system of dams, aqueducts and tunnels; and farther west, the Hoosac Tunnel, the first great railway tunnel, introduced many new advances in tunneling. Boston also has the greatest filled area for residences in the world. Keeping with this tradition, the cofferdams built for the Ted Williams Tunnel, which opened in 1995, were the largest in scope in North America. The early engineering projects, which led to the formation of the first engineering society in the nation in 1848, the Boston Society of Civil Engineers, required an ever-expanding need to understand the area's geology, perhaps explaining why Boston was the first city to have a geologic map in 1818 and Massachusetts the first state to have a geological survey in 1833. What surely would have astonished John Winthrop was the first modern description of an earthquake in 1755, "shorn of God's vengeance," by his direct descendant and namesake John Winthrop of Harvard College. This earthquake started Winthrop's student John Adams on his career of writing.

Early Settlement

Native Americans reached southwest Pennsylvania some 16,000 years ago, south of the retreating glacial ice front, but were not recorded in Boston until much later when they built extensive fish weirs in the Back Bay (now near

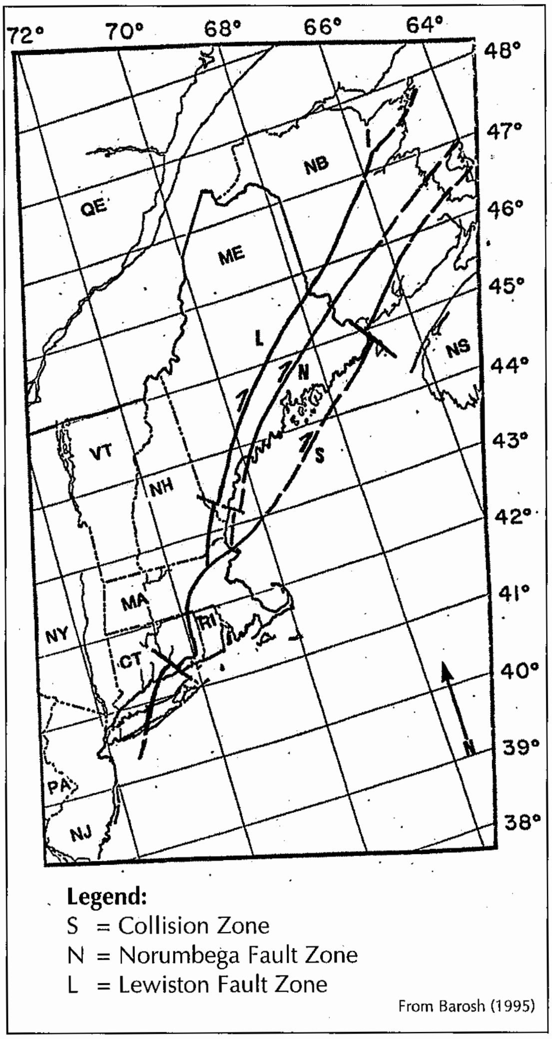


FIGURE 1-3. Map of New England and adjacent Canada showing the collision zone between ancient North America (Laurentia) on the northwest and ancient Africa (Gondwana) on the southeast, along with regional faults.

Boylston Street) between 5,300 and 3,700 years ago. These remains were uncovered in various subway and deep foundation excavations (Decima & Dincauze, 1998). More important are the Indian hornfels quarries in the Blue Hills that were being worked about 7,000 years ago for arrowhead material, which was very scarce in the region. This arrowhead hill, or Massachusetts in Algonquin, gave name to both the area and the tribe that lived there (Bowman & Zeoli, 1977). Norsemen were believed by some (without evidence) to have explored the Boston area between 900 and 1000 A.D. This belief was held by some to a sufficient degree that a statue commemorating Leif Erikson was erected on Commonwealth Avenue at Charlesgate East in 1887. Many early European fisherman, traders and explorers followed from the end of the fifteenth century. At least fourteen explorations of the northeast coast of North America were made in the sixteenth century and twenty-seven known ones made in the first twenty years of the seventeenth century (Dexter, 1984). The quest for cod brought sixteenth-century English, Basque and Portuguese vessels that would have visited the waters around the Shawmut Peninsula — Shawmut being a Native American name meaning "living waters." By 1625, these vessels numbered three to four hundred or more annually, some ninety years after the first failed settlement of Quebec and nearly a hundred years after the first ten fishing boats were spotted. In 1602, Native Americans in Basque boats wearing European clothes sailed by a temporary settlement on Cuttyhunk Island in southeastern Massachusetts set up by Bartholomew Gosnold, who later founded Jamestown in sunnier Virginia. Soon a flurry of mostly short-lived outposts and settlements dotted the coast in the region. Samuel Champlain mapped the Massachusetts shoreline in 1605 as did Captain John Smith who made a foray up the coast from Virginia in 1614. Smith decided New England was a suitable name for the region and Prince Charles bestowed his name to the Massachusetts River washing the western side of Shawmut Peninsula (see Figure 1-4).

Sites north and south of Boston were settled by Europeans first, saving the best for last. Boston might easily have been the home of the Pilgrims had they not balked at hiring Smith as their guide in 1620. When Captain Miles Standish, with a small group of Pilgrims and Native American guides, came along the shore from Plymouth in a small open sailboat and entered Boston Harbor on September 19, 1621, they realized that this site was ideal, but decided they had already invested too much at Plymouth to move. David Thompson founded a trading post in the bay on the

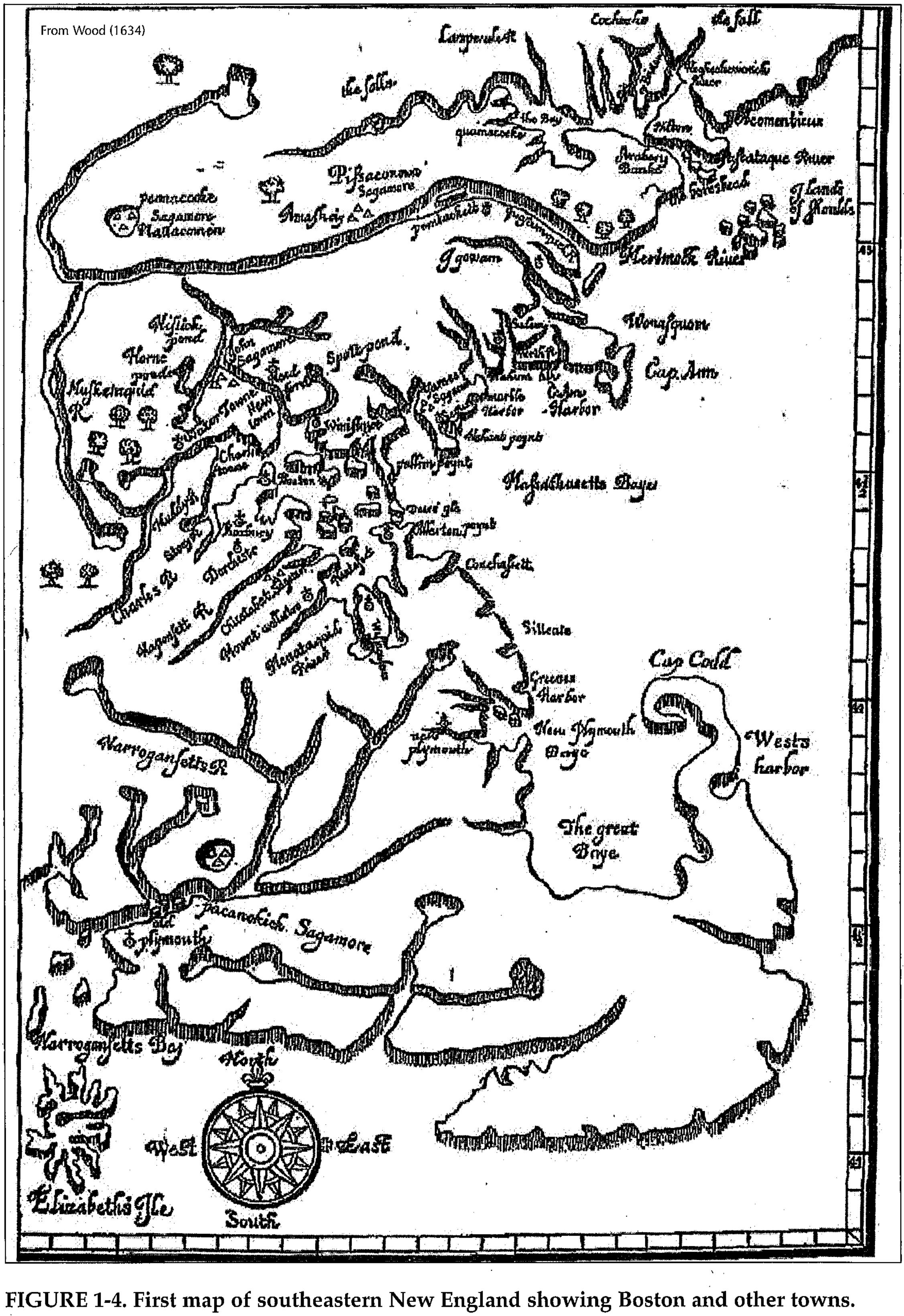


FIGURE 1-4. First map of southeastern New England showing Boston and other towns.

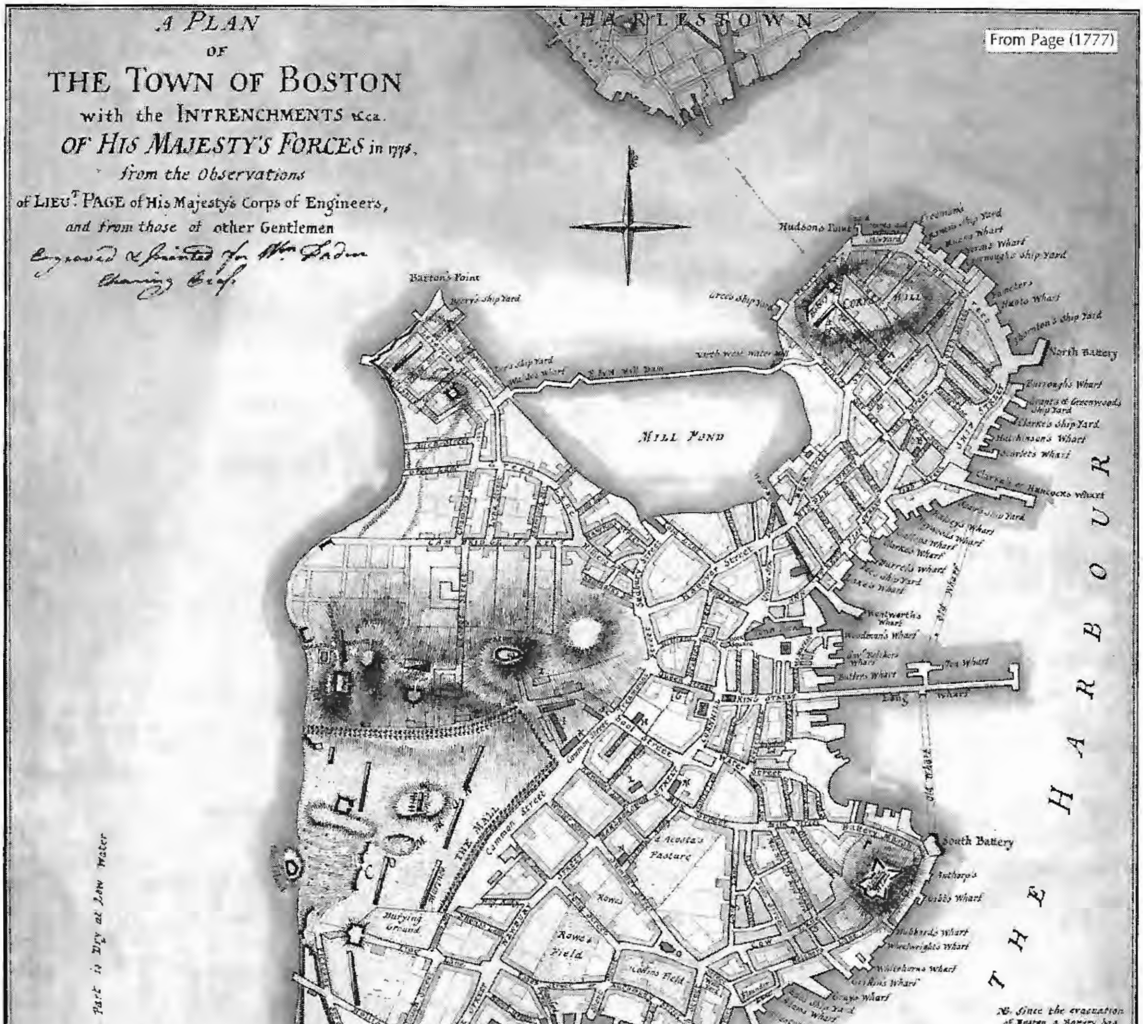


FIGURE 1-5. A plan of the town of Boston in 1775.

appropriately named Thompson Island and the retired Episcopal minister William Blaxton (Blackstone) arrived on Shawmut Peninsula in 1625. There were perhaps fifty people in several settlements close to Shawmut to greet the Pilgrims.

Shawmut Peninsula

The Shawmut Peninsula, which was later christened as Boston, was shaped by all the geologic events described above. For much of its history, from its founding in 1630 to the filling of the tidal flats along the coastline and the Charles River in the eighteenth and nineteenth centuries, Boston had the smallest land mass of any major city (see Figure 1-5). It was quite small at the beginning, only about 487 acres, and was dominated by the three prominent joined hills called the Trimountain — or, in the looser spelling of the day, either Tramount, Tremount, Tramountaine or Trimountain. Nowadays it is spelled Tremont. If Boston Neck to the south is included, the city was 717 acres (Seasholes, 2003). At low tide it formed the peninsula, but at high tide it was an island complex connected to the south by a narrow neck that was awash at times and deep enough to drown unwary travelers (see Figure 1-6). It was one of over fifty islands counted in 1621 in the large Massachusetts Bay that stretches out to the east and indents the New England coast (see Figures 1-4 & 1-7). The number is now down to thirty-eight, since islands such as Nix's Mate (now just a shoal) and Calf Island (now a small rock remnant) have disappeared, but they still act as a buttress to the Atlantic storms and shelter Boston. An incredible mixture of drumlins, moraine, marine clay and thrusted sediments (which include outwash sand, clay and till) was packed into this small city that now is dominated by Beacon Hill. The peninsula juts northward and was flanked by broad tidal flats on the west along the Charles River, but a snug harbor on the east that sent ships around the world was the pride of Boston. The ancient rift basin forming the depression in which the city and the bay lie is mostly filled with relatively soft argillite bedrock, a sedimentary rock formed mostly from mud. The western and southern edges rise into hilly areas underlain by more resistant conglomerate and volcanic rock — a step below the higher surrounding granite cored terrain that juts seaward north and south of the bay. The city's one shortcoming is the lack of a major navigable river connecting it to the interior, such as the Merrimack to the north, but this deficiency helped turn its attention outward into the broader world.

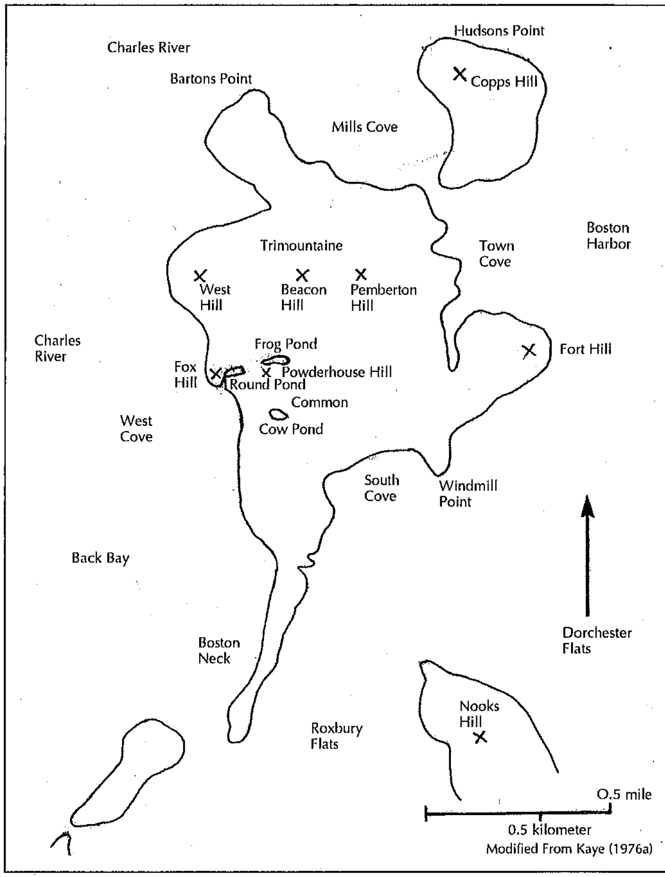


FIGURE 1-6. Shawmut Peninsula at mean high tide in 1630 with early colonial names for topographic features.

Serendipity or Divine Providence

On June 12, 1630, John Winthrop and his fel-

FIGURE 1-7. Boston Harbor islands in 1782.

low Puritans reached Salem and were greeted by a landscape of barren rock and little soil, a brutal contrast to their native, fertile southern England. Pressured by his followers, Governor Winthrop, after spending just five days in Salem, left for Charlestown where a group of

Englishmen had already settled in search of more promising land. By July 6, eleven ships had arrived at Salem or Charlestown, carrying the survivors of stormy seas and sickness, which had decimated their ranks. Within a couple of weeks, the new settlers at Charlestown were nearly defeated by sickness, death and lack of water. Winthrop blamed his troubles on the one source of water available, a brackish spring that was only exposed at low tide. Their sickness was compounded since the English traditionally drank water from springs rather than dug wells, although beer was apparently their first choice. Help came in the person of the hermit William Blackstone, a retired Episcopal minister who had been living alone across the Charles River for five years. Blackstone had been the chaplain of the unsuccessful Robert Gorges's Plantation, which had settled on the south side of Hingham Bay at Wessaguscus or Wessaguset (now Weymouth) in 1623 (see Figure 1-4). Blackstone was the first English settler on the Shawmut Peninsula and built a cottage on the south side of Beacon Hill near the Common, where Spruce Street now meets Beacon Street. Blackstone told Winthrop of the abundant and refreshing spring water available on his land. Accepting his invitation, Winthrop and his group moved across the river to the peninsula. According to Lathrop (1800), abundant spring water did exist on what was to become Louisburg Square on Beacon Hill, Pemberton Hill and Spring Lane east of Pemberton Hill (see Figure 1-6). The discovery of many old colonial wells in modern excavations attests to this gift of geology. The group settled near Spring Lane, the North End and at the Great Cove (Town Cove) at the bottom of what is now State Street. Winthrop built his house close to the "Great Spring" at what is now 276 Washington Street. Blackstone must have regretted the invitation, since he soon sold his property and moved to the wilds of what became northern Rhode Island, where he preached a tolerant Christianity and developed a new variety of apple.

Thus, Winthrop founded his "city on a hill." The hill was a mountain with three small rising hills on top of it called the "Trimontaine." This prominent feature (with various spellings) can be seen from Charlestown. At 8 A.M., September 7, 1630 (Julian calendar) by order of the Court of Assistants, Governor Winthrop presiding, it was so decreed "[t]hat Trimontaine shall be called Boston." The name came from Boston, England, in the parish of St. Botolph, and was a contraction of "Botolph's town," after "Bot" meaning boat, and "ulph" meaning help. St. Botolph was the patron saint of fishing. Boston's roots were thus established. So was its characteristic accent, shown by an alternate spelling "Baston," which reflected how settlers spoke the word. It was named for the home town of the Reverend John Cotton, who had sent them off with a farewell sermon, and being so honored, he came three years later. The choice was a goodly one since "[Shawmut] being a neck bare of wood, they are not bothered with the three great annoyances of wolves, rattlesnakes and mosquitoes" (Wood, 1634).

Topography

Excavation and filling, along with natural erosion, has greatly changed the topography within the sea-flooded basin holding Boston and the harbor islands since settlement. Fortunately, Boston is blessed by many early accurate maps and drawings that display the original features, thereby allowing an interpretation of their origin. The early hills of the Shawmut Peninsula are well known. Trimontaine was formed by three prominent coalescing hills rising 46 meters (150 feet) above its surroundings (see Figure 1-8). The westernmost hill was West Hill, later called Mount Whoredom on British maps, or Copley's Hill and finally Mount Vernon, when it was lowered and developed. The central peak was Beacon, or Sentry, Hill. And the easterly hill, separated by the small Valley Acre, was first called Pemberton Hill and then Cotton Hill (see Figures 1-6, 1-9 & 1-10). Place and street names in the town also tended to be casual and continually changing due to different ownership or activity. Several lesser hills also were scattered about the Shawmut Peninsula. Copp's Hill, also called Windmill Hill from the one built there in August 1632, or Snow's Hill, rising 15 meters (50 feet) in the North End, and Fort Hill, also called Corn Hill, rising 24

FIGURE 1-8. View north at Boston and Trimountain from east of the Shirley House, Roxbury on the road to Dorchester in 1775.

meters (80 feet), were situated on points of land facing the sea to the east (see Figures 1-5, 1-6, 1-11 & 1-12). Smaller hills or knolls were also found, such as Fox Hill and Powderhouse Hill (also known as Flagstaff Hill), situated to the southwest on the Boston Common (see Figures 1-6 & 1-13). Other high rounded hills rose up on the mainland such as at Charlestown to the north (Breed's Hill, Bunker Hill, Morton's Hill) and across Dorchester to the southeast (Telegraph Hill, Dorchester Heights, Savin Hill). The tops of many more rise above the water in the harbor to form islands, such as the nearby Castle Island in South Boston and Camp Hill in East Boston (see Figures 1-14 & 1-15). Most of the protect-

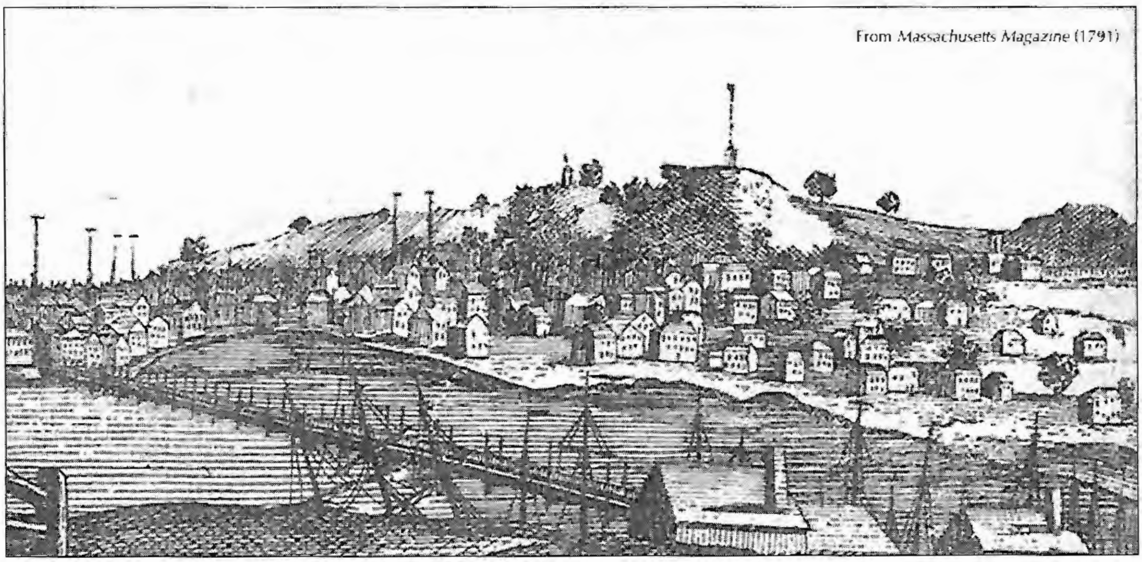


FIGURE 1-9. View south at Boston from Breeds Hill in Charlestown at Beacon Hill with Mill Pond in the foreground.

ed mainland shore was bordered by broad salt marshes and tidal flats (see Figure 1-16) except for the inner harbor area at Boston. Broad shoals surrounded the more exposed of the islands and many of the islands were actively eroding away and surrounded by bluffs, with the smaller ones eventually disappearing (see Figures 1-17, 1-18 & 1-19).

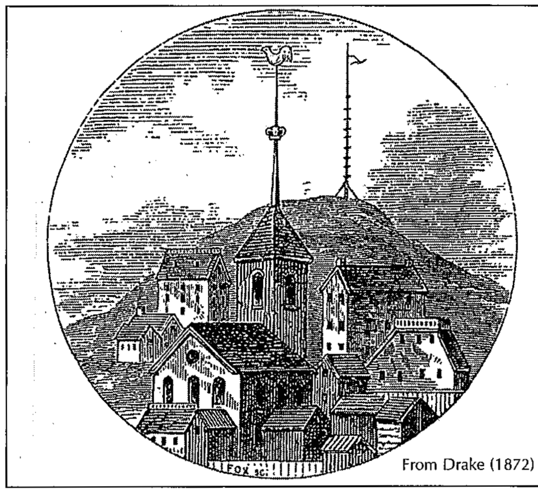


FIGURE 1-10. View west across Old Kings Chapel at houses on Pemberton Hill, with Beacon Hill rising behind it in the early eighteenth century.

Geological Influences Affecting Settlement

There were several major geological influences that affected the founding of Boston (Kaye, 1976a). Being a seafaring people, the early settlers looked for a safe harbor. Boston's island-studded harbor is formed by a deep indentation in the coastline of Massachusetts (see Figure 1-7). This indentation exists primarily because the underlying rock, mostly argillite, is softer and more easily eroded than the hard highland conglomerate and granitic rock, which surround the Boston Basin (the name of this large topographic and structural depression). Glacial ice further eroded the broad valley and, with subsequent melting of the ice, the sea level rose and flooded the depression, thereby forming the bay and "a safe and pleasant harbor." "This harbor is made by a great company of island, whose high cliffs shoulder

FIGURE 1-11. View northeast across Long Wharf at Boston Harbor (circa 1790), with Beacon Hill in the center, Copp's Hill on the right and the rounded hills of the mainland in the distance.

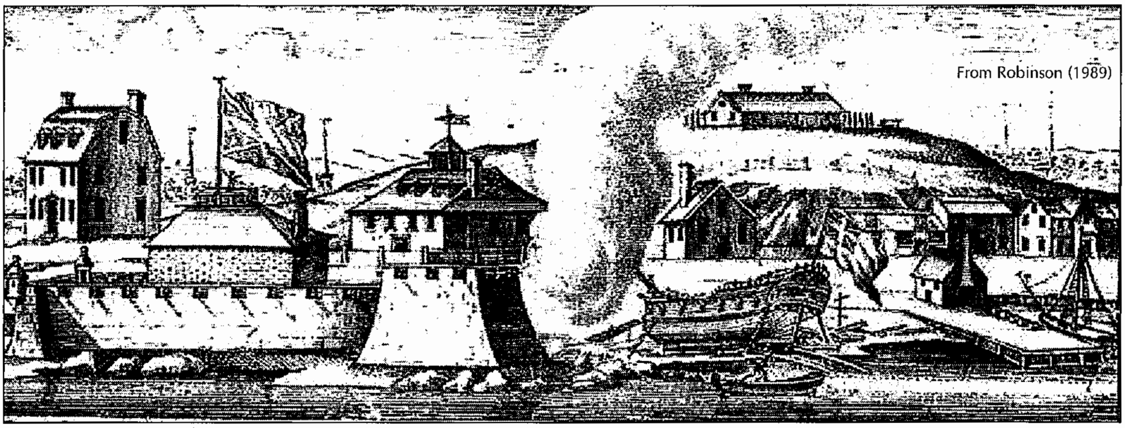


FIGURE 1-12. View south at South Battery with cliff-faced Fort Hill (behind) circa 1765.

out the boisterous seas, yet may easily deceive any unskilfull [sic] pilot; presenting many fair openings and broad sounds, which afford too shallow waters for any ships" (Wood, 1634). Three ships could sail abreast through the narrow inlet that protected the harbor and once within there was anchorage for five hundred ships (Wood, 1634). It was this safe harbor, which served as the chief port for numerous settlements of the hinterland, that made Boston the most noted and frequented city in the Northeast (as well as the seat of the Massachusetts Bay Colony), even though it was neither the greatest nor richest city in the region.

The second important factor was that the settlers looked to the land for protection from their enemies. Boston had many drumlin hills naturally situated for fortifications to protect it from attack from the sea, along with those forming the harbor islands. Trimontaine overlooked the harbor and sea coast to serve as the site of the warning beacon. Copp's Hill at the north end and Fort Hill to the east both served as locations for batteries (especially the latter) that commanded a view of any ship that sailed into the harbor (see Figure 1-12). Forts were built on Castle Island and many of the other islands over the next two centuries. Later, even the small Fox and Powerhouse hills on the Boston Common were used for defense. However, many of these drumlins, including Trimountaine (now only represented by Beacon Hill), are not the simple drumlins they first seemed.

Third, the Shawmut Peninsula was an island at high tide. The land to the south, called the Neck, which connected to Roxbury, was very narrow and low, and at best served as a causeway for travelers, but it was also easy to defend (see Figure 1-6). The British Regulars cut through the Neck in front of gun emplacements during the British occupation of Boston (see Figure 1-5).

Fourth, the primary and literally life-giving element was the abundant water available to the settlers. The Shawmut Peninsula became the Town of Boston because of sweet and pleasant springs, along with water of good quality under artesian pressure from shallow dug wells. Much of the area is underlain by a sandwich of thick, pervious sand and gravel between lodgement till and marine clay, and the thick deposits beneath Beacon Hill fed reliable springs at its base. The water was of such quality that some even preferred it to good beer and most to bad beer, whey and buttermilk (Wood, 1634).

Fifth, the surrounding salt marshes and mud flats provided the salt marsh hay preferred by the cattle. The marshes and flats also supplied abundant shellfish and smaller fish for the colonists. Some marshes also were dammed to power tidal mills (see Figures 1-5, 1-9, 1-16 & 1-17), as at the North Cove (Mill Pond).

Sixth, the hills in Boston provided suitable material to fill lowland and tidal flats.

Seventh, the stone and rock of the region provided for general building material, the split argillite for roofing, and the clay deposits for brick and tile. Boulders on the surface in Boston provided foundation material. Roofing was quarried from islands and promontories

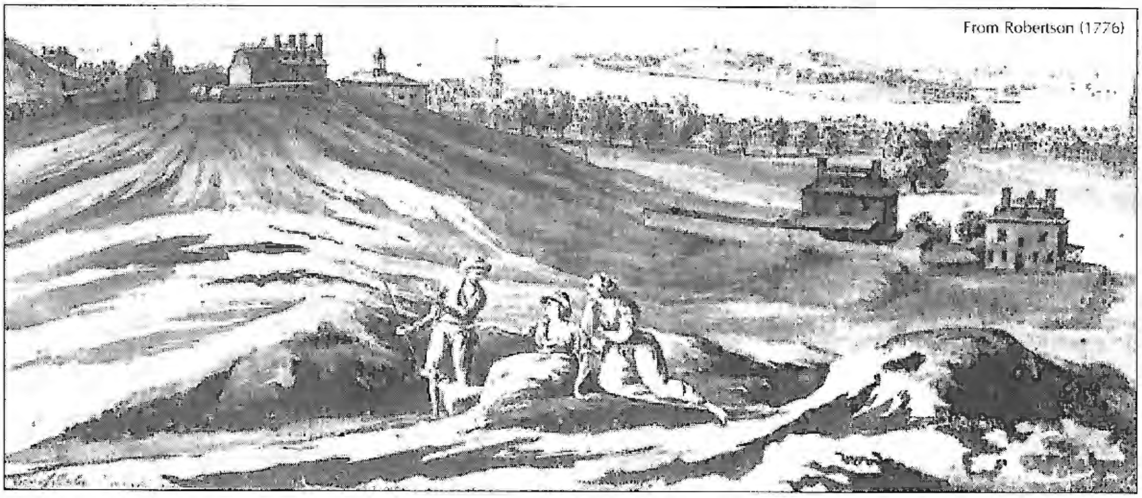


FIGURE 1-13. View east along the south edge of Beacon and Pemberton Hills from West Hill (later developed and named Mount Vernon) with the Common and Powderhouse Hill on the right.

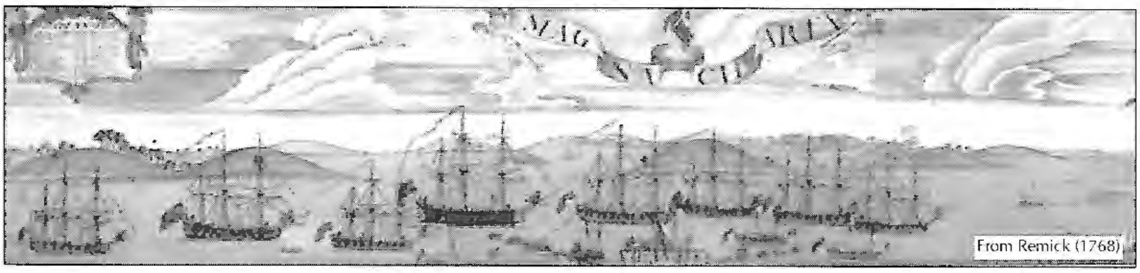


FIGURE 1-14. View east from the end of Long Wharf at English ships and islands in the harbor in 1768 (opposite view from Figure 1-12).

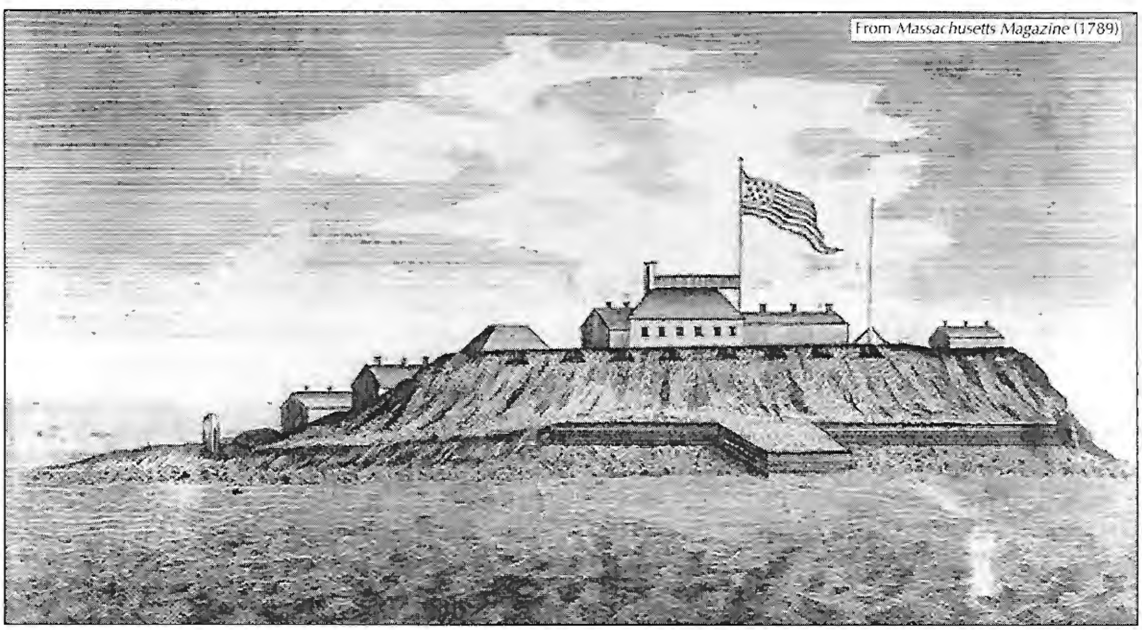


FIGURE 1-15. A north view of Castle William on Castle Island circa 1789.

(see color version on page 449)

FIGURE 1-16. Boston and the lower Charles River estuary showing marshes in 1775.

at the south side of the bay. In addition, clay for brickworks was found at Charlestown and elsewhere.

Lastly, the surrounding area had sufficient rivers and streams to power mills to grind corn and saw wood.

These factors all contributed to a notable population increase and considerable development of the Shawmut Peninsula (see Figure 1-20) during the seventeenth and eighteenth centuries (Krieger & Cobb, 1999; Seasholes, 2003; Haglund, 2003). To reclaim the surrounding marshy lowlands, early land developers looked to the hills. Fox Hill was the first to go when the shoreline was extended (see Figure 1-6) and then the three hills of Trimountain served as a ready source of fill. In 1799, about 15 to 18 meters (50 to 60 feet) of West Hill was excavated by the Mt. Vernon proprietors to fill in the cove at its base, thus creating Charles

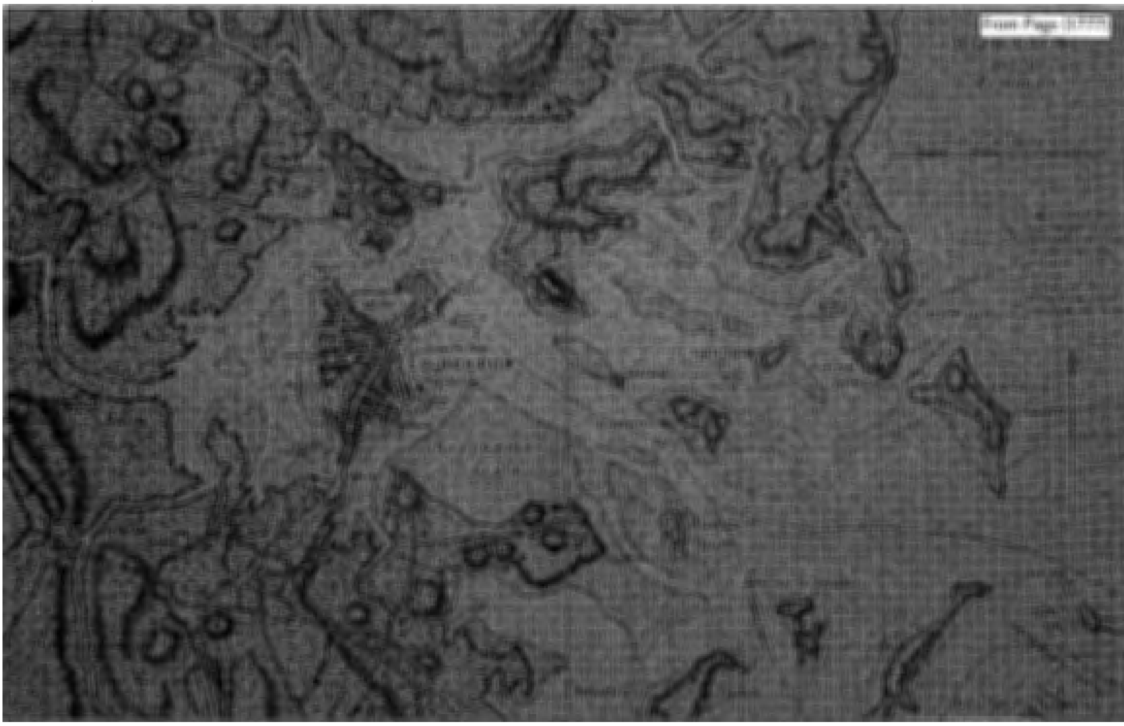


FIGURE 1-17. Boston and its environs showing marshes, tidal flats and shoals in the bay in 1775.

Street. The Mill Pond, created in 1643, was the next area attacked in the enthusiasm for increasing the land area of Boston (see Figure 1-5). The central peak of Beacon Hill, itself a source of gravel since 1758, was lowered by 18.3 meters (60 feet) by John Hancock's heirs and Mill Pond was filled in. The last hill, Pemberton Hill, had its top shaved off by Patrick Tracy Jackson, a railroad man, in 1835 to fill new land north of Causeway Street and develop Pemberton Square. The remaining ridge connecting the former peaks of Pemberton and Beacon hills was leveled in 1845 (Whitehill, 1968). A scheme developed during the War of 1812 to build a long Boston and Roxbury Mill Dam across the Back Bay for tidal power was finally carried to fruition in 1821 to serve as a road bed for a future railroad and then as Beacon Street (Marchione, 1996). The latter half of the nineteenth century saw the last major filling (see Figure 1-21), as the Back Bay was created from sand and gravel brought in approximately 13 kilometers (8 miles) by railroad from Needham to the west and dumped behind the mill dam (Newman & Holton, 2006).

FIGURE 1-18. Rocks on the east end of Little Brewster Island and the Boston Light prior to the erosion of the sides of the island.

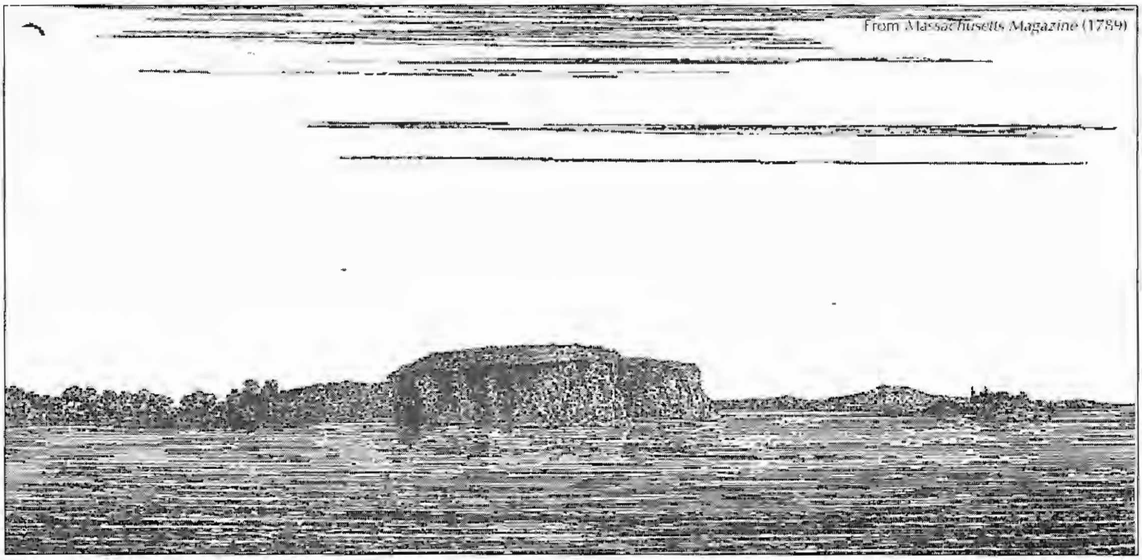


FIGURE 1-19. Nix's Mate Island circa 1789 before being eroded to a shoal.

FIGURE 1-20. Map of the colonial Shawmut Peninsula of 1700s (heavy line) superimposed on an 1880 map of Boston.

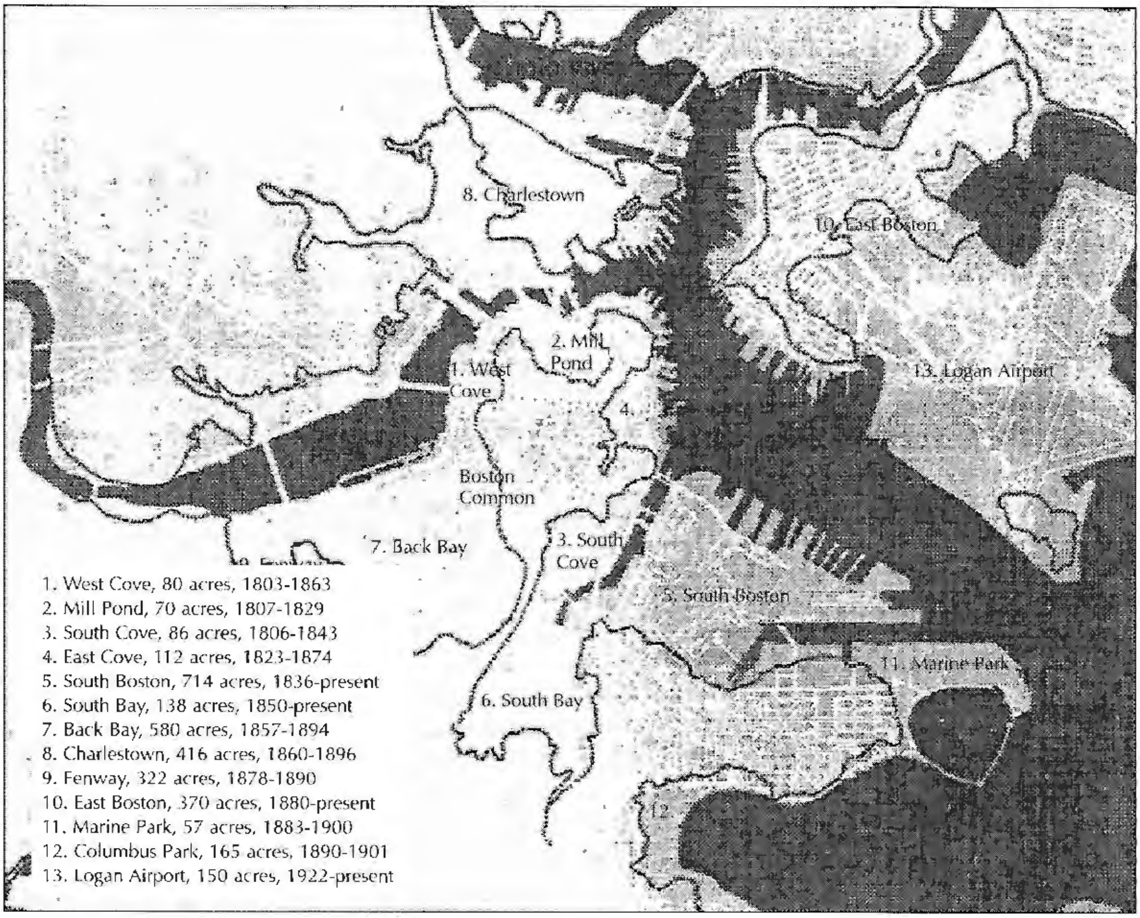


FIGURE 1-21. Map of the Boston metropolitan area showing the historic land filling that expanded the original 717 acres to over 3,000 acres in 1976. (Courtesy of the Boston Society of Architects.)

Other geologic factors helped guide development and helped shape the rugged independent character of the early inhabitants of the city and surrounding towns in Massachusetts. The lack of mineral resources and the limited fields that grew rocks every spring did not favor the development of large plantations with landed gentry and a subclass of farm laborers. Even lime for fields was lacking except in the western mountains, where it was then of limited value, and small deposits in Rhode Island. The drowned offshore coastal plain deposits, however, provided banks that suited the growth of cod and attracted whales. This fact led to Massachusetts developing offshore whaling and eventually becoming a leader in world-wide whale hunting and maritime trade, an endeavor aided by fine harbors at the home ports. The lowering of Beacon Hill and then quarrying of granite north and south of Boston led to the development of the first railways in the country. The latter connected the quarries to the docks, from which the stone was shipped to other East and Gulf Coast cities. The trade in overseas manufactured goods led to promoting local factories, which made full use of the water power at dams across streams in the many fault-controlled valleys. From the very first, settlers proposed modifying the sometimes hostile land to fit their needs. They drained coastal marshes for hay fields and built some of the first canals, railroads, railroad tunnels and water tunnels in the country. Large projects seemed to be ingrained in the populace. Soon after Concord was settled in 1635, it was proposed to either divert part of the Concord River to the south or blow up the falls to the north to tame the spring floods, and in 1639 part of the Charles River was diverted into the Neponset River to supply mills with greater waterpower. The bridge to Charlestown in the eighteenth century and the Hoosac Railroad Tunnel through the highest ridge of the Berkshire Hills, at the then-immense cost of $17 to 21 million, in the mid-nineteenth century were the Big Digs of their day. The tunnel project made an abortive effort to use the first tunnel-boring machine and introduced the use of nitroglycerin at a great cost in miners' lives. Now the nearly $15 billion Central Artery/Tunnel Project to depress and extend highways in Boston is the greatest one of its kind. All of these endeavors required an understanding of Boston's local and regional geology.

Evolution of Local & Regional Geologic Understanding

The foundations of American geology began around Boston, and the region has been a leader in research. The contributions of many eminent geologists helped unravel the area's complex geology, which has been a remarkable achievement. That evolution and refinement in geologic understanding continues today as new projects uncover and expose new details of the geology. Much of the information presented herein reflects the known body of knowledge and facts about the various bedrock and soil layers found throughout the Boston area and region. These "data" collectively support the theories expressed by several earlier researchers (as discussed herein). A more complete understanding can be acheived by tracing the evolution of geologic viewpoints, including various interpretations and re-interpretations about the geologic origins of the region and the Boston Basin, and its current status.

Boston and the surrounding region have been blessed by many outstanding geologists over the past two hundred years whose fieldwork revealed the geologic framework of eastern North America. Early noted geologists such as Edward Hitchcock, Charles Lyell, C.H. Hitchcock, Rafael Pumpelly, Charles Walcott, William Otis Crosby, Amadeus William Grabau, William Morris Davis, Nathaniel Shaler, B.K. Emerson, J.B. Woodworth, William Hobbs, Lawrence LaForge, Walter Goldthwait and many others made numerous fundamental discoveries prior to World War I. A short history of this work is presented by LaForge (1932). Much of this achievement was due to a concentration of effort in the region by the fledgling United States Geological Survey (USGS), building on the impressive earlier work. Massachusetts had the first state-funded geological survey, which was directed by Edward Hitchcock, who produced a state map and report in 1833. This effort was so successful that it was emulated quickly by Rhode Island (Jackson, 1840) and Connecticut (Percival, 1842; Foye, 1949), along with many other states in the United States and countries in Europe (Hitchcock, 1871), where the 1845 survey of Austria was one of the first on that continent.

Boston made its geological debut on Maclure's 1809 geologic map of the United States, which shows the Boston-Narragansett region described as Transition Rocks set into Primitive Rocks along with the Secondary Rocks of the Connecticut Valley (see Figure 1-22). E. Hitchcock's 1832 geological map of Massachusetts clearly shows the Boston, Norfolk and Narragansett basins. Hitchcock indicated that these basins contained wacke and graywacke of his 4th Group surrounded by various igneous rocks of his older 1st Group. Argillaceous and flinty rocks of the 4th Group also are shown along the inside border of the Boston Basin. In the compiled geologic map of the United States and Canada in 1847, Lyell showed these basins and listed the primitive metamorphic and igneous rocks of southern New England as mostly pre-Cambrian and showed them plunging under Paleozoic strata to the north in Maine and the Maritimes as well as to the west in New York (see Figure 1-23). The discovery of the Cambrian trilobite *paradoxides harlani* (see Figure 1-24) in eastern Massachusetts demonstrated that the ancient rock also was overlapped by Paleozoic strata on the east (Rogers, 1856 & 1857), as indicated on Hitchcock's greatly refined 1871 map of Massachusetts (see Figure 1-25). This map still shows most of the state as pre-Cambrian and blocks out the major geologic divisions within

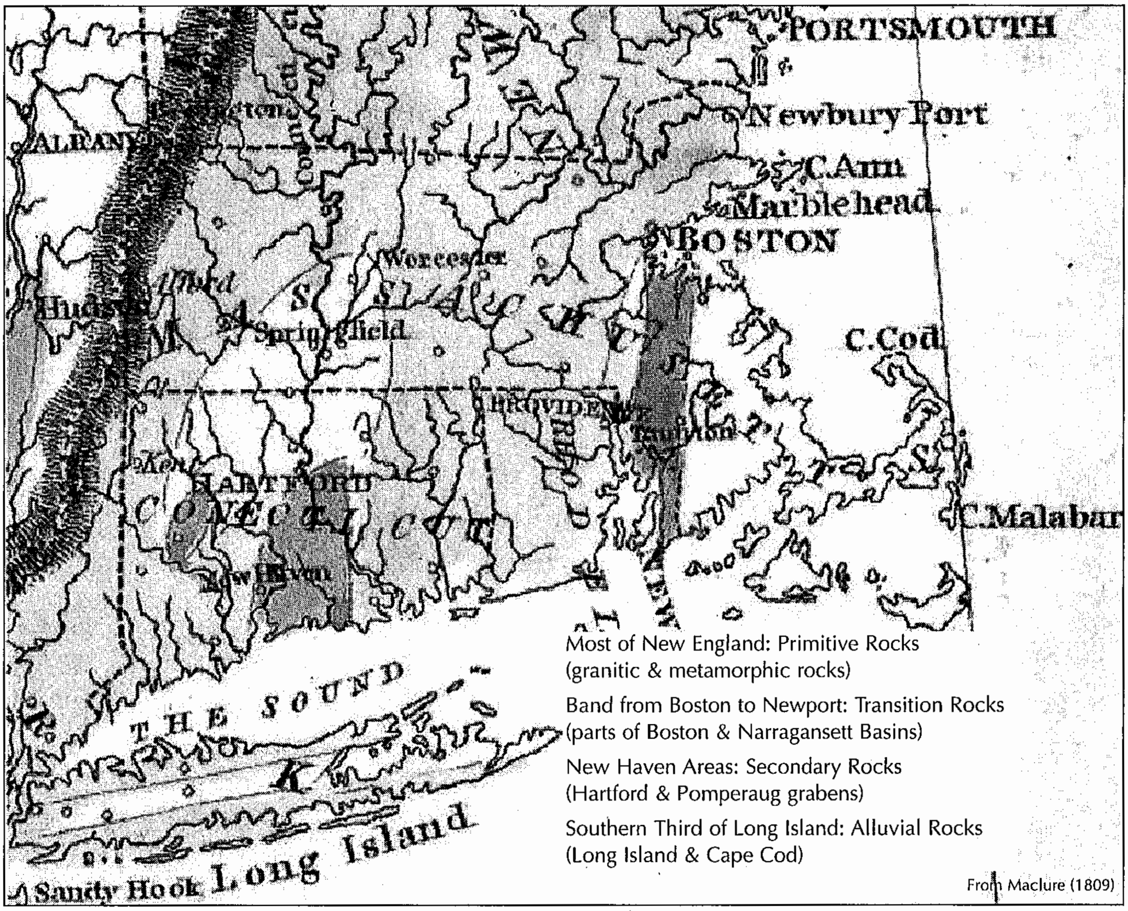


FIGURE 1-22. Southern New England portion of the geologic map of the United States of America.

the state, with assigned rock ages surprisingly similar to those found by modern work. The fossils in the Cambrian strata on either side of Massachusetts then were found to be very different by the studies of Walcott (1891a & 1891b), who found that a profound geographic barrier had existed between the two faunas along eastern North America. Thus began the understanding of ancient plate tectonics in the region.

The geology of the Boston Basin itself received early attention (Lathrop, 1800; Dana & Dana, 1818) and it was quickly found that the topographic basin also was a structural one (see Figure 1-26). The basin was considered synclinal and grouped with the Narragansett Basin to the south as Devonian (Lyell, 1845b). Hitchcock (1871) left the age of most of the Boston Basin as undetermined, although the Cambrian strata on the south side were considered to overlie the conglomerate fill in the basin (see Figure 1-25). Shaler (1869) noted that "the association of the several different sets of beds which are exposed in the neighborhood of Boston is very difficult to determine satisfactorily; being nearly destitute of fossils, and extremely complicated by disturbances, they have not presented a very inviting field for research." However, an explosion of research soon followed that lasted until World War I. W.O. Crosby met the challenge and produced the first large map of the Boston Basin (at a scale of 1:63,360) in 1877 and presented detailed traverses in his report in 1880 (see Figures 1-27 & 1-28). He found that the thick conglomerate in the center of the basin did not lie over the slate (argillite) in a syncline, but underlay it, although in part it was contemporaneous and interfingered with the slate. The conglomerate, in turn, was underlain by a

FIGURE 1-23. Southern New England portion of the United States and Canada.

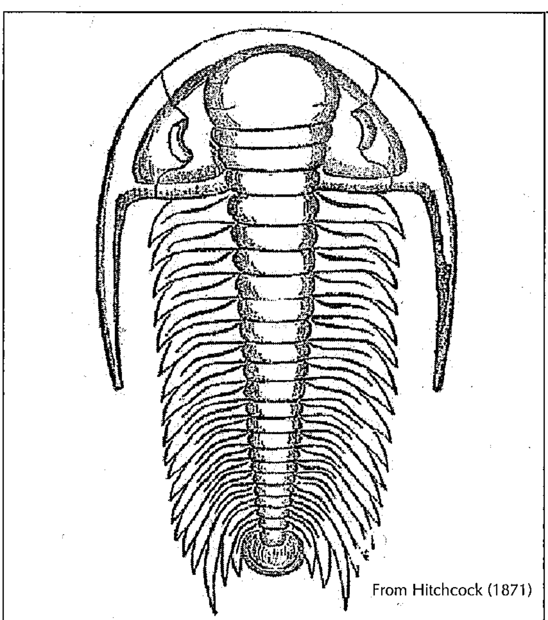


FIGURE 1-24. *Paradoxides harlani.*

varied and complex volcanic rock sequence that sits unconformably on the granite. The conglomerate and argillite are considered to be basal Paleozoic and conformable beneath the fossiliferous Cambrian sequence, which overlaps beyond the basin. He noted that the basin consisted of faulted folds and extensive parallel and transverse faults were found to characterize a large part of the basin. Crosby interpreted the folds from both changes in dip and local stratigraphic sequences, considering the bands of conglomerate as cores of anticlines. The faults repeated the strata to produce large apparent thicknesses.

Other studies followed that Emerson (1917) summarized in a report on the geology of Massachusetts and Rhode Island. He used the work of LaForge, who was also mapping at the time, for the region around Boston. LaForge recognized that an area of volcanic rock over the granite, called the Framingham Basin, was a western outlier of the Boston Basin. He reverted to equating the conglomerate with that to the south in the fossiliferous carboniferous Narragansett Basin and stating its possible glacial origin, interpretations that were inconsistent with those of Crosby (1880), who thought otherwise. The argillite thus was considered basal Permian from Emerson's correlation and a pebbly lens within it, the Squantum Member, a tillite and part of a worldwide Permian glaciation following the interpretation of Sayles (1914 & 1916; Sayles & LaForge, 1910). Emerson further postulated that the basin was bordered by high relief during deposition in a mostly terrestrial setting. By now, a basin stratigraphy had been formalized: a basal Mattapan Volcanic Complex, above the granite, overlain by the Boston Bay Group. This group consists of

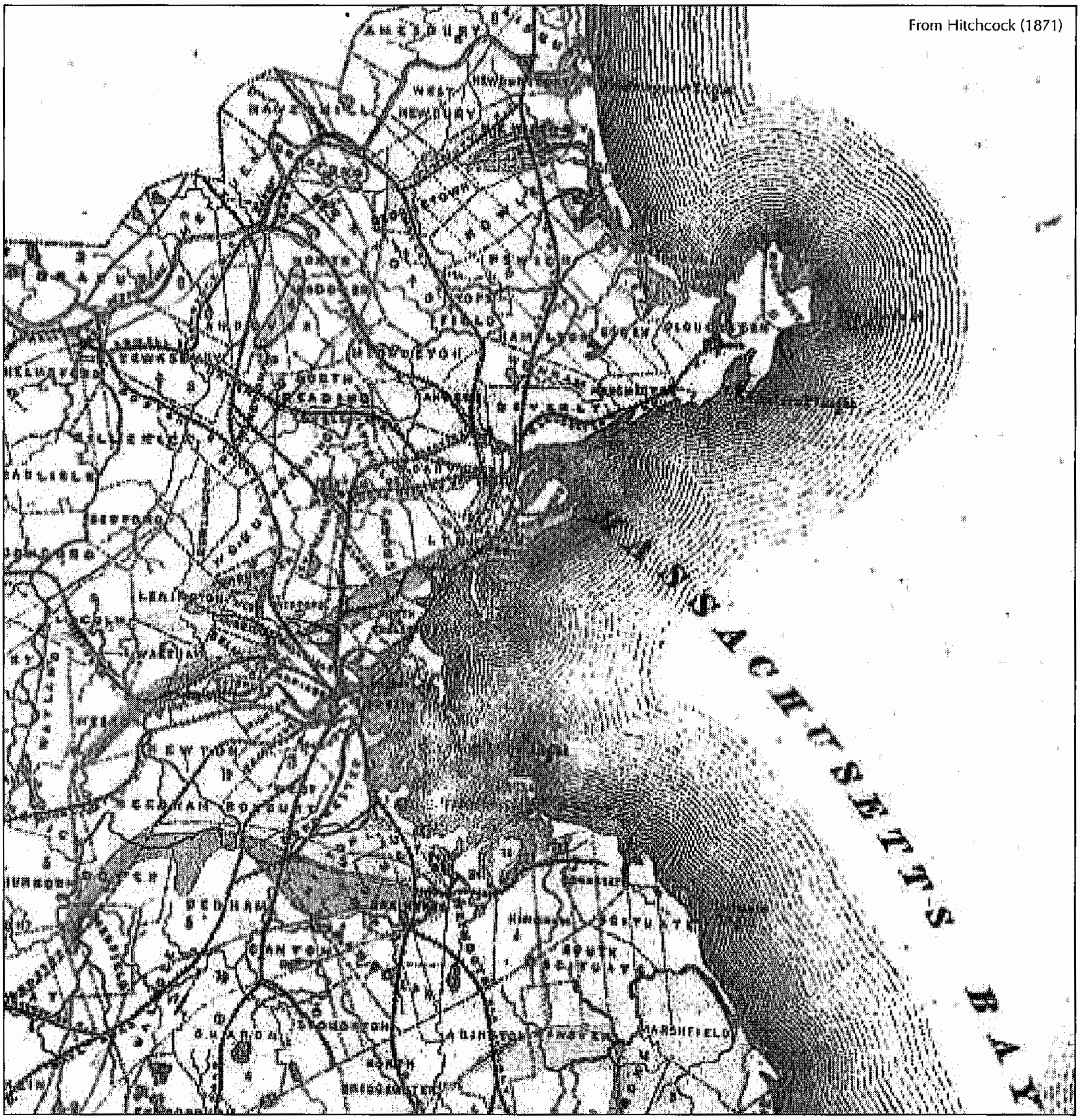


FIGURE 1-25. Boston and environs on the geologic map of Massachusetts by Hitchcock.

the Roxbury Conglomerate, which is composed of three members: Brookline Conglomerate, Dorchester Shale and Squantum Tillite, and an overlying Cambridge Slate (see Figure 1-29). The slate is usually an argillite or mudstone whose local fissility gave rise to it being mislabeled.

Laurence LaForge finished a detailed, 1:6,000 scale study of the northern part of the Boston Basin in 1903 and spent the next twenty-two years preparing the first modern geologic map of the entire basin and its environs (LaForge, 1932) at a scale of 1:62,500 (see Figure 1-30). He disagreed with Emerson's correlation with the Narragansett Basin, but still placed the basin strata as perhaps Devonian or Carboniferous in age on the basis of possible tree trunks in the conglomerate (see Figure 1-31). He thought of the stratigraphic units as relatively simple layers and accepted the interpretation of the Squantum as a tillite, although he did not consider it a mappable unit and useful for separating the argillite into two units. The Roxbury Conglomerate is found locally intruded by dark-colored porphyritic basaltic rock, referred

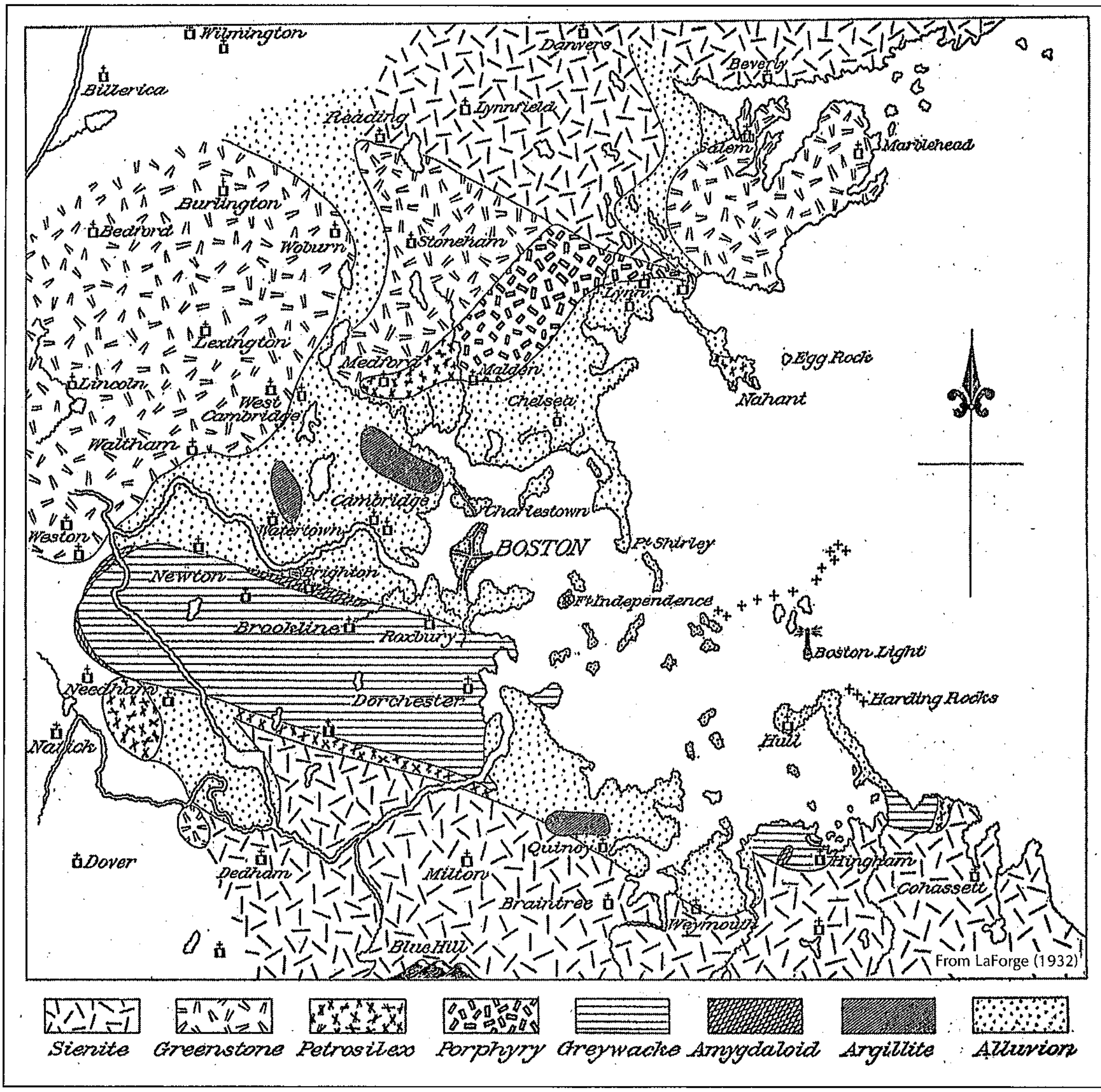


FIGURE 1-26. First geologic map of Boston and vicinity by Dana and Dana (1818).

to as melaphyre, which may or may not be a continuation of the earlier volcanism. Also, the basin rock is cut by numerous basic north-south and east-west dikes that commonly follow faults and may be offset themselves (LaForge, 1932). LaForge described the Boston Basin as essentially a fault-bounded synclinorium with a central, broad, east-plunging anticline. He found that the anticline to be faulted and that faults were the most abundant and characteristic structural feature of the basin. He noted that, in the southern half of the basin, "the strata have been fractured and tilted in different directions to form a patchwork of blocks without determinable structural relations to one another." However, folds also are shown in his generalized cross-section of the basin.

Faults had been noted as the principal structure in eastern Massachusetts by Crosby (1880), and Hobbs (1904a & 1904b) found indications of regional fault zones in southern New England. Hobbs observed that faults cutting Mesozoic strata could be followed into the metamorphic rock by their geomorphic expression. By a process of analyzing the topography and changes in geologic contacts, he eventually determined a series of regional structures that he referred to as lineaments. Their intersections

FIGURE 1-27. Simplified geologic map of Boston Basin and vicinity by Crosby.

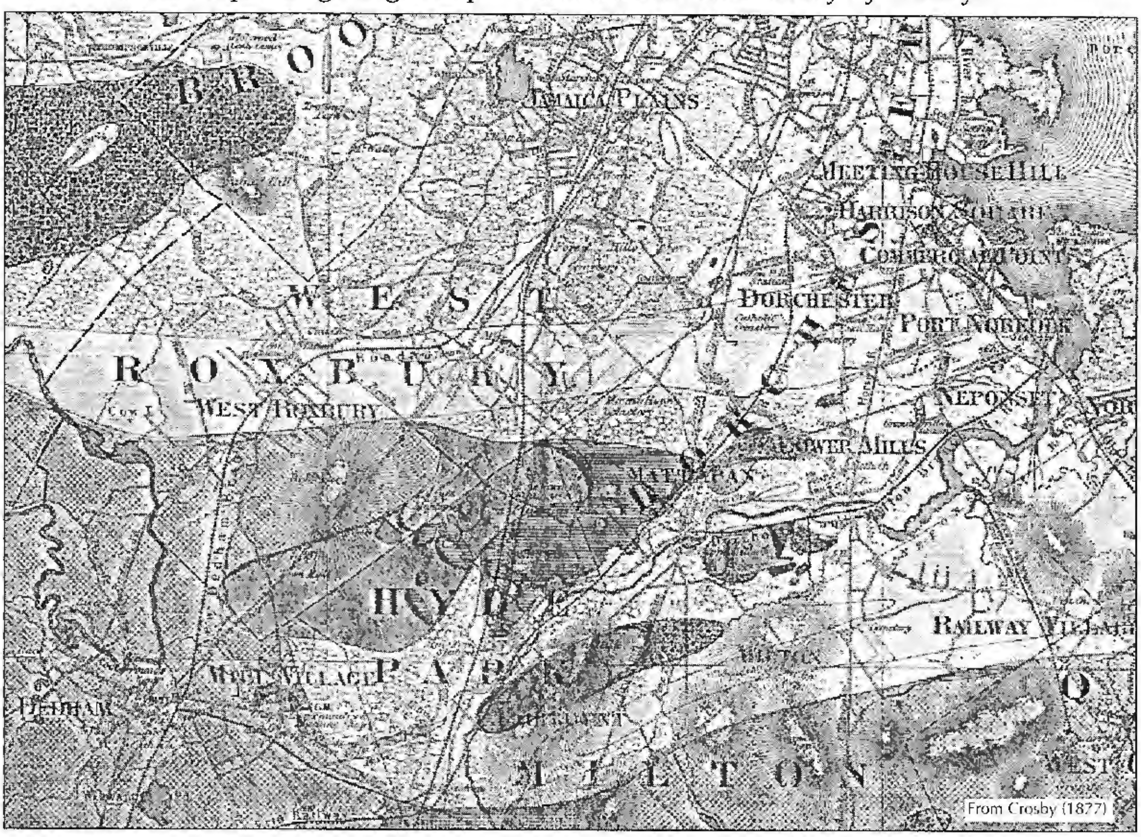


FIGURE 1-28. Portion of the southern part of the geologic map of Boston and vicinity by Crosby mapped at a scale of 1:63,360.

Age	Unit
	Cambridge slate Roxbury conglomerate 1. Squantum tillite member
Carboniferous Sedimentary Rocks	Unconformity (?) 2. Dorchester slate member 3. Brookline conglomerate member
Early Carboniferous Igneous Rocks	Mattapan volcanic complex (lower part called Lynn volcanics) Nephelite-bearing rocks Squam granite Quincy granite Blue Hills granite porphyry Beverly syenite Quartz syenite Nephelite syenite Essexite

From Emerson (1917)

FIGURE 1-29. Stratigraphic column for the Boston Basin by LaForge.

were later found to be spatially related with earthquakes in the region (Hobbs, 1907), a relation proven seventy years later (Barosh, 1989). Hobbs's work was based in large part on newly available topographic maps and was, in effect, the first remote sensing study. His technique was quickly adopted for guiding field work in the rest of the country and has continued in the use of aerial photographs and radar and satellite images. However, his contributions were not accepted by certain geologists in New England (Johnson, 1925) who believed that complex folds could explain changes in the geologic pattern.

This theory of folds rather than faults apparently derived from publications depicting large complex folds, due to soft deformation in gravity thrust sheets, in the Alps, and the myriad of small folds seen in New England road cuts. Each different trend of the small-scale folds was considered to represent a different regional fold set, regardless of their actual origin from drag, slump or local slip. The lack of confirmation of the folds by attitudes of the rock in the field was thought to be due to their complexity and that local rock attitudes were unimportant (Stanley, 1975; Robinson, 1963; Ratcliffe & Harwood, 1975). Such folds found no support in detailed field mapping (Schnabel, 1976; Peper *et al.*, 1975) nor in geophysical data (Barosh *et al.*, 1977b). Thus began an antipathy between theoretical-laboratory and field-oriented studies in the region.

Many universities in the region had turned largely away from field geologic reconnaisance work by World War I and began to concentrate on laboratory studies as the modern way to explain geologic processes. This change in philosophy seems to, at least in part, have prevented several of the USGS's map sheets of the state from being published in the 1920s. Excellent work in mineralogy, x-ray technology and geochemistry continued at the universities and a new specialty — metamorphic geology — emerged to study mineralogical transformations.

However, these lab research developments were poorly integrated with the field data. New concepts evolved in which the metamorphic rock began to be described by mineral content rather than the appearance of the rock, its sedimentary features, or stratigraphic relations (Toulmin, 1964; Abu-Moustafa, 1969). Furthermore, the sedimentary features were being attributed to metamorphic changes. In addition, the differences due to regional and contact metamorphism were blurred and separate metamorphic events were not fully understood. This laboratory approach, favored by many, combined with theoretical structure, evolved into a unique geology very different from that used elsewhere in the world but one that many New England geologists of the day felt was on the cutting edge.

LaForge presented lectures on the results of his mapping of the Boston Basin at Harvard in 1925 while preparing his report that was eventually published by the USGS in 1932. Meanwhile, Marland Billings, who as a student assisted LaForge at Harvard, published a synopsis of part of Boston in 1929, with a page-sized map (see Figure 1-32). This map is apparently a modified version of LaForge's page-size summary map (see Figure 1-30) with some data from Billings's work and sev-

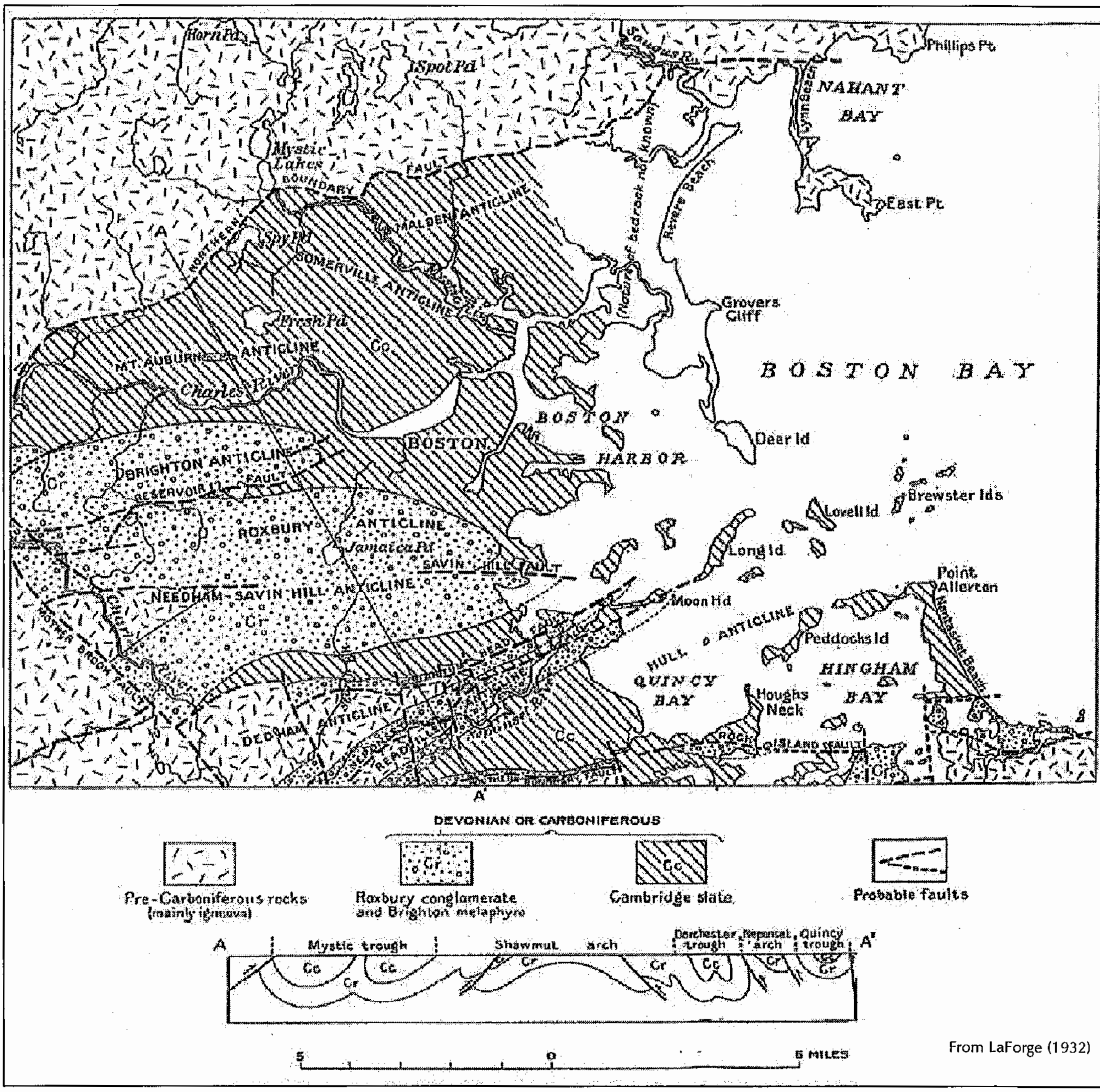


FIGURE 1-30. Geologic map of Boston and vicinity by LaForge (simplified from his 1:62,500 scale map).

eral others (Billings, 1929). Billings' synopsis paper became the standard geology cited for Boston. Billings simplified LaForge's data to develop what he considered to be a more cohesive picture of the Boston Basin. He reinterpreted LaForge's structure by changing some faults into folds, renaming structures and reverting to some of Emerson's, and perhaps Crosby's, stratigraphic usages. Billings (1929) placed all of the Boston strata in the Permian above a Pennsylvanian Mattapan on the basis of the possible tree trunks and emphasized the use of Squantum Tillite as a stratigraphic member in opposition to LaForge's findings.

While the differences in geologic theories were evolving, the very practical problem of building in Boston in the varied and unstable glacial and later surficial material (and the hazards they posed) was being recognized. The relative stability of the material was demonstrated by the earthquake of 1755, which resulted in most damage occurring on fill around the harbor. A map showing the relative stability across Boston by I.B. Crosby in 1932 was one of the first, if not the first, earth-

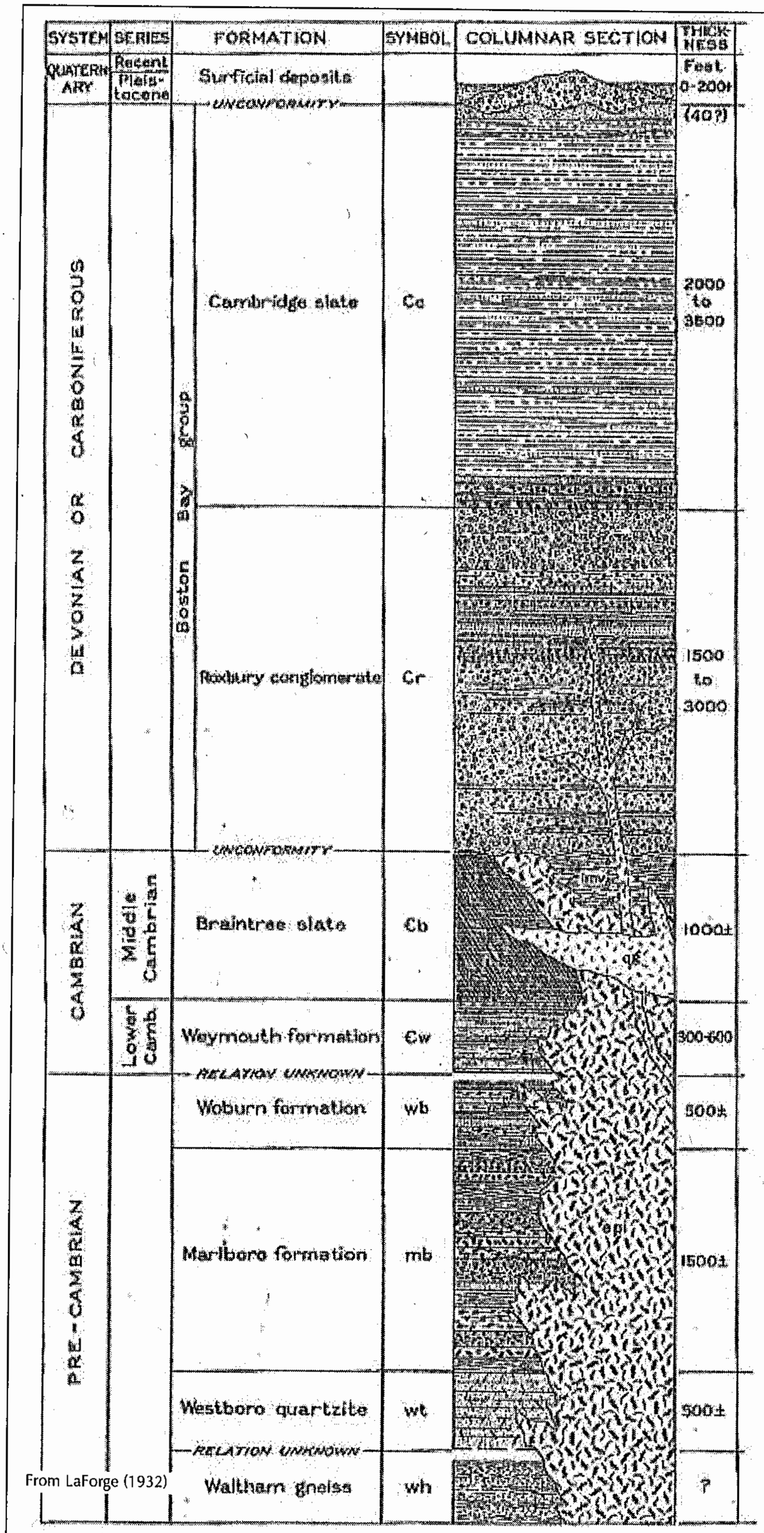


FIGURE 1-31. Stratigraphic column for the Boston Basin by LaForge.

quake hazard maps in the country. The instability of the cover material found in the building of the Massachusetts Institute of Technology (MIT) was studied by Terzaghi, Casagrande and others, and led to the development of soil science (Lambe & Whitman, 1969; Peck *et al.*, 1974). These and other studies laid the foundation for the successful engineering geology that has greatly benefited the city.

The fold-versus-fault controversy continued through the construction of several bedrock tunnels in and adjacent to the city during the 1960s. Some geologic mappings of tunnels showed numerous faults. However, the role of folding in the summaries for other tunnels appears to have been exaggerated, apparently influenced by drag and slump folds. The sketch map of the Boston Basin shown by Billings in 1976 (see Figure 1-33) still shows an essentially folded basin with a few north-dipping thrust faults in the southern part, but without the high density of faults found by Crosby (1880), LaForge (1932) and others. Crosby (1899a) mapped the numerous exposed faults of the Clinton Newbury Fault Zone (one of the largest fault zones in North America) during construction of the Wachusett Aqueduct. However, Billings (1962) only mentioned that unmapped small faults were present

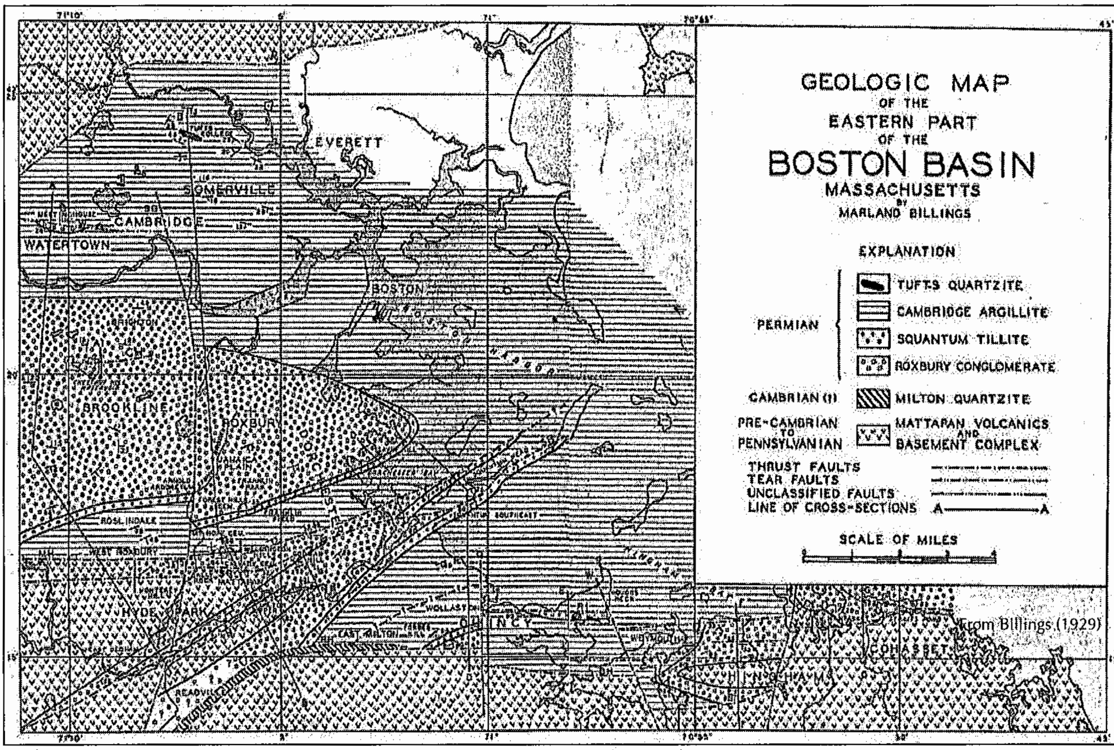


FIGURE 1-32. Geologic map of Boston and vicinity modified from LaForge by Billings. (Courtesy of the Geological Society of America.)

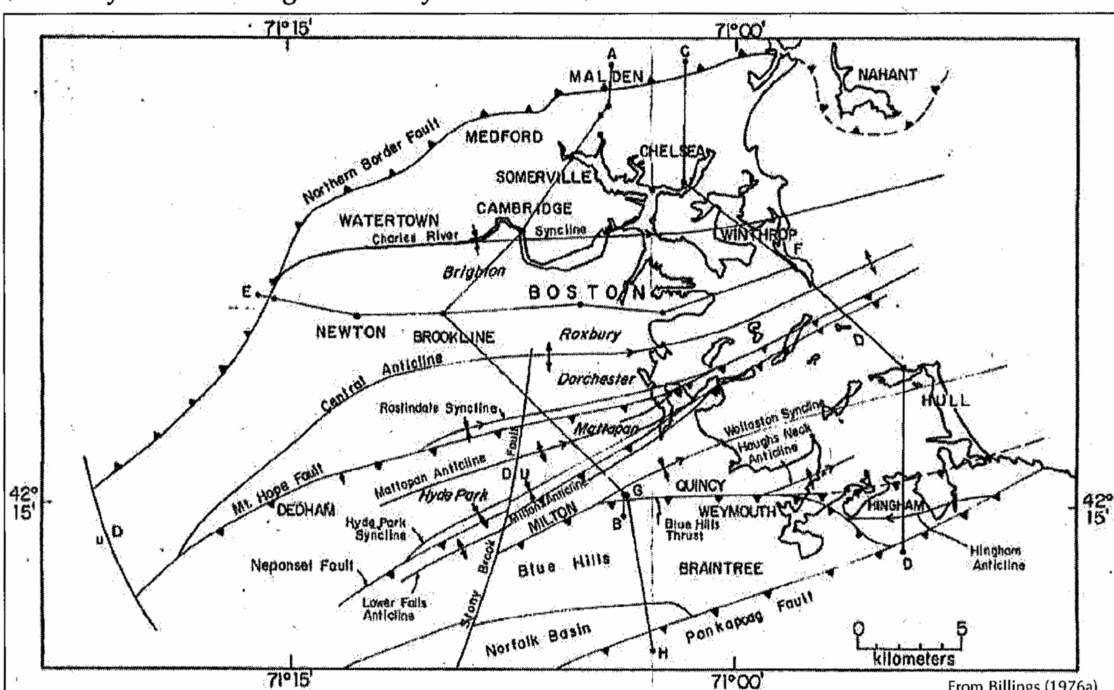


FIGURE 1-33. Structural map of Boston and vicinity by Billings. (Courtesy of the Geological Society of America.)

in the nearby Cosgrove Tunnel constructed in the mid-twentieth century. The difference in observations is remarkable.

The USGS had begun mapping again in Massachusetts and adjacent states in 1940, but this effort was put on hold by World War II until the 1950s. These cooperative studies with the states, along with the work at the Nevada Test Site and in Kentucky, were the last major mapping efforts by long-experienced field geologists of the USGS. The study using 7.5-minute quadrangles began in eastern Massachusetts by W.R. Hansen, R.H. Jahns, N.E. Chute, N. Cupples and others, and in Rhode Island by Alonzo Quinn, G.E. Moore and others. Eastern Connecticut was mapped by M.H. Pease, T. Feininger, R. Dixon and others, and much of the western part of that state was covered by R.M. Gates, C.W. Martin and others through the State Geological and Natural History Survey of Connecticut. This effort began defining mappable stratigraphic units in the metamorphic strata and began collecting structural data. Major structures started to be revealed as mapping progressed. These discoveries increased as other experienced geologists were brought in by the USGS, and more detailed field and stratigraphic data became available to provide control. This geologic mapping was reinforced by the use of aerial photography and aeromagnetic data.

More and more primary sedimentary features were recognized in the highly metamorphosed rock as the mapping progressed. A major discovery was that despite metamorphic changes, sufficient sedimentary features were preserved to allow the subdividing of the rock into mappable units as in unmetamorphosed strata and to understand their environments of deposition. A series of modern stratigraphic studies, following the formal Stratigraphic Code — which dictates how formations are to be described (NACSN, 2005) — were started in the late 1960s to measure and describe the formations and establish type sections (Peper *et al.*, 1975; Bell & Alvord, 1976). These were the first such detailed studies in New England and provided a basis for much more accurate mapping. The defined mappable units west of Boston were found by D.C. Alvord and K.G. Bell in 1970 (Alvord *et al.*, 1976) to conform very closely to the pattern shown by the aeromagnetic data, which also showed additional discontinuities due to fault offsets (Barosh *et al.*, 1974 & 1977b). Gradually more structural features were recognized with the refined control. The region was revealed to be offset by large thrusts and cut up by a mosaic of smaller faults (Bell & Alvord, 1976), as Crosby (1880) and LaForge (1932) noted earlier. Previously theorized folds, such as those by Robinson (1963) and Dixon and Lundgren (1968), have not been found. Interestingly, the one area found to be highly folded, the Connecticut-Rhode Island border region, had not been previously theorized to be folded (Feininger, 1965; Barosh, 1972; Barosh & Hermes, 1981). Furthermore, the proven large ancient folds that are present may be bent slightly, but are not refolded.

Thus, the USGS's work established that:

- metamorphosed strata retain abundant sedimentary features;
- mappable stratigraphic units can be established for the metamorphosed strata by measured and described type sections following the Stratigraphic Code;
- folds are described by attitudes in the rock as in unmetamorphosed strata;
- faults are shown by offset contacts, exposed fault zones, discordant features, drag folds, juxtaposition of rock of different metamorphic grade or degree of deformation, discontinuities in geophysical data and other such features as in other regions;
- significantly different degrees of regional metamorphic grade and deformation reflect different periods of deformation;
- the geomorphology (topographic maps, aerial photographs, satellite data, radar maps) closely reflects the structure, except where the surficial material is very thick; and,
- magnetic and gravity data closely reflect rock units and structure given sufficient detail.

The concurrent detailed surficial mapping was, in many cases, done as a specialty and J.P. Schafer, J.H. Hartshorn, C.A. Kaye,

C. Koteff, R. Oldale and F. Pessl worked out new principles in mapping and understanding the glacial deposits. Their efforts built upon the pioneering work of W.M. Davis (1890), J.W. Goldthwait (1905) and S.S. Judson (1949) to reveal more of the complexity of the Pleistocene material (White, 1949). It was demonstrated how the deposits formed repeated sequences with each ice stand during the retreat of the Late Pleistocene glacier margin, formed vast lakes at times and were later tilted from rebound.

This program of modern mapping was done from the Boston Office of the Geologic Division of the USGS under L.R. Page and his successor M.H. Pease, Jr. The program produced a virtual explosion of new information that completely changed the understanding of the region, as well as the Appalachian orogen. Major goals were to provide data for engineering and environmental work, to demonstrate how geologic information can be used for planning and to gather geologic data for practical application for construction in Boston, influenced by the early teachings of Goldthwait (White, 1949). One pioneering study years ahead of its time was the Connecticut Urban Pilot Study, which demonstrated the many ways to apply geologic work in the Connecticut River Valley to environmental studies and town planning.

The important development for Boston was the establishment of the position of a City Engineering Geologist under the USGS's Greater Boston Urban Geology Project (Kaye, 1967b) — a position capably filled by Clifford A. Kaye, who began preparing a 1:12,000 scale geologic map of Boston. He was aided by the work of Kenneth G. Bell, who continued the mapping of the Boston area (Bell, 1948) that he began for his doctoral thesis at MIT. MIT had developed excellent field-oriented geologic training, which ended later in the 1960s when geophysical studies were emphasized. Kaye and Bell's work brought a new understanding of the Boston Basin whose strata were proven to be much older, Eocambrian (Proterozoic Z), as had been interpreted by Crosby (1880) and not the Carboniferous or Permian age of LaForge (1932), Billings (1929) or others (Pollard, 1965). Kaye's work also revealed the extreme complexity of the glacial geology and the hazards posed by soft alteration zones in the underlying argillite. The Cambridge Argillite was found to contain many slump structures (Rahm, 1962) and the Squantum Tillite member was shown to be scattered lenses of pebbly mudstone that represent slump deposits (Dott, 1961; Kaye, 1982b), similar to ones commonly seen in California coastal strata. Neither the Squantum Tillite nor other features in the Cambridge Argillite are consistent with a glacial origin (Caldwell, 1981). Kaye also determined that several formations previously interpreted as folds were actually longitudinal faults cutting through the basin (see Figure 1-34) and the basin itself was found to be dropped into a Late pre-Ccambrian batholith that underlies southeastern New England (Barosh *et al.*, 1977a).

The mapping played a major part in the understanding of plate tectonics that was not fully appreciated. To the west of Boston, it was recognized by 1960 that the parts of the Clinton-Newbury and Bloody Bluff faults (Crosby, 1899a; Novotny, 1961; Cupples, 1961) constituted major fault zones (Page, 1994). These and other faults in New England found by the USGS contributed to J.T. Wilson's (1966) formulating the concept that a predecessor of the Atlantic Ocean had closed against an ancient plate collision zone that extended from the Canadian Maritimes to west of Boston. This general concept of plate movements in New England was elaborated on by Bird and Dewey (1970), but the stratigraphic and structural data were still too sparse to show this well. Continued detailed mapping by the USGS refined the position of the zone and the stratigraphic changes across it. This "type collision zone" was found to cross coastal New Brunswick, lie just off shore of Maine and New Hampshire, traverse east-central Massachusetts (approximately between Route 128 and Interstate 495) and eastern Connecticut to turn south and pass beneath mid-Long Island and seaward (see Figure 1-3). The pre-Silurian stratigraphy and structure are strikingly different on either side of this plate collision zone (Barosh, 1977a & 2005; Barosh *et al.*, 1977a), which makes a profound structural, stratigraphic and geophysical break not seen else-

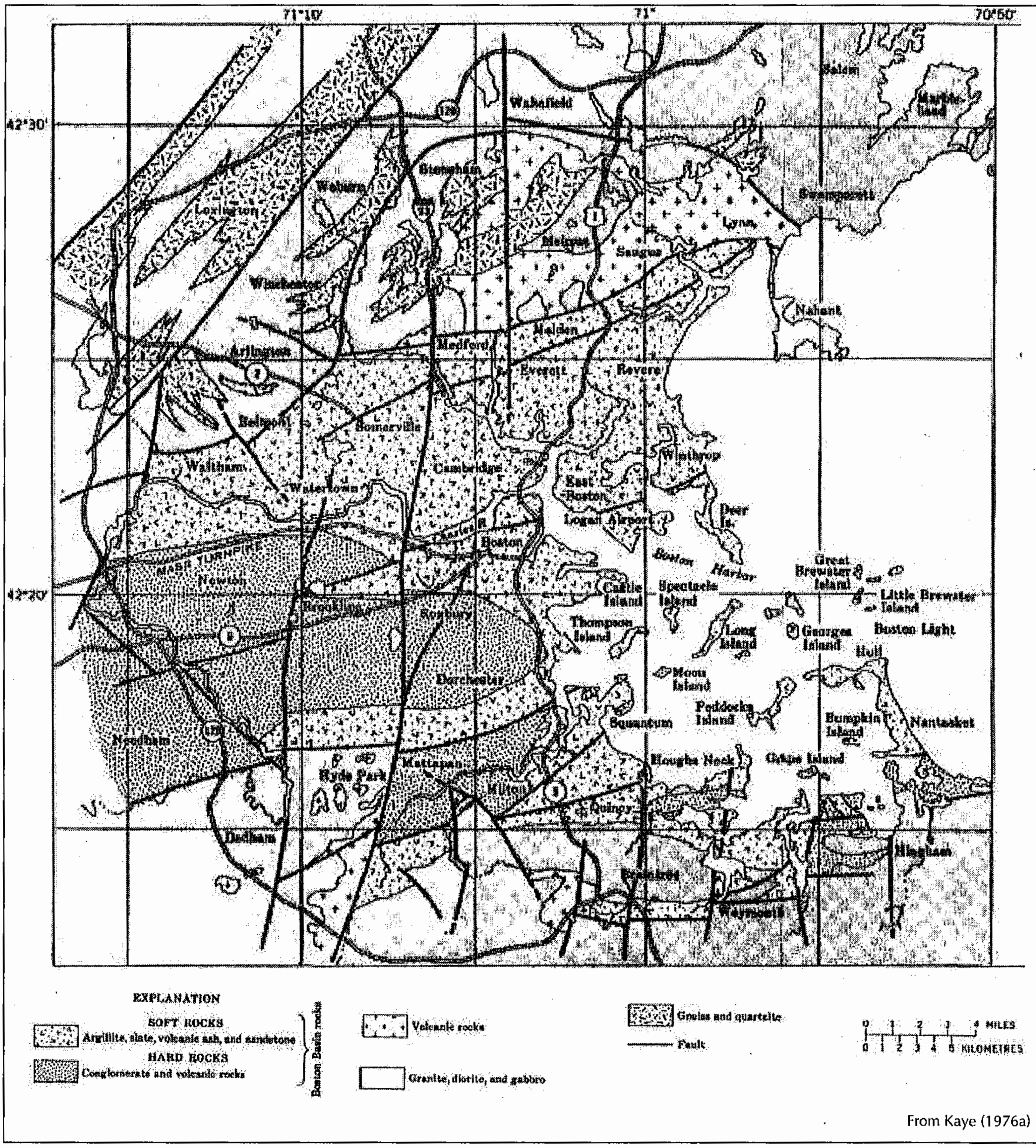


FIGURE 1-34. Simplified geologic map of Boston and vicinity by Kaye.

where in the northeastern United States (Barosh & Pease, 1974; Alvord *et al.*, 1976). Thus, Boston was recognized as a former part of northwest Africa left dangling on the North American side when the Atlantic Basin opened later. It became clear that the two defining events that shaped the structure of New England were a plate collision that peaked near the end of the Proterozoic and the opening of the North Atlantic Basin in the Mesozoic.

When detailed large-scale state geologic maps of Connecticut and Massachusetts were being prepared under the direction of M.H. Pease, Jr., at the Boston office of the USGS for publication in 1978, the office was closed and the mapping program ended. Only the preliminary map sheet for eastern Massachusetts was completed and released (Barosh *et al.*, 1977a). The publication of about twenty Massachusetts geologic quadrangles that had been completed, or nearly so, also were halted. A few revised maps were released, but the emphasis appeared to be on folds, again resurrecting the old fold-versus-fault controversy. A substitute smaller-scale geologic map of Massachusetts (Zen *et al.*, 1983) and its description (Hatch *et al.*, 1991) were later produced by the USGS's main office in Reston, Virginia. These maps reintroduced many hypothetical structural features and stratigraphic usages that found no support by the USGS mapping and geophysical data. Also, the compiled data of eastern Massachusetts were altered and most of the faults on Barosh *et al.* (1977a) were omitted. The result carried on two incompatible geologies with different structures, stratigraphy and ages being described simultaneously for the same area.

Kaye did release preliminary maps for Boston (Kaye, 1982b), as did Bell, but was unable to complete his studies. In these maps, Kaye abandoned the earlier stratigraphic terminology as inadequate and described the units by their lithology as a first step in reassembling them into a new stratigraphic framework that better described the relations. Kaye, as well as Bell, recognized the complex intertonguing relations of the units both toward the center of the basin and laterally. This feature, however, is very difficult to describe in formal stratigraphic nomenclature, which was to have been Kaye's next step.

The cause of earthquakes in the region in the 1950s was attributed to a non-fault origin, such as stress associated with granite plutons. This approach changed with the building of the first nuclear power plants and the need for a better evaluation of the earthquake hazard. Studies in the 1970s for the Boston Edison nuclear power plant did discover faulting in the plutons that released stress buildup, causing earthquakes.

The concern for nuclear power plant safety ushered in a series of evaluations of the seismic hazard at specific sites in the region that included compilation of more complete records and finding discrepancies in the older ones (Fischer & Fox, 1967; Devane & Holt, 1967). Investigations for the Pilgrim Nuclear Power Plant site in Plymouth, Massachusetts, and the nuclear plant site at Seabrook, New Hampshire, provided new information and important re-evaluations of earthquake data. A study of many of the historic earthquakes to improve intensity assignments and epicentral locations and assemble isoseismal maps was a major contribution (Boston Edison Company, 1976a, 1976b & 1976c). The pluton theory was adopted by Boston Edison, but during this same period the non-fault causes of earthquakes became suspect as geologic mapping revealed that the region is similar to California in the number and size of faults (Bell & Alvord, 1976; Barosh, 1976d & 2005).

The emerging awareness of the hazard and uncertainties as to the cause and distribution of the seismicity and the complexities of the geologic structure aroused further concern for power plant safety. The U.S. Nuclear Regulatory Commission began, in 1976, a program under Neil B. Steuer to expand research on earthquakes in the eastern United States. The Northeastern U.S. Seismic Network began a much-needed expansion and the New England Seismotectonic Study was begun to investigate the cause of seismicity and formulate an earthquake zonation map of the northeast United States under the direction of Barosh (Barosh, 1981b & 1982a; Barosh & Smith, 1983). This large cooperative study, supported mainly by the U.S. Nuclear Regulatory Commission, involved university and state geological survey personnel to make detailed geological, geophysical and historical investigations of the individual seismically active areas. This program continued much of the work of the USGS, which by then was more focused on offshore mapping than onshore mapping in the Northeast. It produced a vastly improved epicentral map and earthquake catalogue (Nottis, 1983), found the causative zones of faults, identified source areas and estimated the maximum probable earthquakes for each area (Barosh, 1986c, 1986d & 1990a). This mapping established the general structural and tectonic control of the large 1755 earthquake northeast of Boston.

No significant mapping program to gather geologic data on land has occurred since the mid-1980s, and the 1977 geologic map of the Boston 2-degree sheet is still the latest regional geologic map (Barosh *et al.*, 1977a). Other studies have continued under the USGS Water Resource Division and Office of Marine Geology. The marine geology group, headquartered in Woods Hole, Massachusetts, has carried out extensive studies of the stratigraphy and structure offshore to aid in the evaluation of potential petroleum resources in the 1970s and 1980s. More recently, the work has shifted closer inshore to provide basic information for environmental needs. Several surficial quadrangles on Cape Cod were completed under the auspices of the Office of Marine Geology to aid the study of serious environmental problems (Oldale & Barlow, 1986). Some temporary USGS and state funding allowed the completion of three quadrangles covering Cape Ann (Dennen, 1991a, 1991b & 1992), the Georgetown quadrangle (Bell *et al.*, 1977 & 1993) and three south of Worcester (Barosh, 1974, 1996a & 2005), but the funding for publication ended after the first group was printed.

During the past twenty years the dominant geologic programs in and adjacent to Boston have been those associated with both the new water and sewer tunnels and facilities of the Massachusetts Water Resources Authority and the Central Artery/Tunnel Project construction to depress the expressway through the city and connect it to the airport (Miller, 2002). In addition, considerable valuable information has been obtained by the myriad engineering, environmental and water resource investigations, as well as some seismic evaluations for the U.S. Army Corps of Engineers. This work has greatly expanded our understanding of the complexities of the glacial deposits underlying Boston and the harbor. The structural and stratigraphic data from the many new tunnels provides a much clearer understanding of the bedrock and interpretation of the structure, showing a highly faulted basin with few folds. However, the massive amount of data generated has presented a challenge to its preservation and accessibility. A newly re-established Office of the Massachusetts State Geologist is tasked with creating a well inventory and data set, saving unpublished geologic files and establishing a core repository. In addition, this office is trying to complete and publish geologic quadrangle maps, but is hindered by the lack of experienced field geologists. Recently, the USGS has begun making major revisions of the geology, stratigraphic and age changes west of Boston (Wintsch *et al.*, 2007) that are incompatible with the previous mapping by the USGS, but which are more in line with those proposed earlier by Billings.

The geology described herein makes full use of the quadrangle maps in eastern Massachusetts that have been mapped, although many are as yet unpublished and only available in open-file reports, as well as in scattered files and reports. This summary also incorporates the mapping of a great many people whose work could not be all cited here (much of that earlier work is listed in Barosh *et al.* [1977a]). The references cited tend to represent summary reports and newer findings based on field mapping. The geology is presented in two parts, the overall geologic framework of southeastern New England and the geology of the Boston Basin, followed by sections of the geotechnical and environmental implications. The regional geology was first compiled in 1977 (Barosh *et al.*, 1977a) using all the USGS mapped data and then modified in 1981, 1984 and 1991 as new information became available (Barosh & Hermes, 1981; Barosh, 1984a; Woodhouse & Barosh, 1991). These revisions incorporate many clarifications on stratigraphy, structure and ages found since and completes a preliminary earlier version (Barosh & Woodhouse, 2006).

Regional Geologic Setting for the Boston Area

Much has been learned over the last generation to fuel a broader understanding of the geologic structure and development of Southern New England.

PATRICK J. BAROSH

The understanding of the geologic development of southern New England has changed greatly over the past fifty years. Earlier, it was thought that the geology of the area developed primarily due to some great Devonian Acadian Orogeny followed by a lesser Permian Alleghanian Orogeny. Features ascribed to these events are found to have occurred much earlier and the revealed plate collision records additional complex events. The ancient edge of North America (Laurentia), formed in the Middle Proterozoic, and its younger offshore basin, collided with and was underthrust in the Late Proterozoic by the volcanic terrain of ancient northwest Africa (Gondwana). This collision changed most of this northwest edge of Gondwana into batholithic granite and squeezed out much of the intervening sea (see Figure 1-2). The subsequent rapid rise of this batholith and the formation of the Boston Basin were followed by a rising sea from the east that spread onto the land in the Cambrian. Further underthrusting at the end of the Ordovician closed any remaining gap between Gondwana and Laurentia and caused volcanism. Most of the resulting fused landmass (Pangea) then rose to form land or shallow coastal waters in the Early Silurian. The terrestrial setting continued the rest of the Paleozoic with extensional faulting and volcanism over most of the region. In the Mesozoic, the land began to fracture and slip into the developing Atlantic Ocean to the east.

A Piece of Africa

The principal geologic events of the Boston Basin are the great Late Proterozoic Pan-African Orogeny, a lesser Taconic Orogeny toward the end of the Ordovician, and the Mesozoic Orogeny that has dwindled down to today's activity. A series of smaller events occurred during Silurian-Devonian time, of which the Middle Devonian Acadian Orogeny was probably the largest, and was followed by a Pennsylvanian event and weak Permian activity in the south. The main orogenic episodes appear to have started in the east and moved westward first as the orogen was compressed inward toward the core of North America and then as the land collapsed into the Atlantic. Many events, rather than being distinct orogenic episodes, appear to be times of relatively greater deformation during more or less continuous activity.

The shallow sea that filled the Boston Basin and spread onto eastern North America in the Cambrian was matched by one that lapped onto the west side of the land in the Berkshire Hills that created a barrier to the early marine life forms as discovered in a series of brilliant studies by Charles Walcott (1891a & 1891b) at the end of the nineteenth century. He discovered that the Early Cambrian fossils in the Berkshire Hills and those around Boston are different. This fossil divide then was found to extend not only through eastern North America and Canada, but in northwestern Europe as well. This finding posed a question on possible connections across the North Atlantic Basin and laid the grounds for the discovery of the ancient plate collision by J.T. Wilson in 1966. Wilson's revelation was followed by studies by the Boston office of the United States Geological Survey (USGS) that produced perhaps the most detailed description of any collision zone.

Much later in the Mesozoic, Pangea began to breakup about 235 million years ago and gradually widened into today's Atlantic Ocean, leaving a piece of the ancient northwestern African coast and the site of Boston behind. As a result, the geology around Boston is very similar to parts of Morocco, but greatly different from central Massachusetts and Connecticut. The movement caused the broken edge of the continent to sag down and become buried offshore while superimposing new sets of extensional faults across the region. The fissure east of Boston became the Mid-Atlantic Ridge and both sides of it began a slow separation, which is still continuing, with new rock filling in from sub-sea intrusion. From the fragments of Pangea emerged the modern crustal plates of North and South America, Africa, Europe and other areas. The continental break occurred just east of the old collision zone and left fragments of Gondwana on the west side of the growing North Atlantic Ocean. The only exposed fragment in the United States forms southeastern New England. Other less complete pieces lie along coastal maritime Canada, and the rest are deeply buried along the Mid-Atlantic coast and underlie the carbonate deposits of central Florida.

The understanding of this opening of the Atlantic Ocean and continental drift was not an instant breakthrough, but occurred over a period of three hundred years of collecting evidence. The way the continents fit together across the Atlantic Basin was first described by Abraham Ortelius in 1596 (who suggested that the Americas were torn from Europe and Africa), and were followed by more detailed description, such as Federico Sacco in 1895 and Frank B. Taylor in 1910. Between 1908 and 1912, Alfred L. Wegener assembled extensive evidence showing the previous connection of the continents. It was not, however, until after World War II when the magnetic pattern of the rock filling the ocean basin was mapped that most American geologists accepted this theory. The magnetic pattern displays the progressive addition of new crust at the Mid-Atlantic Ridge as well as the mechanics of separation. The close correlation of the geology and magnetic pattern in southern New England shown in the early 1970s illustrates how the oceanic features come ashore. The initial phase of the stretching formed down-dropped blocks that resulted in extensive basin-and-range mountains, now mostly drowned off the coasts of New England and Morocco (see Figure 1-2). The early faults mostly trend northeast and some appear to modify the southern Boston Basin. These faults were soon followed by more extensive north-south faults across the basin and a final set of regional northwest-trending faults, which account for most of the earthquakes in the region. During this time, the edge of the continent sagged into the growing Atlantic as the sea again flooded the Boston Basin and rivers carved into the rock as they flowed into the nascent harbor. Thus, the foundation of Boston was formed in the closing and separation of continental plates. However, much was still to come since glaciers modified the basin over the last million years. The sea fell and rose with the forming

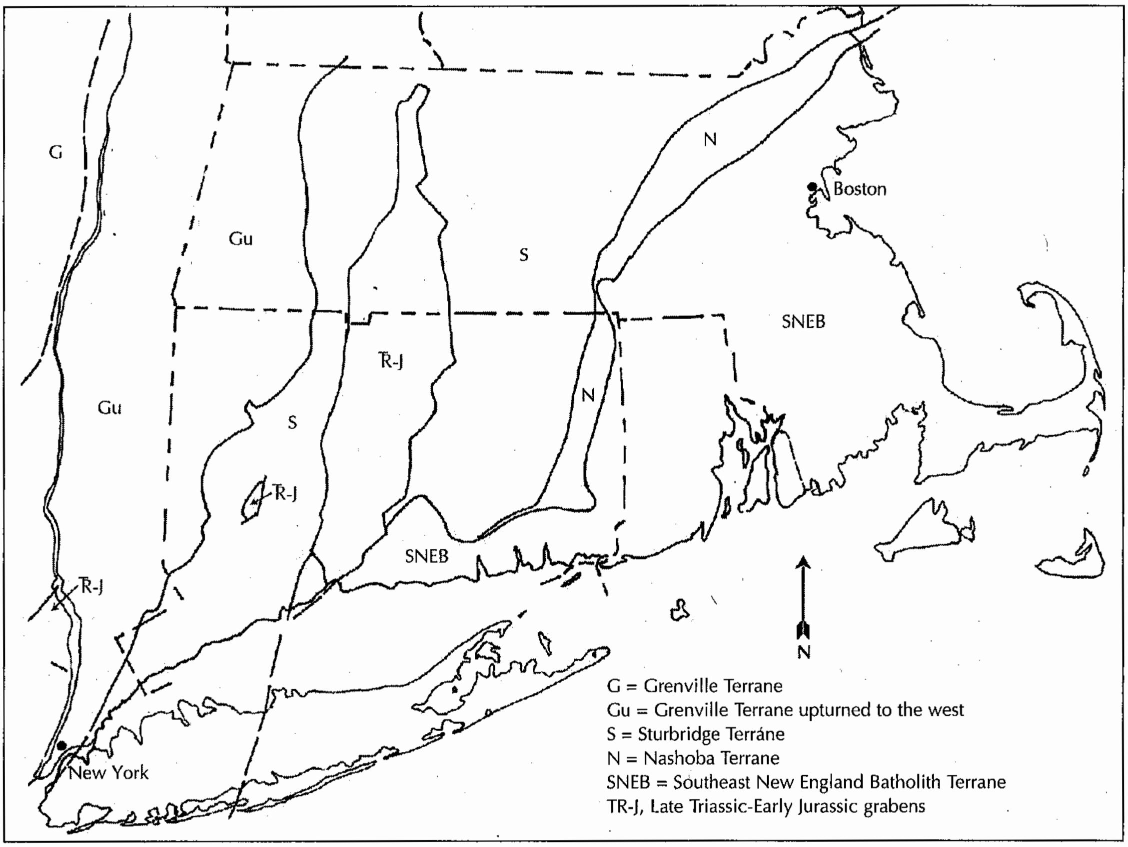


FIGURE 2-1. Geologic terranes and major Triassic-Jurassic grabens of southern New England.

and melting of ice as glaciers advanced and retreated across the environs of Boston, leaving a confused infilling mixture of different types of terrestrial and marine deposits, which makes for one of the most complex geologic areas in the country.

The collision of the Gondwana and Laurentia continents also resulted in four principal geologic provinces between the Hudson River and the Atlantic Ocean and set the character of the geology of southern New England (see Figure 2-1). These provinces, or *terranes*, constitute the basement and consist chiefly of deformed moderately to highly metamorphosed strata and generally foliated granitic rock. They have been identified as:

- the Grenville Terrane, which lies along the New England-New York border and forms the southern extension of the Green Mountains where they devolve into the Berkshire Hills and the Taconic Range;
- the Sturbridge Terrane to the east, which consists of the lower rolling land, split by the Connecticut River valley, and forms most of Connecticut and central Massachusetts;
- the Nashoba Terrane, which forms some higher ridges in a zone that trends north along easternmost Connecticut and northeast across eastern Massachusetts; and,
- the Southeast New England Batholith Terrane, which forms the hilly region farther east that slopes to the sea across southeastern Connecticut, Rhode Island and eastern Massachusetts, and contains several very low basins.

The Boston Basin, filled with the latest Proterozoic strata, is the earliest of these fault-bounded basins (see Figures 1-2 & 2-1). Each terrane consists primarily of a basement of one group of ancient rock with a local cover of deposited early Paleozoic strata, down-dropped blocks of younger strata, later plutons and local exposures of the over-ridden rock.

These structural terranes provide an unrivaled exposed cross-section of Appalachian structure seen nowhere else in North America. The exposure is largely due to a later regional northerly tilt, which raised into view the deep structural zones along the Connecticut and Rhode Island coasts while relatively lowering northern New England. The terranes were compressed by underthrusting from the east on several occasions during the continental plate collision and their principal structural contacts dip to the west.

The landform of the terranes reflects the crustal movement, the relative ease and length of time of bedrock erosion, and glacial processes. Southern New England, despite the low relief, is fortunate in that the geology is generally well expressed in the topography because repeated glaciations have cleaned away soil and weathered rock and etched out the fault zones. The relative hardness of general metamorphic rock types is reflected in different terrane heights, but specific formational differences forming the smaller ridges and valleys commonly are very subtle, except around Sturbridge, Massachusetts, where they stand out remarkably well. The expression of the etched faults is discernable unless covered by thick glacial till or outwash and lake deposits. In fact, the thickness of the glacial material can be estimated by the degree it masks the bedrock features (Barosh, 1978a). The glacial features have excellent expression and also commonly reflect those of the underlying bedrock. The north- and northwest-trends of the youngest fault sets are particularly noticeable in stream and river courses across the entire region (Hobbs, 1904a & 1904b); most notably is the latter set, which controls the locations of many of the roads of the pre-expressway era. All types of remote sensing are effective in distinguishing them, which is especially significant since these faults are very important in engineering, environmental and water resource investigations.

Geologic History

The eastern side of ancient North America, Laurentia, was convulsed 1,200 to 900 million years ago in the Middle Proterozoic to form the belt of metamorphic rock and granite of the Grenville Province that underlies most of New York and the western edge of New England. Stretching into Canada, the belt also extends to the south at depth under the western side of the Appalachian Mountains and is exposed only locally along the spine of the mountains. Uplift and erosion created a mountainous continental margin through western New England from these rocks by 800 million years ago in the Late Proterozoic and the debris was carried eastward to form a large coastal plain and offshore basin in the sea (Barosh, 1979a). This ancient ocean, which is known as Iapetus (after the father of Atlas), separated the western continent from ancient Gondwana to the east. The basin may have developed similar to the present Atlantic Coastal Plain and offshore continental platform, although the source region for sediment was moderately unstable with some volcanic activity. "Dirty" sand with volcanic debris, tuff, silt and limy, aluminous and sulfidic mud were deposited southeastward, usually by turbidity currents, forming the very thick strata of the Sturbridge sequence, remnants of which now constitute much of Connecticut and central Massachusetts.

The future site of Boston then lay at the east side of the Iapetus Ocean in a volcano-studded region along the coast of the larger continent now called Gondwana, which is now northwest Africa (see Figure 2-2). The region was undergoing considerable volcanic activity, with sand and more heterogeneous volcanic rock being deposited. Clean sand was laid down near shore between influxes of fine volcanic material and eventually overwhelmed by an irregular mixture of mafic lava flows, including some pillow basalt, basaltic and rhyolitic tuff and some calcareous mud. These deposits now form the Westboro Formation (quartzite, schist and amphibolites), Middlesex Fells Volcanic Series and Burlington Formation sequence north and west of Boston and the partially equivalent Blackstone Series in Rhode Island. A deeper marine basin that lay offshore, perhaps around volcanic islands, was filling with a thick sequence of volcaniclastic sedi-

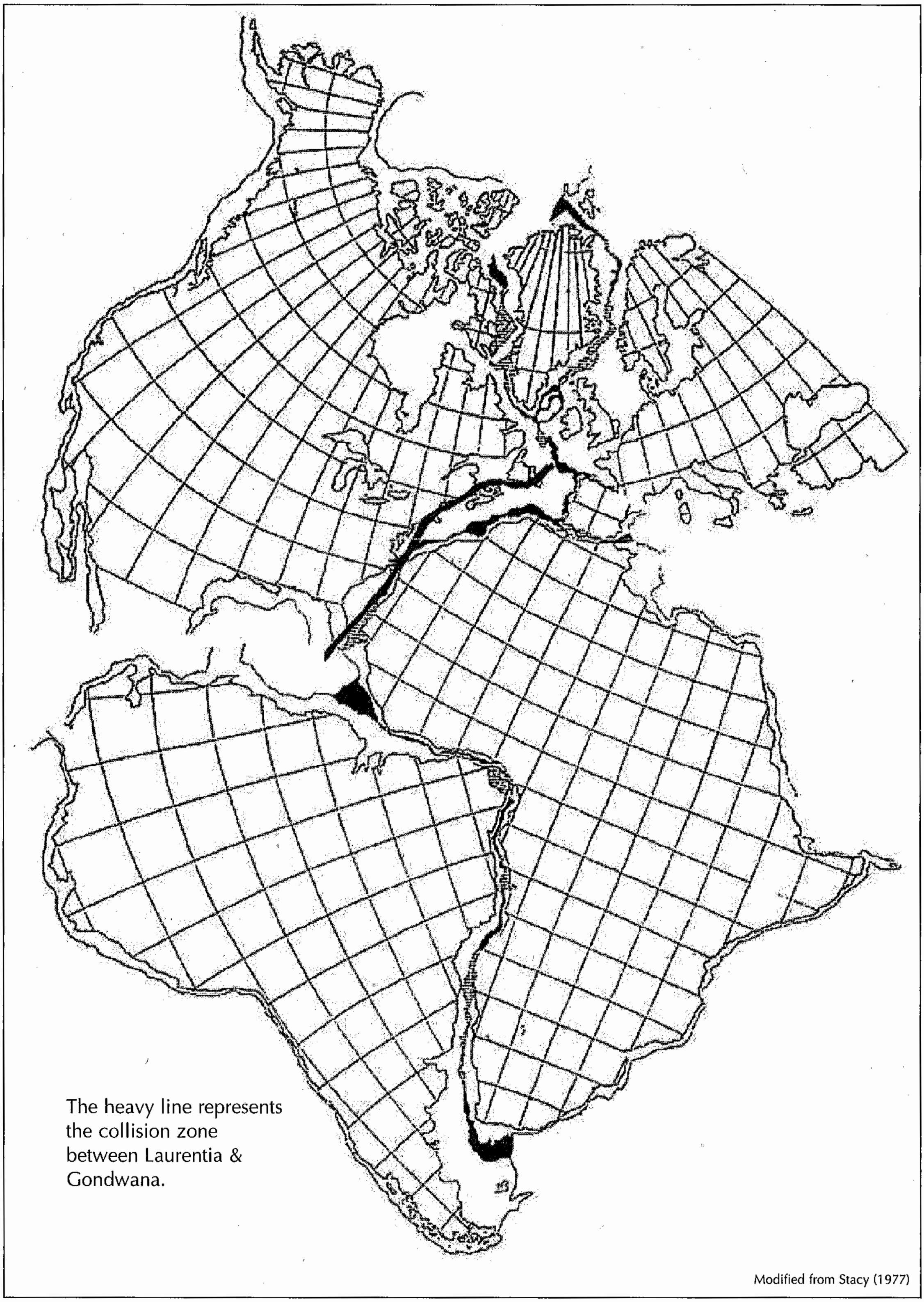


FIGURE 2-2. Western part of Pangea.

ments carried in from the southeast. These sediments were dirty sands with much andesitic debris, interlayered with tuff, tuffaceous silt and mud, aluminous mud, limy mud, thin calcareous material and mafic (dark, low-silica rock such as basalt and andesite) flows. Much of the sediment was carried by turbidity flows and laid down as graded beds that shaped the Nashoba and adjacent formations west of Boston.

The Gondwana plate moved relatively westward to squeeze the Iapetus Ocean. The western edge of its plate boundary collided against the deep marine basin offshore of Laurentia and slid under it during the Late Proterozoic. The collision zone now passes west of Boston and is roughly bracketed by Route 128 and Interstate 495 (see Figure 1-3). This collision triggered the Pan-African Orogeny (a period of deformation and mountain building) referred to as the Cadomian Orogeny in southwestern Europe (Barosh, 1976c & 1998). The collision tore the outer volcaniclastic basin apart in the ensuing subduction zone, and left only remnants of the strata as thrust sheets in the Nashoba Terrane. By 650 million years ago, the Sturbridge strata of the Laurentian plate, against which the collision broke, was sliced into thrust sheets as it began to be underthrusted by Gondwana and compressed from the east, but remained more intact. The lower units of the Sturbridge sequence, however, were progressively cut out to the west by the underthrusting. Further movement drove the collision zone downward beneath an oceanic trench and much of the rock in the lowered eastern Gondwana plate was converted into a granitic batholith between 630 and 620 million years ago. As the granitic batholith formed and plunged beneath the collision zone, its margin and the bordering rock folded against the underside of the zone and the folds became more compressed and broken downward. Elongated granitic bodies formed along some of the early thrusts in the overlying Sturbridge strata and a considerable amount of pegmatitic material formed throughout the strata as they were being metamorphosed and faulted.

When this movement slowed nearly to a halt by 600 million years ago, the future southeastern New England still lay relatively off to the east of its present position. The thickened granitic crust formed during the collision then rose rapidly and dramatically to form a high alpine mountain range across all of southeastern New England. Relaxation of the compression of the plate collision had allowed the thick, relatively buoyant crust to rise and the rapid uplift was accompanied by deep erosion that uncovered the batholith. Tension during the rise resulted in down-dropped extensional fault blocks that formed a basin-and-range topography that spread into coastal New Brunswick and across the then-adjacent Gondwana region, now Morocco (see Figures 2-2 & 2-3). One east-west zone of faults, which passed along what would become Framingham, Blue Hills and the South Shore, dropped the rock down to the north and initiated the Boston Basin by 595 million years ago when the first volcanic debris began to accumulate within the basin (Kaye, 1982a; Kaye & Zartman, 1980). The initial terrestrial and near-shore rhyolite and andesite flow and ash were spewed from volcanoes that were triggered by the faulting and rose up the fault zone bordering the south side of the basin. The debris intermixed with, and then was succeeded by, boulder fans shed northward from the adjacent highlands. The boulder deposit and sand graded north, downslope into mud and silt, which quietly accumulated in marine waters that invaded from the east as the area began to subside. Earthquakes during deposition caused occasional basinward slumping and sliding of the sediments. These basin deposits formed the present intertonguing Mattapan Volcanic Complex, Roxbury Conglomerate and Cambridge Argillite. At that point, if any of the Iapetus Ocean remained west of the range, it was very shallow and restricted from the uplift. The eastern edge of the Grenville Terrane of Laurentia also was elevated and undergoing mild erosion to act as a barrier separating any remaining Iapetus Ocean from a shallow inland sea farther to the west. This western terrane still lay at a considerable distance from the Boston Basin.

The following Early Cambrian to Middle Ordovician was a time of general subsidence, with advancing seas from the east and west.

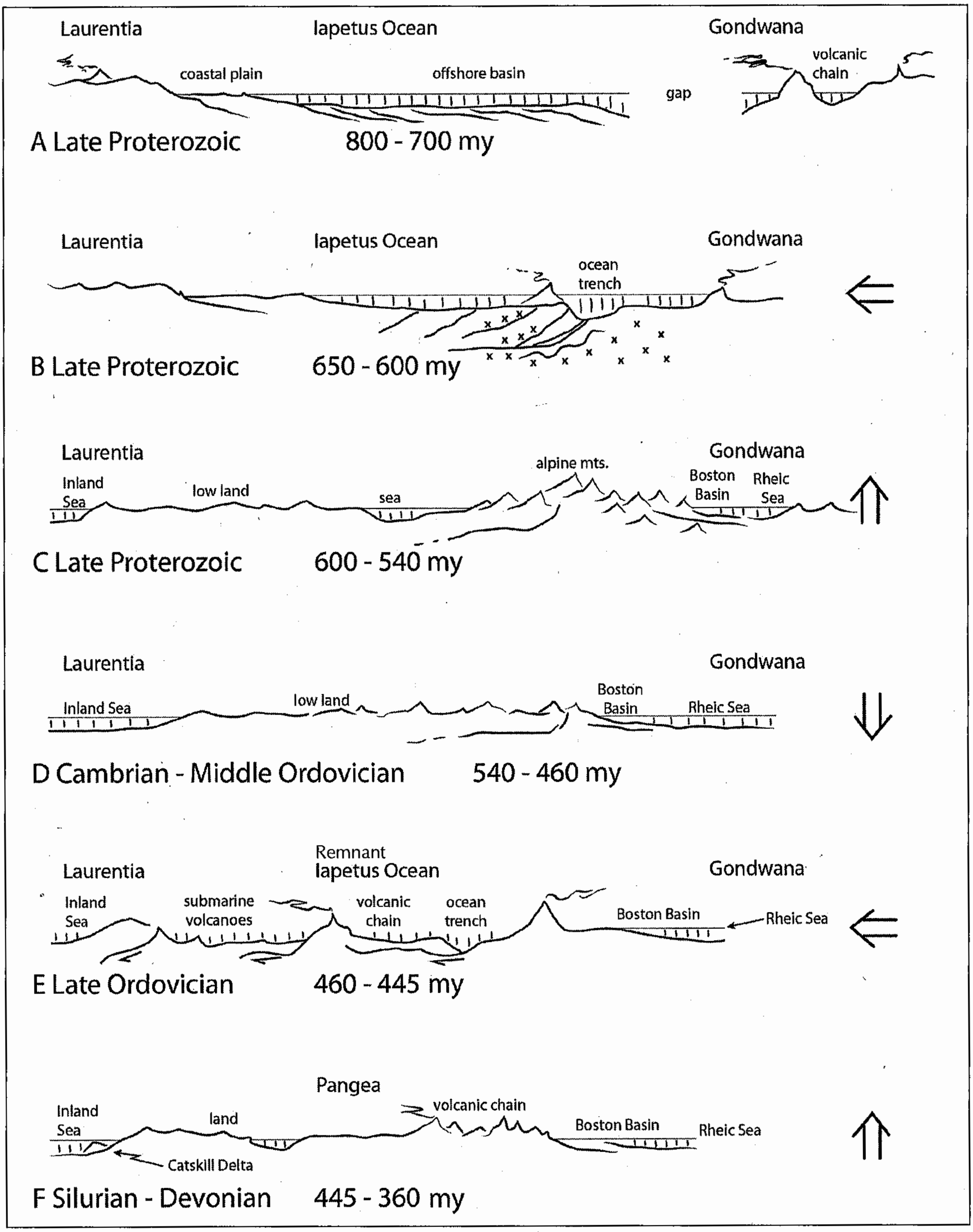


FIGURE 2-3. Paleo-geography of southern New England.

However, the intervening region gradually became mobile again as collision commenced once more. The subsidence farther east near Boston became more general and the Rheic Sea, which spread over Gondwana to the east, rose to overtop the fault bluff of the Boston Basin and spread over the countryside while the first hard-shell marine life emerged during the Cambrian period (the Cambrian explosion) about 545 million years ago. Silt, mud and calcareous mud accumulated in the Boston Basin during Early and Middle Cambrian apparently without a break from the earlier deposition in the Boston Basin and spilled out over the bordering batholithic rock in the advancing shallow waters.

Sand and carbonate mud also were deposited in another shallow inland sea bordering the western side of New England as it extended eastward onto the Grenville rock (Walcott, 1891b; Pumpelly *et al.*, 1894). The two seas on either side of what is now New England formed over sags in the continental plates and, unlike the Iapetus Ocean, which would have been underlain by a true oceanic basaltic crust that would have mostly disappeared during the earlier collision. Thick clean sands accumulated in the advancing Rheic Sea to the east in the Early Ordovician, while mud and carbonate material covered the Cambrian in the far west. The area of the previous remnant of the Iapetus Ocean buckled downward and deepened to become a sea again during the Ordovician 490 to 443 million years ago as the Iapetus Ocean re-formed over a region that included most of Connecticut and central Massachusetts. The ocean then narrowed as the sides once more moved toward one another to cause underthrusting along its western edge and to cause the formation of an oceanic trench along the reactivated collision zone with the Gondwana plate (see Figures 2-1 & 2-3). Submarine volcanism occurred along the western edge that is well recorded in Québec, but only marked by remnant feeder dikes in Massachusetts. The Middle Ordovician Bronson Hill ridge rose across the middle of the Sturbridge Terrane and probably supported a volcanic chain that extended northeastward into Maine (Moench, 1980). The granitic ridge separated a basin to the west that received marine mud and basic submarine volcanic material of an ophiolite suite (an assemblage of basic, magnesium-rich igneous rock and basalt) and the trench along the collision zone, which began filling from the west with turbidic silt and mud deposits over what may be Cambrian age basaltic debris.

Other long northeast-trending faults apparently cut across the Boston Basin and guided new outpourings of volcanic rock, causing volcanoes, with underlying granite, to form in the Blue Hills south of the Boston Basin and to the north at Cape Ann, thus completing the basic geologic framework of Boston. Meanwhile, in the west underthrusting had raised the edge of the old continent, including the Taconic chain of mountains along western New England. The term *Taconic Orogeny* has been applied to this time of collision and deformation, which caused the uplift of mountains across the Berkshire region.

Increased compression and underthrusting during the Middle and Late Ordovician caused the widespread deformation and intrusion of the Taconic Orogeny. Generally small scattered granitic bodies intruded in the west while larger ones formed in the reactivated collision zone, and others developed beneath volcanic complexes to the east where the land once more rose. The Salem Gabbro-Diorite intruded as a large basaltic complex north of Boston and extended southwest along the edge of the collision zone as a series of small basaltic cones. Also a series of mafic dikes and small plutons invaded the Boston Basin to mark the beginning of this activity. Large andesitic and rhyolitic volcanoes formed in Cape Ann and the Blue Hills in the batholithic region on either side of the Boston Basin. The Lynn Rhyolite north of Boston was accompanied by the Cape Ann Granite, which overlapped in time and area with the episode of Salem activity and continued later (Dennen, 1981). To the south, the ash-flow tuffs in the Blue Hills erupted from a volcano whose conduit is represented by the Quincy Granite (455 million years ago). Other small bodies of Quincy, which extend southwest into Rhode Island (Quinn, 1971), may represent feeders to small volcanic cones. The large Spencer volcanic complex farther south may date from this time, too. The Boston Basin strata were very slightly metamorphosed by this activity and the mafic dikes were altered to greenstone. The renewed collision, which brought on the Taconic Orogeny, also affected the Nashoba Terrane west of Boston, with extensive intrusion by the Andover Granite in Late Ordovician. Reactivated thrusting in the Sturbridge Terrane caused parts of the Sturbridge strata to be repeated by faults, which also trapped the overlying Ordovician trench deposits in the Nashua and Haverhill troughs (Peck, 1976; Smith & Barosh, 1981). The metamorphism accompanying the orogeny was generally moderate in the Sturbridge and Nashoba terranes — being distinctly less than the earlier collision and deformation — and did not produce the ubiquitous pegmatite lenses that commonly occur under intense shearing and metamorphism. The western side of the Sturbridge Terrane underthrust the edge of the Grenville Terrane to jack it up to send some of the Cambrian-Ordovician onlap deposits sliding off to the west toward the Hudson River.

The direction of tectonic movement then changed to northwest over southeast during the Taconic Orogeny. The thrusts in the collision zone overrode the folded edge of the batholith in southeastern Massachusetts and while the North Boundary Fault of the Boston Basin broke and moved to the southeast, some folding occurred within the basin. By the end of the Ordovician, thrusting had ended in the collision zone and any gap between it and the Ordovician turbidite deposits to the west was closed, thus allowing the Andover Granite to cross-cut the Nashoba sequence and extend into those to the west (LaForge, 1932; Barosh, 2000). The Iapetus Ocean was nearly eliminated in southern New England, but lingered as a narrow strait to the north at the close of the period owing to the greater compression in the south that gave New England its characteristic V-shape. This final push at the end of the Ordovician, some 450 million years ago, ended the collision between Laurentia and Gondwana in New England. At that point uplift again returned to the region, marking a change in the geologic regime. Southern New England became part of the supercontinent Pangea, formed of an amalgam of the ancient Americas, Africa, Eurasia and other continental masses (see Figures 1-2, 2-2 & 2-3).

After this period of collision ended, the land was again buoyed upwards because of the thickened crust of land that formed most of southern New England. This uplift caused extensional faulting to create small rifts and a volcanic chain was built across the region. A chiefly terrestrial volcanic chain, which had occasional incursions from the sea, formed along eastern New England and overlapped the closed collision zone from the eastern Sturbridge Terrane to the batholithic complex (Gates, 1969; Shride, 1976; Bell *et al.*, 1993). The well preserved fossiliferous sections in the coastal volcanic belt of eastern Maine show that the activity began in the Early Silurian and continued through the Devonian (from 444 to 359 million years ago) while normal faulting was occurring (Gates & Moench, 1981). The Late Silurian-Early Devonian Newbury Volcanic Complex in northeastern Massachusetts (Shride, 1976) may have been down-dropped by such general faulting or it may have been dropped as a basin under tension that was related to right-lateral movement along the Clinton-Newbury Fault Zone. Volcanoes supplying the Newbury Volcanic Complex produced a mixture of both basaltic to rhyolitic tuff, flows and breccia that interfingered with tongues of sediment ranging from red mud to boulders and an occasional thin near-shore limestone bed. Circular- to irregular-shaped nonfoliated granitic and mafic plutons intruded farther south and served as volcanic conduits during this time. A Devonian granite pluton occurs in Worcester and a Silurian mafic one in southeastern Connecticut (Dixon & Femlee, 1986). In Rhode Island, Devonian alkalic rock constitutes the East Greenwich Group (Hermes *et al.*, 1981b) and the Spencer Hill volcanic rocks appear to be co-magmatic with the nearby Devonian-aged Cowesett Granite (Quinn, 1971). The large circular Middle Devonian granite bodies in Maine are ascribed to an Acadian Orogeny at this time, but this minor orogeny seems to be the only more active occurrence during a wider period of instability from Early Silurian (Gates & Moench, 1981) to at least Late Devonian (Schluger, 1973) and may extend to the Mississippian, as in New Brunswick. The coastal volcanic belt in Maine was flanked on either side by a sea, but only limited marine waters remained to the west and in the south, where some Devonian carbonate was deposited in the northern Connecticut River valley of Massachusetts. Southern New England was elevated during the Silurian and Devonian and it sent an immense amount of eroded debris westward to build the Catskill delta westward out into the inland sea in New York. Southern New England had reached roughly its present extent by that time, about 345 million years ago. All of New England appears to have been uplifted to land by the Mississippian, to judge by the redbed land deposits in New Brunswick. The record is blank in southern New England, which may have been eroding until the Pennsylvanian (318 to 299 million years ago), when extensional faulting formed the Narragansett, Norfolk and smaller basins. Rivers and streams deposited into these basins a wide variety of valley fill, river and back-swamp deposits, some of which formed peat bogs that later became coal (Shaler *et al.*, 1899). These basins were apparently part of a broad lowland that extended northeastward into the Bay of Fundy within a broader basin-and-range setting. Bordering fault scarps apparently aided the development of fans of pebbles to boulders, while erosion of the uplands stripped away the Paleozoic strata (layered sedimentary lithology) in southeastern New England. These fan deposits extended well into the sand and shale of the basin, at times creating intertonguing deposits in addition to coarse gravels carried by rivers. Faulting in the Norfolk Basin south of Boston may have been aided by right-lateral moment along the Clinton-Newbury Fault Zone (Barosh, 1983a & 1995). However, the Pennsylvanian strata on the west side of the fault zone in Worcester, Massachusetts, suggest that any offset was limited.

Only local deformation, intrusion and metamorphism affected the southern edge of New England during the Permian "Alleghanian" Orogeny (Zartman *et al.*, 1965; Quinn, 1971). During this time, the Pennsylvanian strata in southwestern Narragansett Basin were mildly deformed and metamorphosed in a tectonic episode, which culminated in the intrusion of the Narragansett Pier and Westerly granites (Quinn, 1971; Burkes, 1981; Hermes *et al.*, 198la), whose dates range from Permian to Middle Triassic in age (see Figure 2-4). The activity may have begun with uplift that first produced some slumping in the Narragansett Basin strata and then intensified to produce some compressional deformation about the mouth of Narragansett Bay. The metamorphism of the Pennsylvanian strata is highest adjacent to the granite and rapidly drops off toward the north side of the basin, demonstrating that it was essentially contact metamorphism. A regional bedrock heating event, which was probably contemporaneous with the intrusion, dated at 240 million years ago (Middle Triassic), extended to New Hampshire (Zartman *et al.*, 1965). Pink pegmatite dikes, associated with the Narragansett Pier granite, also extend beyond it to New Hampshire. The nonfoliated post-tectonic granite in southwest Rhode Island was emplaced in a relatively passive manner that did not disturb the earlier structure of the rock and indicates that compression had ended before the intrusion (Hermes *et al.*, 1981a). A late phase of the granite intrusion produced the Westerly Granite that forms a system of east-west, south-dipping dikes along the Rhode Island and eastern Connecticut coasts (Feininger, in Quinn & Moore, 1968). The extensional fractures controlling the dikes cut across the older structure and appear to be a precursor to the formation of the south coast of New England by the Cretaceous (145 million years ago). The fractures might be related to the raising of southern New England that created a regional northward tilt. This tilt probably occurred near the beginning of the Late Triassic (if the age of 240 million years is correct), and is responsible for the northward plunging structures, northward decrease in effects of different metamorphic events, uplift of the Narragansett Pier Granite and progressively younger strata to the north. There is no sign of an Alleghanian Orogeny north of the Narragansett Basin and the nearly undeformed Permian redbeds in Prince Edward Island indicate that this time was quiet in the north. The relatively mild deformation of the orogeny at the southern edge of New England may be the northernmost part of the uplift of the Appalachian Mountain spine to the southwest that caused the great gravity thrusts to slide westward and fold across much of Pennsylvania where the orogeny was named. The rapid uplift and erosion of southern New England during the Early and Middle Triassic was followed by extensional faulting during the Late Triassic and Early Jurassic (235 to about 190 million years ago) that inaugurated

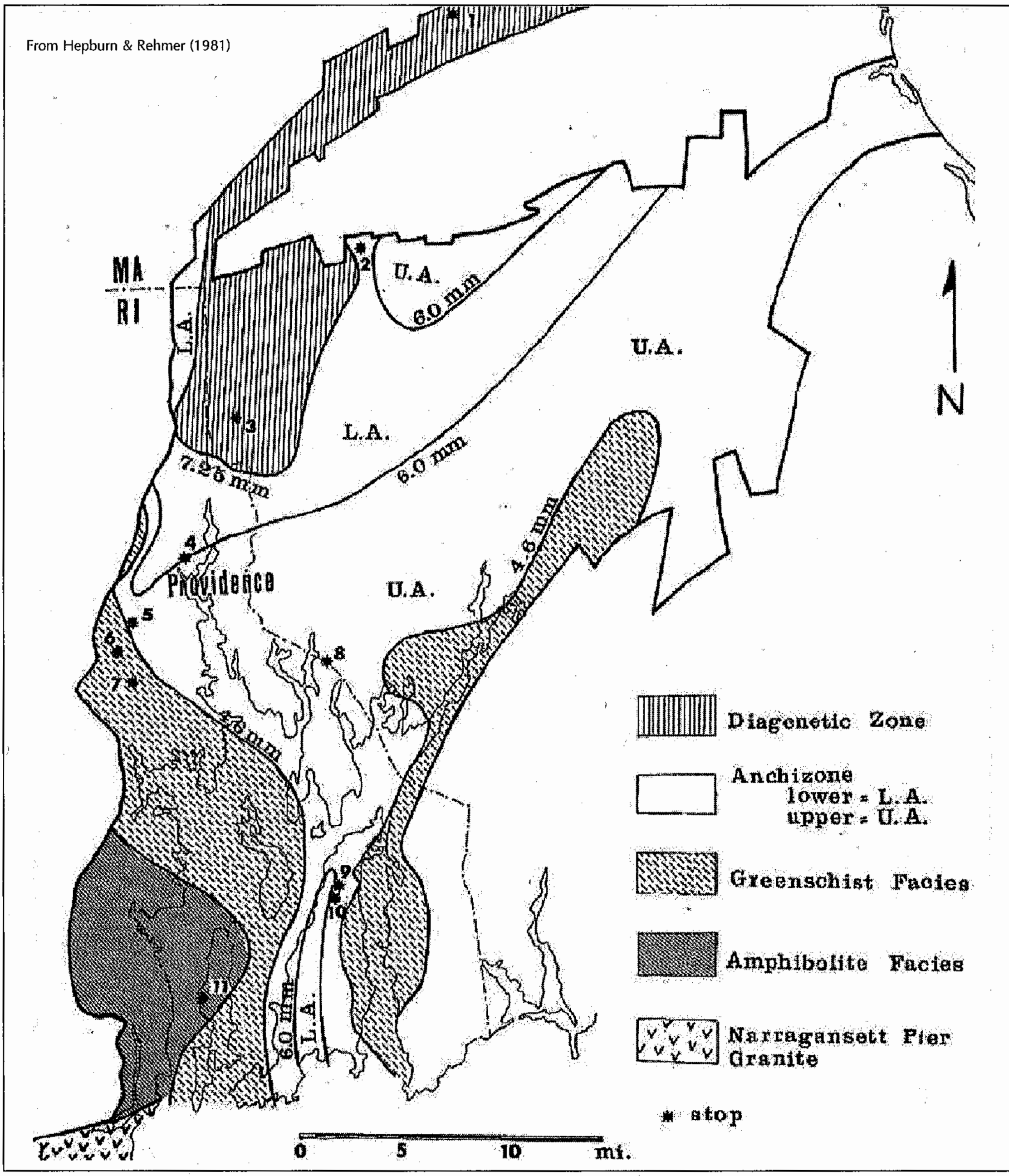


FIGURE 2-4. Metamorphic effects in the Pennsylvanian Narragansett Basin strata extending out from the Narragansett Pier Granite of Permian to Triassic age. The metamorphic grade decreases upward in divisions shown to none in the Diagenetic Zone.

major rifting and the formation of the North Atlantic Basin. The center of rifting occurred east of the earlier plate collision zone and left southeast New England attached to North America. A smoothed upland plain that had developed across southern New England in the early Mesozoic was broken by normal faulting into a generally northeast-trending basin-and-range topography across the region (see Figures 1-2 & 2-5) and continental clastic red sediment and basalt accumulated in the basins (Hubert *et al.*, 1978; Kaye, 1983a). Most of the valleys formed by the basins presently lay off-shore to the east (Ballard & Uchupi, 1975) and diminish in number toward the northwest. Many normal faults were formed by reactivation of earlier ones, including thrust faults, one of which controlled the aberrant northerly trend of the Hartford Graben (Barosh, 1976c). There may have been minor left-lateral movement along faults (Ballard & Uchupi, 1975) when the geologic constraints are taken into consideration, but no large-scale offset is evidenced, although such was hypothesized by Kent and Opdyke (1978) from paleomagnetic data.

A pulse of extensional activity at the beginning of the Jurassic (200 million years ago) produced widespread basalt flows and numerous diabase dikes along faults along the Atlantic Seaboard. In New England, the few local lamprophyre dikes (composed chiefly of biotite, hornblende and pyroxene) present may be of similar age (Ross, 1981). A volcanic conduit lay against the southeast boundary of the Hartford Graben in the southern Connecticut River Valley (where extensive lava flowed northward) and now stands out as ridges in the valley. A line of very large diabase dikes called the Higganum Dike also extends from the conduit northeastward across Connecticut and central Massachusetts to the New Hampshire border. Some of the larger dikes may have reached the surface to form basaltic volcanic cones. Many smaller northeast-trending diabase dikes invaded eastern Massachusetts west of Boston. Numerous northeast-trending faults offset the basalt flows in the Hartford Graben by further movement in the Jurassic.

As the Atlantic Basin widened, the fault blocks subsided and evaporite deposits formed in the eastern basins (Grow, 1981), now offshore, from saline lakes and restricted seas in the Middle Jurassic (see Figure 2-5). Continued opening of the Atlantic during the remainder of the Jurassic and Cretaceous caused further lowering, and most of the southern and eastern fault-block valleys were submerged below a growing ocean that spread to form the coastline of New England. A thick apron of clastic sediment from rising and eroding Appalachian uplands to the northwest was deposited on this newly formed continental edge and covered the earlier fault basins. The sediment continued to build the Atlantic Coastal Plain in the Tertiary, although this process was interrupted briefly by regional uplift that caused a low sea stand and erosion in the Oligocene at 34 to 23 million years ago (Weed *et al.*, 1974; Valentine, 1981; Kaye, 1983b). This very wide coastal plain was similar in extent to that of the modern Mid-Atlantic coast, before later shrinking due to glacial erosion and sea-level rise.

The widening of the North Atlantic Basin created new sets of faults, which extended across the earlier structural trends on land, in the Late Jurassic or Cretaceous (see Figure 2-6). These faults formed in the Late Mesozoic as adjustments to movement of a widening ocean basin. The western side of the East Coast of America had rotated relatively clockwise with respect to Africa as the basin grew, causing the earlier Triassic rifts to shift to a northeastern alignment and out of the line of the north-south compression that had formed them. New northerly trending rifts then took their place (Barosh, 1986c). New valley systems formed, at least on land, in graben systems along the northerly trending faults. The north-trending Narragansett Bay Graben, which formed across the southwest Narragansett Basin (McMaster *et al.*, 1980), formed a south draining valley system, as well as the smaller Assawompset Graben to the east that is north of, and possibly including, New Bedford (Koteff, 1964a). Some reactivation probably occurred along some faults in the older north-trending Hartford Graben as well. The numerous large north-south diabase dikes in and south of the Boston Basin apparently are associated with the faults that formed then. The Medford Dike was an early one of this set. A buried north-trending basic pluton at the western edge of Cape Cod is also probably a larger member of this set (Barosh *et al.*, 1977b).

Transverse adjustments, called transform fracture zones, also took place as the Atlantic Basin formed. These trend about east-west near the Mid-Atlantic Ridge but swing to the northwest near the East Coast, because of the rotation mentioned previously (see Figures 2-6 & 2-7). They extended onto land to form ubiquitous, generally small northwest-trend-

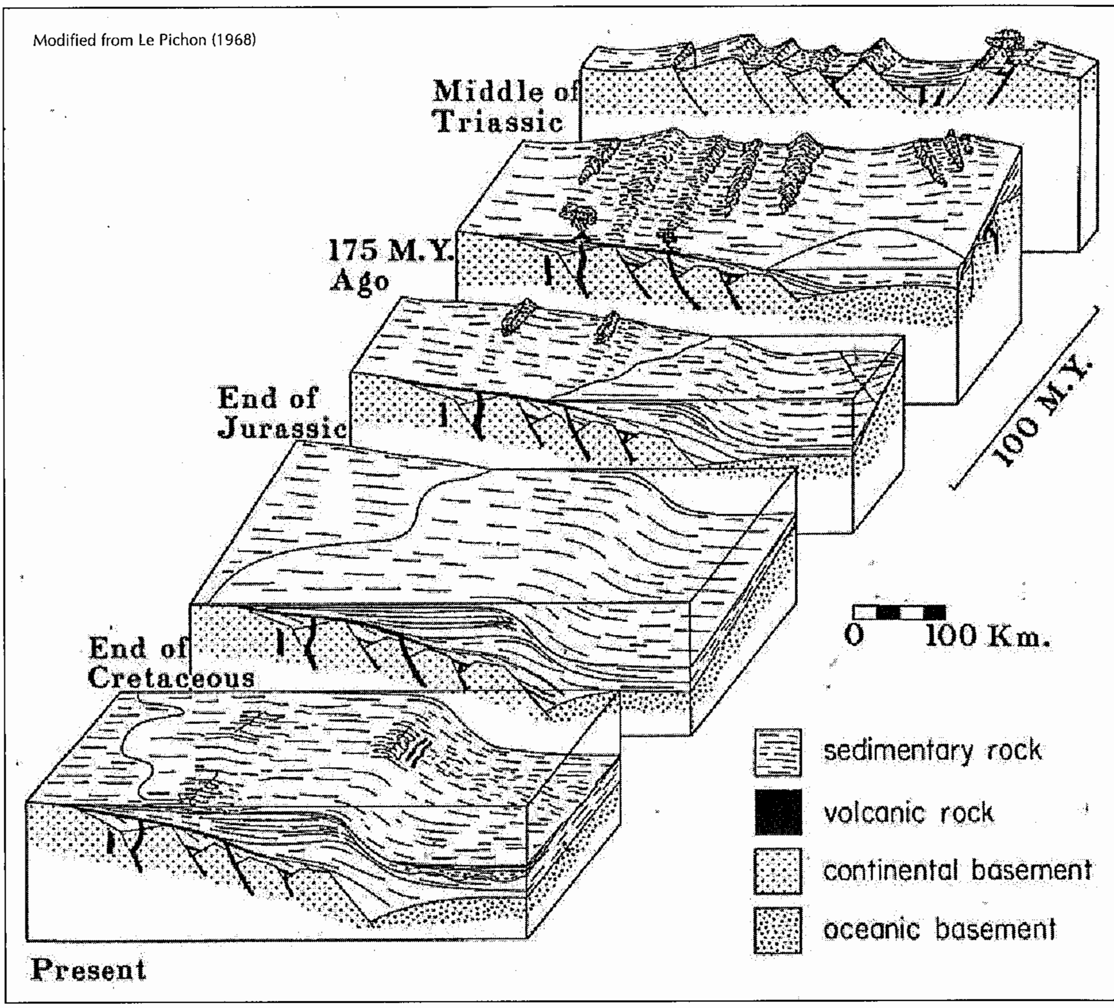


FIGURE 2-5. Formation and development of the Atlantic continental margin.

ing faults across all of New England, but in places they form prominent zones of faults. The northwest-trending faults appear to have been mainly contemporaneous with the northerly ones, but many continued to be active later than the northerly ones and some still are active (Barosh, 2006b). A zone of such faults, which crosses New England to pass near the southern New Hampshire-Maine border and extend southeast offshore, controlled a volcanic chain in the Jurassic and Cretaceous (Barosh, 1992). This chain passed east of Cape Ann and apparently connected in some irregular fashion with the drowned Cretaceous volcanoes of the chain of New England Seamounts, which extended southeastward 1,100 kilometers (682 miles) from Georges Bank (see Figure 2-8). These volcanoes are now deeply submerged due to further subsidence of the sea floor.

The activity slowed, but still continued into the Tertiary, and some regional crustal movements took place. Some of the northwest-tending faults along the New Hampshire-Maine border are continued active and cut volcanoes in the chain (Freedman, 1950; Barosh, 1992). Other north- and northwest-trending faults cut the Cretaceous and Tertiary deposits just offshore to the south (McMaster *et al.*, 1980; Hutchinson & Grow, 1982). The coastal plain deposits along the Atlantic Coast were affected by areas of local subsidence, which appear connected with the propagation of the transform fracture zones. These northwest-trending faults

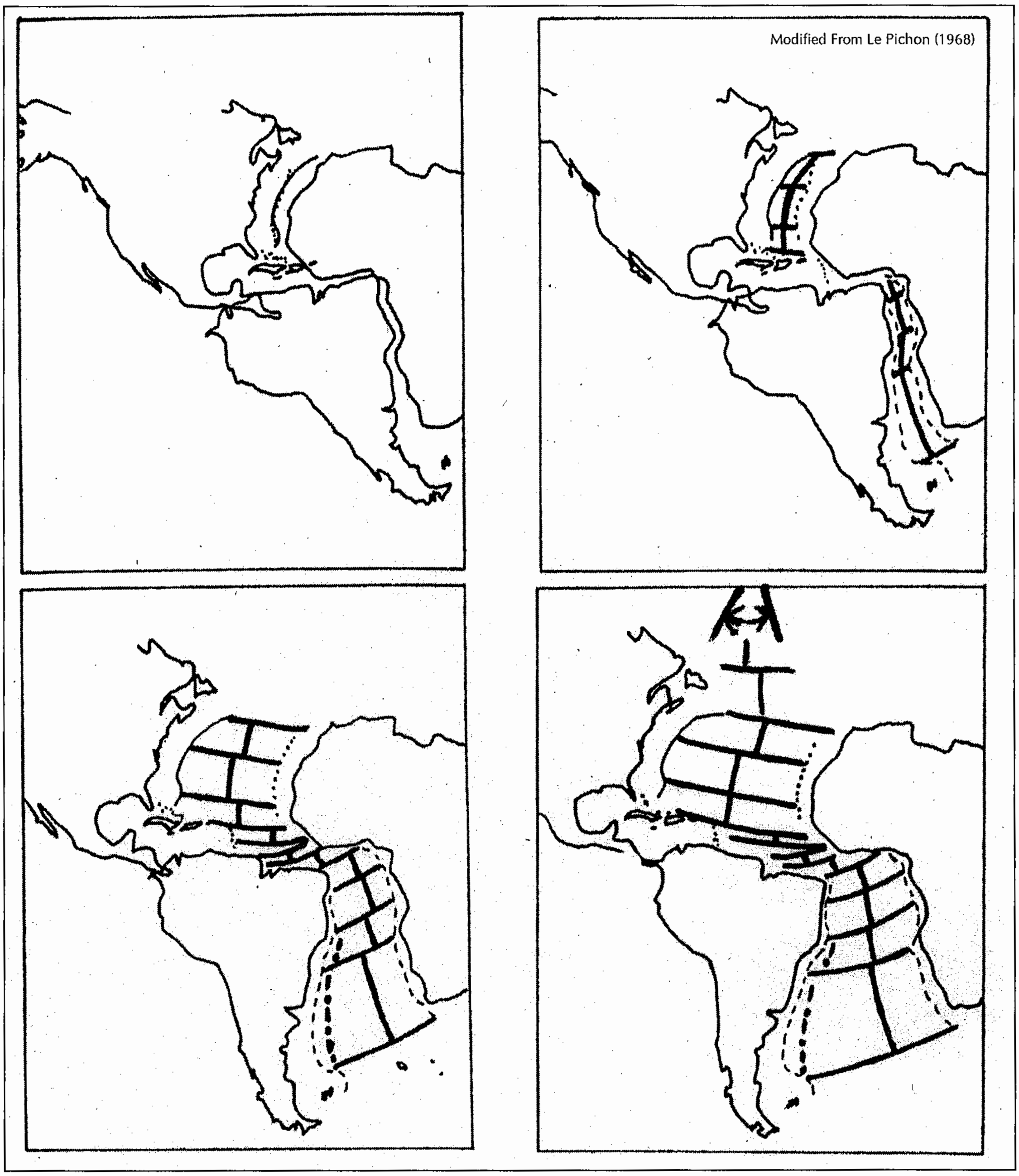


FIGURE 2-6. Progressive Mesozoic opening of the Atlantic Basin showing the Mid-Atlantic Ridge and a few transform zones. The angle at the top of the last frame indicates the lesser opening in the North Atlantic that causes the opposite shores of the North Atlantic to rotate away from one another.

also seem to control an area of submergence centered on the New Hampshire coast (Smith, 1982) and another near New York. In addition, the entire East Coast began a slow downward tilt to the north and a rise to the south again in the Late Cretaceous that caused the coastal plain to emerge south of New York City and to submerge to the north (Barosh, 1986c).

Several periods of glaciation affected the region during the Pleistocene, 2 million to

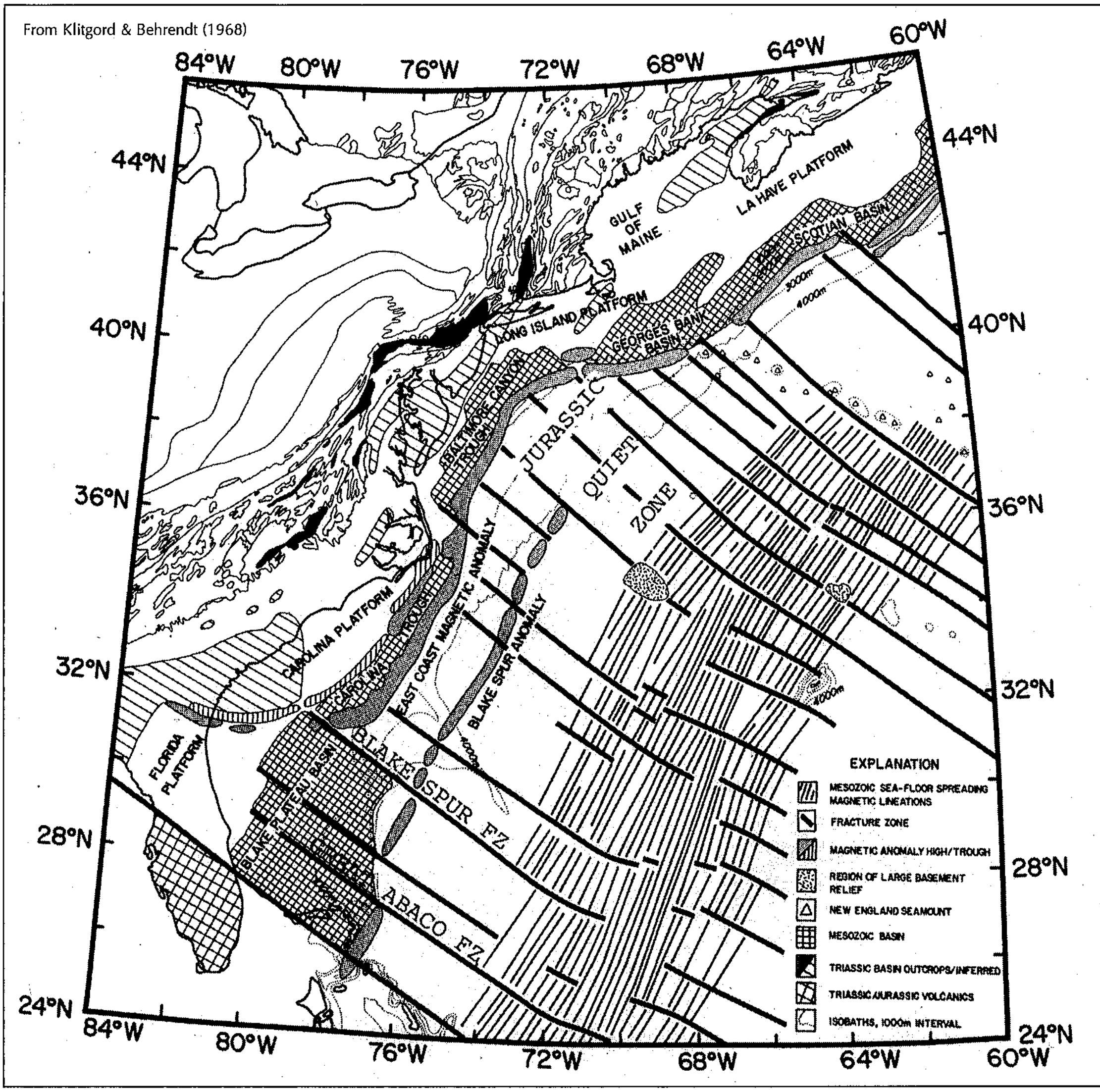


FIGURE 2-7. Western North Atlantic Basin showing major transform fracture zones impinging on the East Coast of North America.

11,000 years ago, but the only clear record of retreat is at the end of the late Wisconsin. At least three Wisconsin glaciations left a very complex array of deposits in the Boston Basin where the sea level varied greatly due to worldwide decline to form glaciers, depression from the ice load, rebound from removal of the load and general sea-level rise from melting. The last rebound of the crust began soon after the ice started its final retreat 13,500 years ago (Larsen, 1987) and caused a regional downtilt to the south of about 90 centimeters per kilometer (57 inches per mile). This tilt and the post-glacial rise in sea level combined to deeply submerge the Late Pleistocene New England shoreline offshore to the south of Boston (Schlee & Pratt, 1970; USGS, 1976; O'Hara & Oldale, 1980), whereas north of a point on the south side of Boston the old shoreline is exposed and progressively rises to the north.

Tectonic activity continues in the region as shown by many local areas of earthquakes from some active north- and northwest-trending faults. The most prominent system and most active of the northwest-trending zones of

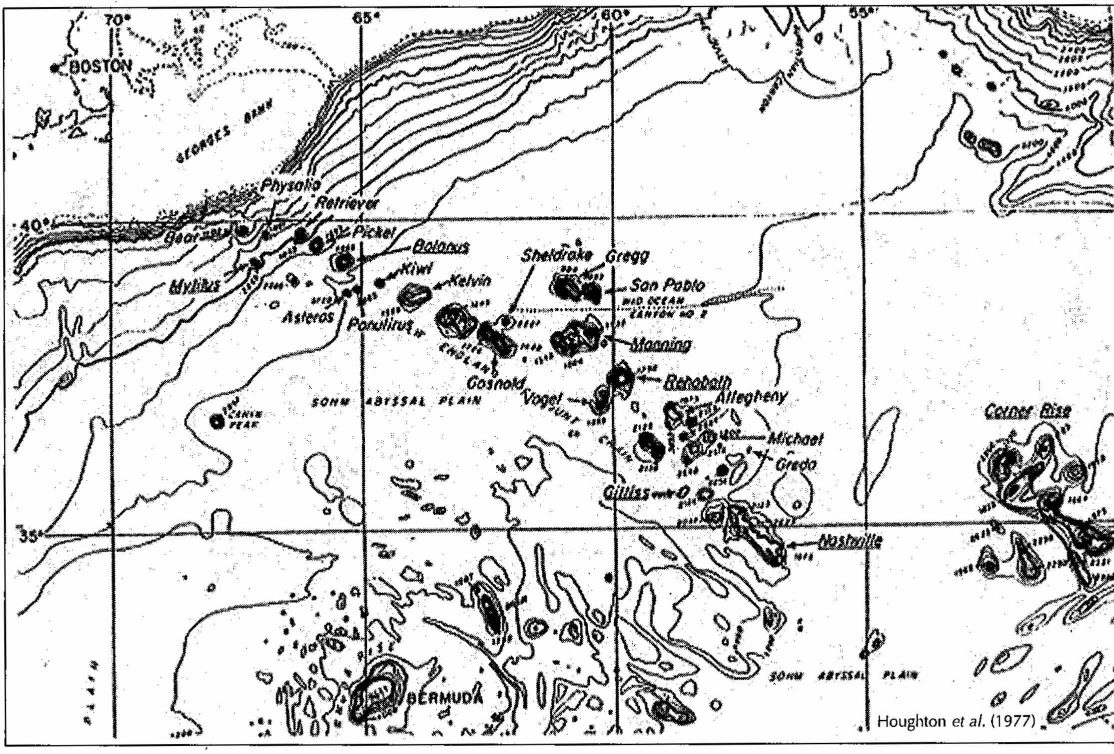


FIGURE 2-8. New England seamount chain extending southeast of Boston to east of Bermuda shown on a bathymetric chart.

faults crosses New Hampshire and passes along the north side of Cape Ann and out to sea just east of Boston (Barosh, 1986a, 1986b & 1986c). These earthquakes appear to result from local crustal subsidence in the bays and river valleys related to continued movement in the North Atlantic Basin. The glacial rebound is long over in New England and its effect on tectonic activity is long passed. The regional tilt to the north is again operating and adding to the shoreline changes from sea-level rise.

Proterozoic & Paleozoic Geology

Grenville Terrane. The Grenville Terrane (see Figure 2-1) is underlain by a wide band of deformed rock along the eastern side of Laurentia that was metamorphosed and intruded in the Middle Proterozoic about 1,200 to 900 million years ago. The restricted portion of the Grenville Terrane described here is its eastern edge where the rock turns up to form the west side of the Appalachian Chain of New England (see Figure 2-9). This portion of the terrane covers the area where the southern Green Mountains divide into the Berkshire Hills and the Taconic Range and the extension into the Hudson Highlands and Manhattan. The region underlain by Grenville is overlapped by a transgressive sequence of Cambro-Ordovician strata and is seen as local exposures, such as the granite on Mount Hoosac in northwestern Massachusetts. There, the younger strata arch over the crest of the granite in a north-plunging fold and extend down its eastern side (Pumpelly *et al.*, 1894). The arch is pierced by the 8-kilometer (5-mile) long Hoosac railroad tunnel, which exemplifies an early achievement in engineering geology, and one that has held up well (see Figure 2-10). Highly metamorphosed schist and gneiss, of apparent Late Proterozoic age, wedges in over the east flank of the Grenville rock in southern Massachusetts and expands to the southwest into New York. There, it includes the New York City Group, which also includes the Manhattan Schist and Inwood Marble units.

The later Cambro-Ordovician strata are deformed in broad north-plunging folds, with

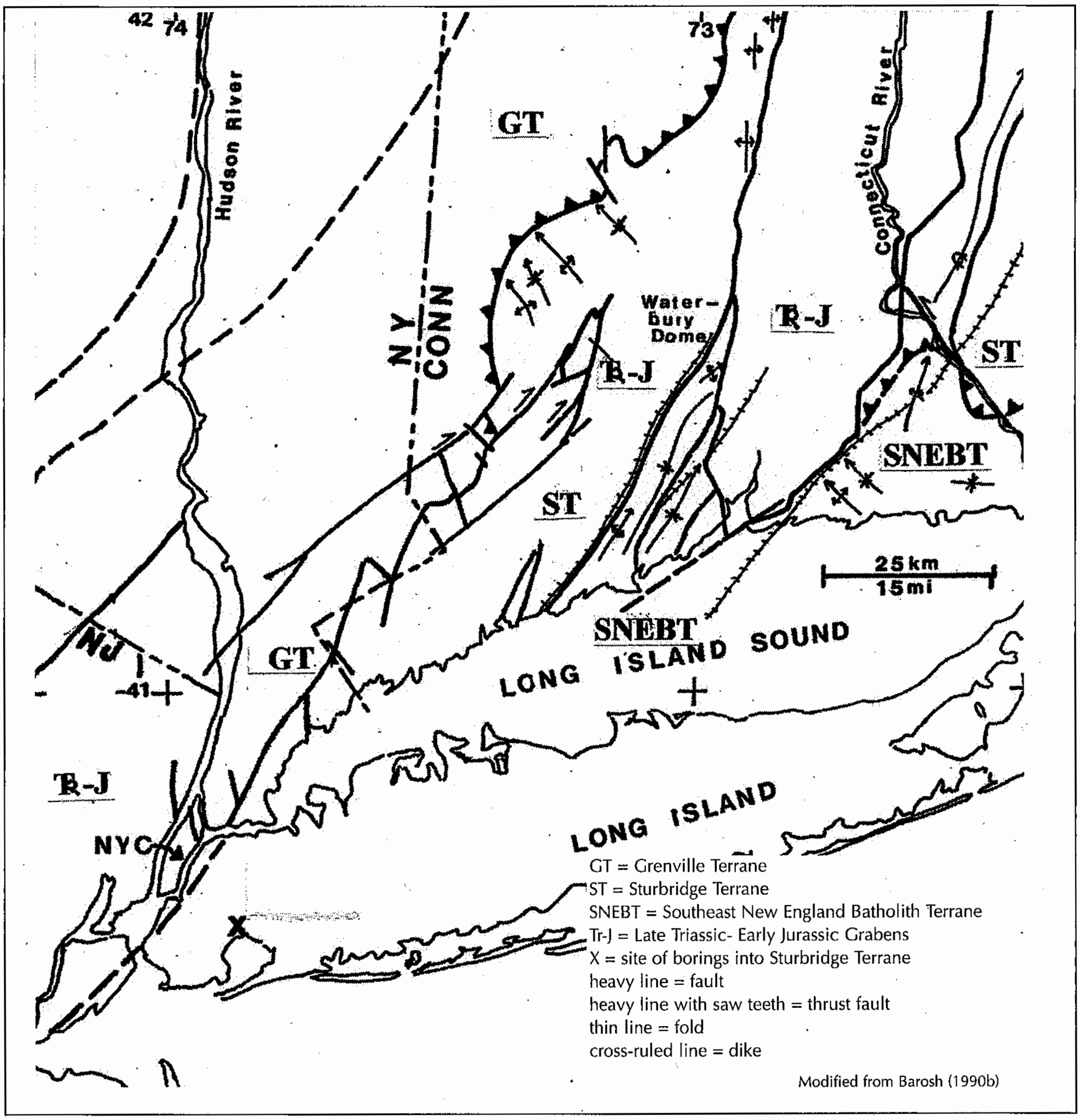


FIGURE 2-9. Map of southwestern Connecticut and adjacent New York showing geologic terranes and selected geologic structures.

smaller local compressed zones that show some overturning to the west. The general structure is relatively simple, but, "[s]mall structures, in contrast to the simple large structures are remarkably complex. Small tight folds may be observed at many outcrops, and boudinage [squeezed into string-of-sausage-shapes] is common. These small structures seem to be rather unsystematic fold axes [that] plunge in different directions" (Quinn, 1967). This result is due to movement in incompetent strata, whereas the enclosing competent layers remain planar (Balk, 1932). Some of these small-scale internal folds have been interpreted to represent very complex regional refolded structures with the different local axial trends representing different periods of folding (Ratcliffe & Harwood, 1975; Stanley, 1975; Zen *et al.*, 1983; Hepburn, 1975). This interpretation, however, conflicts with the attitudes and stratigraphy of the strata (Hobbs, 1904b; Schnabel, 1976; Gates & Martin, 1976), and the geophysical data (Bell

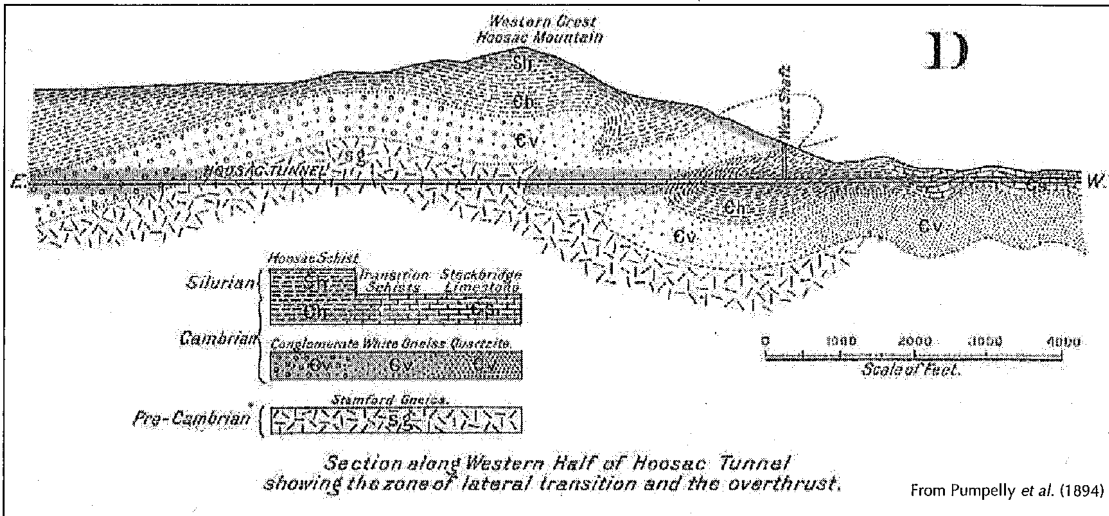


FIGURE 2-10. Geologic section of the Hoosac Tunnel, view south.

& Schnabel, 1972; Barosh *et al.*, 1977b), in addition to being geometrically incompatible and apparently structurally impossible. The known folding appears related to westward-sliding gravity-thrust sheets and slides along the western flank of the mountains toward the Hudson River valley. The Taconic thrust faults are the most notable.

The Grenville Terrane is bounded on the east by a west-dipping thrust zone, sometimes referred to as Cameron's Line (Clarke, 1958; Gates & Bradley, 1952; Gates & Martin, 1976) after a student who recognized it (see Figure 2-11). The moderate west dip of the fault gradually steepens northward across Connecticut into Massachusetts where it is mapped as the Barkhamsted Fault (Schnabel, 1976). The zone swings to the southwest in southwest Connecticut, into a broad right-lateral, northwest-dipping fault zone, which continues southwestward down the East River. This swing is well shown by offsets of geophysical and geologic features (Clarke, 1958; Prucha *et al.*, 1968; Barosh, 1976a; Barosh & Pease, 1976; Tillman, 1981). The Grenville Terrane has been thrust eastward along these faults over the adjoining Sturbridge Terrane (Clarke, 1958) and not the reverse as has been sometimes assumed in northern Massachusetts (Karabinos *et al.*, 1998) where the evidence is lacking.

Sturbridge Terrane. The Sturbridge Terrane (see Figure 2-1) is characterized by a very thick west-dipping section of gneiss, schist and granulite laced with pegmatite and intruded by tabular bodies of foliated granite, which form the Late Proterozoic Sturbridge Province or sequence (Barosh, 1998). These rocks are divided in half by the Upper Triassic-Lower Jurassic strata of the Hartford Graben, which contains the Connecticut River Valley (see Figures 2-1 & 2-9). Moderately metamorphosed lower Paleozoic strata cover the section west of the graben in Massachusetts and occur as down-dropped fault troughs in east-central Massachusetts. Slightly foliated to nonfoliated Paleozoic plutons of mostly Ordovician age are scattered about. The terrane forms a large sheet-like body underthrust by the terranes to the east, which show through locally as windows, such as the Waterbury and Willimantic domes in western and eastern Connecticut, respectively (Pease, 1982 & 1989) and the Pelham Dome in central Massachusetts (see Figures 2-9, 2-12, 2-13 & 2-14). The Sturbridge Terrane is cut into thrust slices with west over east movement. The lower, flatter slices pinch out northward at the Massachusetts border, where the terrane forms a series of west-dipping thrusts (see Figure 2-15). Northeast of Worcester, Massachusetts, and in southeastern New Hampshire, the thrust slices are repeated on the east by steeper thrust faults (see Figure 2-16).

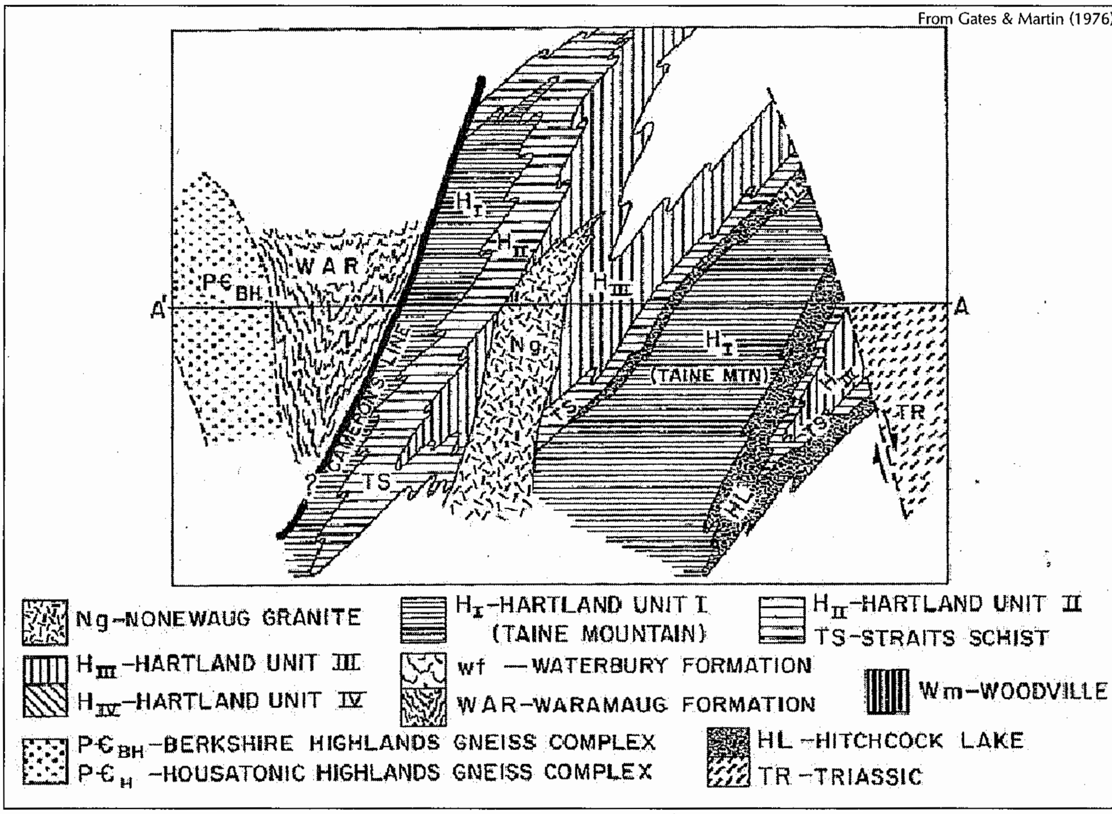


FIGURE 2-11. Section showing west-dipping thrust zone along Cameron's Line, which separates the Grenville Terrane on the west from the Sturbridge Terrane on the east; view north.

The Proterozoic units were broadly defined a century ago (Perry & Emerson, 1903; Emerson, 1917), subdivided in west-central Connecticut (Gates & Martin, 1976) and painstakingly described, measured and redefined in the northeastern Connecticut-Massachusetts border region, and correlated to the northeast into Maine (Pease, 1972 & 1989; Peper *et al.*, 1975; Peper & Pease, 1976; Peck, 1976; Barosh *et al.*, 1977a; Barosh & Pease, 1981; Pease & Barosh, 1981; Barosh & Moore, 1988). These are the only modern studies of these high-grade strata and may be the only such detailed studies following the Stratigraphic Code in the entire Appalachian System. The original strata consist of a turbidic sequence of moderate to gentle west to northwest-dipping and northwest-topping siltstone, graywacke and shale that built offshore of the east coast of Grenville rock. They have generally undergone high-grade regional metamorphism, which produced abundant pegmatitic lenses. The units are, from base upwards, the Oakdale Formation, Paxton Group and Brimfield Group, which are characterized by metasiltstone, metagraywacke, and mixed metagraywacke and schist, respectively. The Oakdale Formation contains a few muscovite schist lenses (the Scotland Schist Member) that may be locally thick. The schist in the Brimfield Group is commonly garnetiferous and contains significant pyrrhotite (a magnetic variety of pyrite) in some units. The section totals 22.5 kilometers (14 miles) in thickness with no top exposed and the base of the Oakdale Formation ends against the collision zone to the southeast. The strata are usually moderately to well-bedded in thin to medium beds that are commonly graded. The lower units are seen to become finer and contain more carbonate to the southeast in New Hampshire and contain some detrital zircons of Grenville age.

These units have been followed from their terminus in east-central Connecticut northeastward across southern New Hampshire into

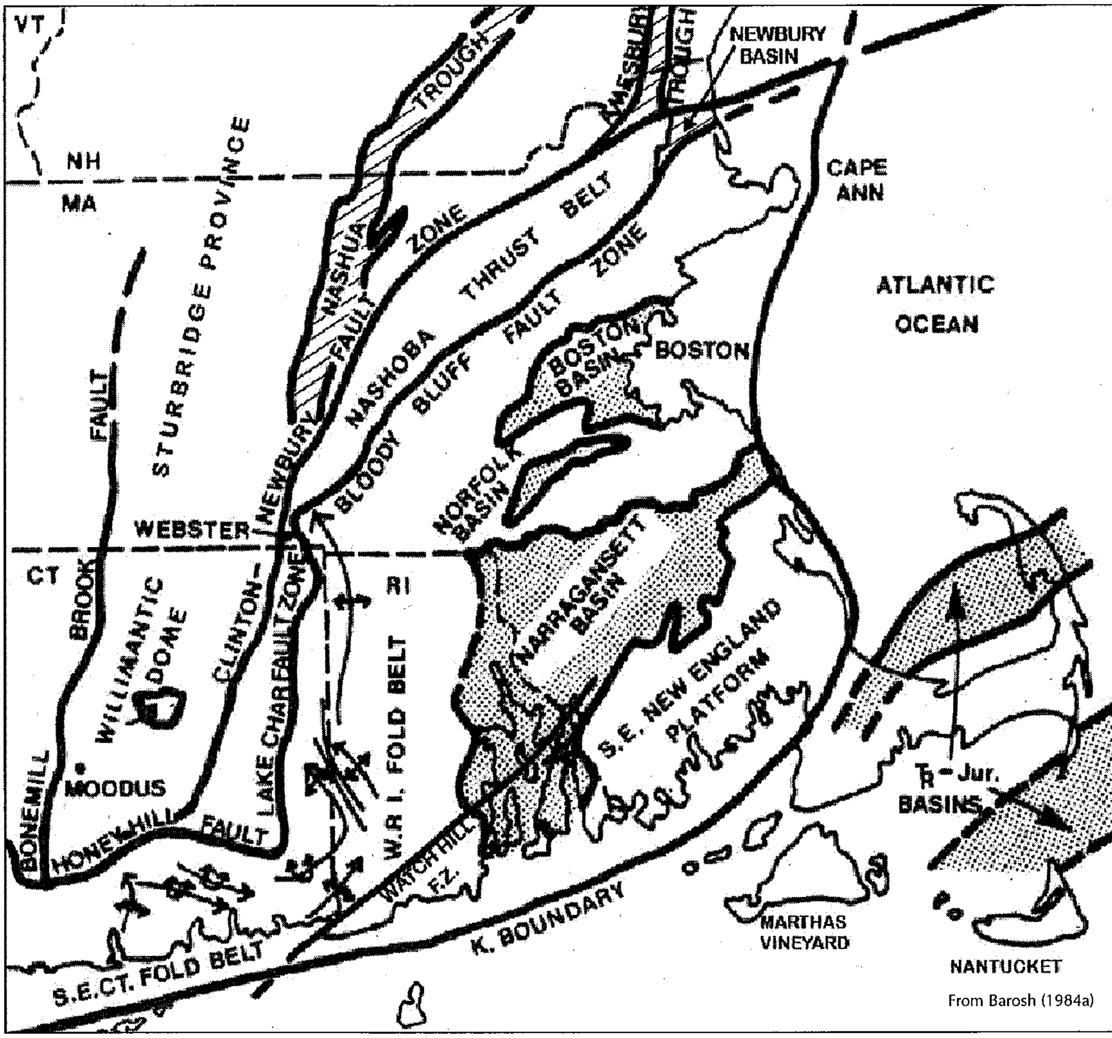


FIGURE 2-12. Map of southeastern New England showing the collision zone, which is marked by the Nashoba Thrust Belt, between ancient North America (Laurentia) on the northwest and ancient Africa (Gondwana) on the southeast, along with major tectonic provinces and structures.

coastal Maine nearly to New Brunswick before becoming completely covered (Barosh & Moore, 1988; Barosh *et al.*, 1977a; Pease, 1989). Parts of the sequence are repeated three times by faulting in northeastern Massachusetts and the different fault slices farther northeast were given different stratigraphic names since the faults were not recognized. In New Hampshire, for example, the Paxton and Oakdale strata along the coast are called the Rye and Kittery formations, respectively, and are grouped as the Berwick Formation to the northwest. The metagraywacke and schist sequence on the west side of the Hartford Graben in Connecticut is referred to as the Hartland Group, but it is essentially the same as the Brimfield Group to the east and apparently a repeat of it. The Hartland Group has been studied and divided into several west-dipping units (Gates & Martin, 1976), some of which have been followed by deep drilling southwestward along strike to beneath western Long Island (Barosh, 1990b). Pegmatitic lenses and "sweat outs" are common throughout the sequence and locally form a high percentage of the rock. A series of elongated tabular foliated granitic bodies are present, especially near the eastern margin where they appear to have formed in place from rock along early thrust faults. These bodies are mainly quartz monzonite in composition, with slight to strong flow foliation, reflecting the degree of movement along the intruded zone as the granite formed. Most of the granitic rock is either a coarsely porphyritic "Ayer" type or a medium-grained muscovite-bearing "Chelmsford" or "Fitchburg" type. These were thought to represent two granitic units, but where mapped in detail are found to consist of several repeated pulses of similar granite (Gore, 1976; Barosh, 1977a; Barosh *et al.*, 1977a).

The Late Proterozoic age of these strata is well demonstrated by the dating of detrital zircons, cross-cutting granite and overlying strata. The much less deformed, moderately metamorphosed Cambro-Ordovician deposits in the Nashua and Amesbury troughs unconformably overlie these highly deformed strata in northeastern Massachusetts (Peck, 1976; Barosh, 1998). These Paleozoic deposits, in turn, are intruded by the Late Ordovician Andover Granite (LaForge, 1932) and the Bare Hill Granite, which appears to be of the same age (Barosh & Alvord, in press). To the north, along the Maine coast, much of the sequence is buried by an unmetamorphosed Silurian-Devonian redbed-volcanic sequence (Gates, 1969; Gates & Moench, 1981). The Paxton and Oakdale contain detrital zircons of Middle Proterozoic age — 1,188 and 1,237 million years ago — as mentioned (Aleinikoff *et al.*, 1979; Barosh & Moore, 1988; Pease, 1989) and are intruded by the Late Proterozoic Massabesic Gneiss, which is a foliated granite, of Late Proterozoic age in southeast New Hampshire. The Massabesic intrudes the country rock (Sriramadas, 1966) along the Brimfield and Paxton contact (Barosh *et al.*, 1977a; Barosh & Pease, 1981; Smith & Barosh, 1982) and most of the "gneiss" represents the migmatitic (or mixed) border zones with these units with foliated granitic rock. It has been dated as Late Proterozoic, approximately 650 million years ago (Besancon *et al.*, 1977; Aleinikoff *et al.*, 1979; Lyons *et al.*, 1982) and 625 million years ago (Dorais *et al.*, 2001). Several dated Ordovician granitic plutons cut the metamorphosed strata and small Silurian and Devonian ones are probably present as well, both east and west of the Hartford Graben (Pease & Barosh, 1981; Barosh & Moore, 1988; Pease, 1989). Diorite bodies, of probable Ordovician age, are aligned in one zone that extends northeast from near Lowell, Massachusetts. Another line of small basic to ultrabasic intrusions, near the west edge of the terrane, apparently served as feeders to a submarine volcanic and ophiolite suite, such as that preserved along strike to the north in Québec (Castonguay *et al.*, 2001). The Sturbridge strata and foliated granite also can be indirectly dated as Proterozoic by correlation with other proven Proterozoic rock. There is only one period producing high-grade metamorphic strata accompanied by well-foliated syntectonic granite, along with matching structure in the Sturbridge, Nashoba and Southeast New England Batholith terranes and it must have occurred at the same time in each. This period is dated as pre-Latest Proterozoic by fossil and radiometric ages in the Boston Basin.

Cambro-Ordovician strata are caught in fault troughs where the Paxton Group and Oakdale Formation are repeated twice by thrust faults in northeastern Massachusetts. A third repetition just off the New Hampshire coast is seen in the Isles of Shoals where pendants of the Paxton Group are present in the granite forming the islands. Both the Nashua Trough, which extends from near the Connecticut line northward along the Nashua River Valley into New Hampshire, and the Amesbury Trough to the east end to the south against the Clinton-Newbury Fault Zone (Barosh, 1974 & 2005; Smith & Barosh, 1981 & 1982), which forms the boundary with the Nashoba Terrane, end to the south (see Figures 2-1, 2-12 & 2-16). The south end of the Nashua Trough has been dragged into slivers by right-lateral movement of the fault, the largest of which forms the ridge beneath Holy Cross College in Worcester.

The Nashua Trough contains a thick sequence of rock consisting of thin-bedded quartzite, fine-grained sandstone, siltstone and mudstone that are only moderately metamorphosed and not laced by pegmatite. Peck (1976) describes these strata of the trough as

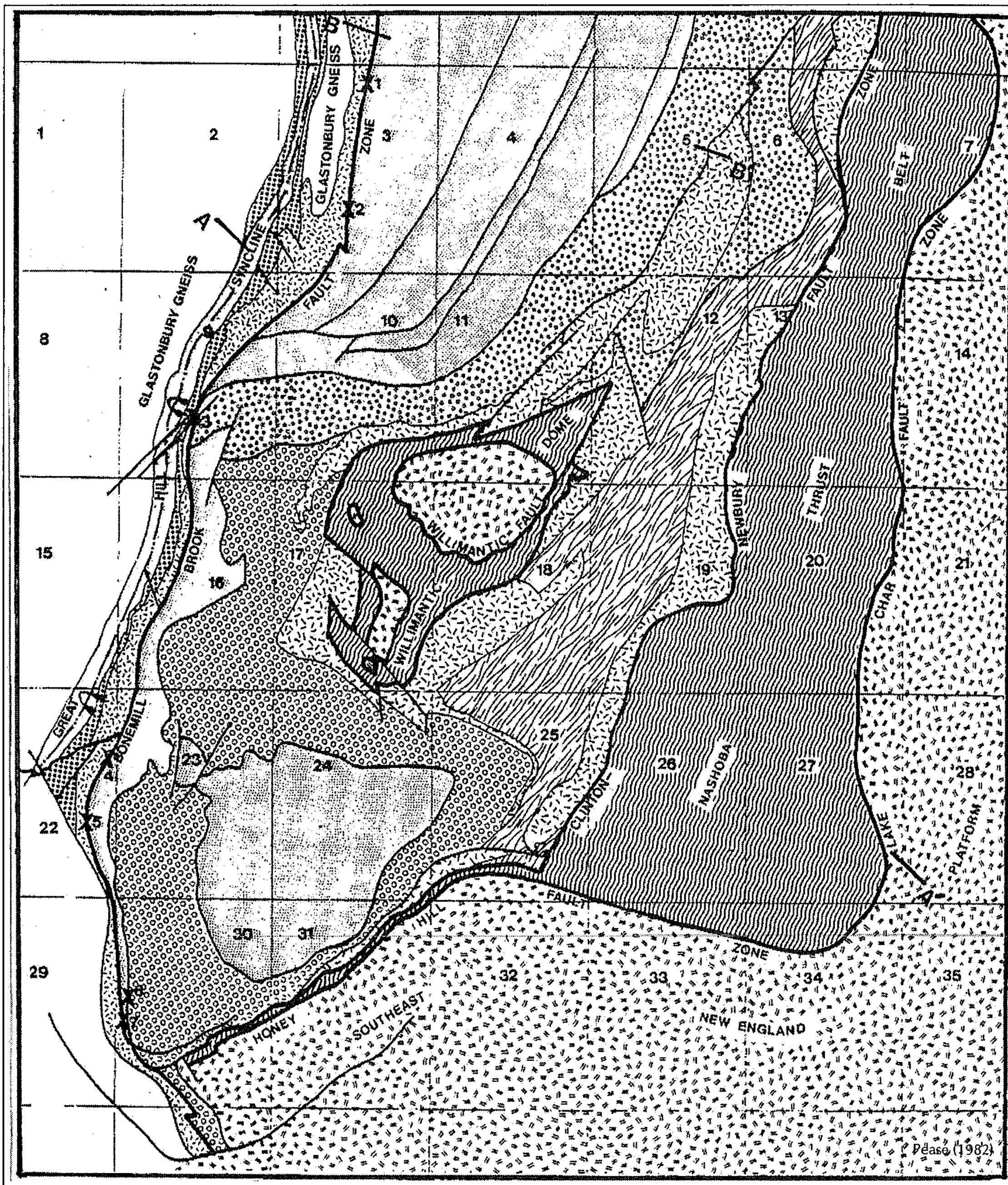
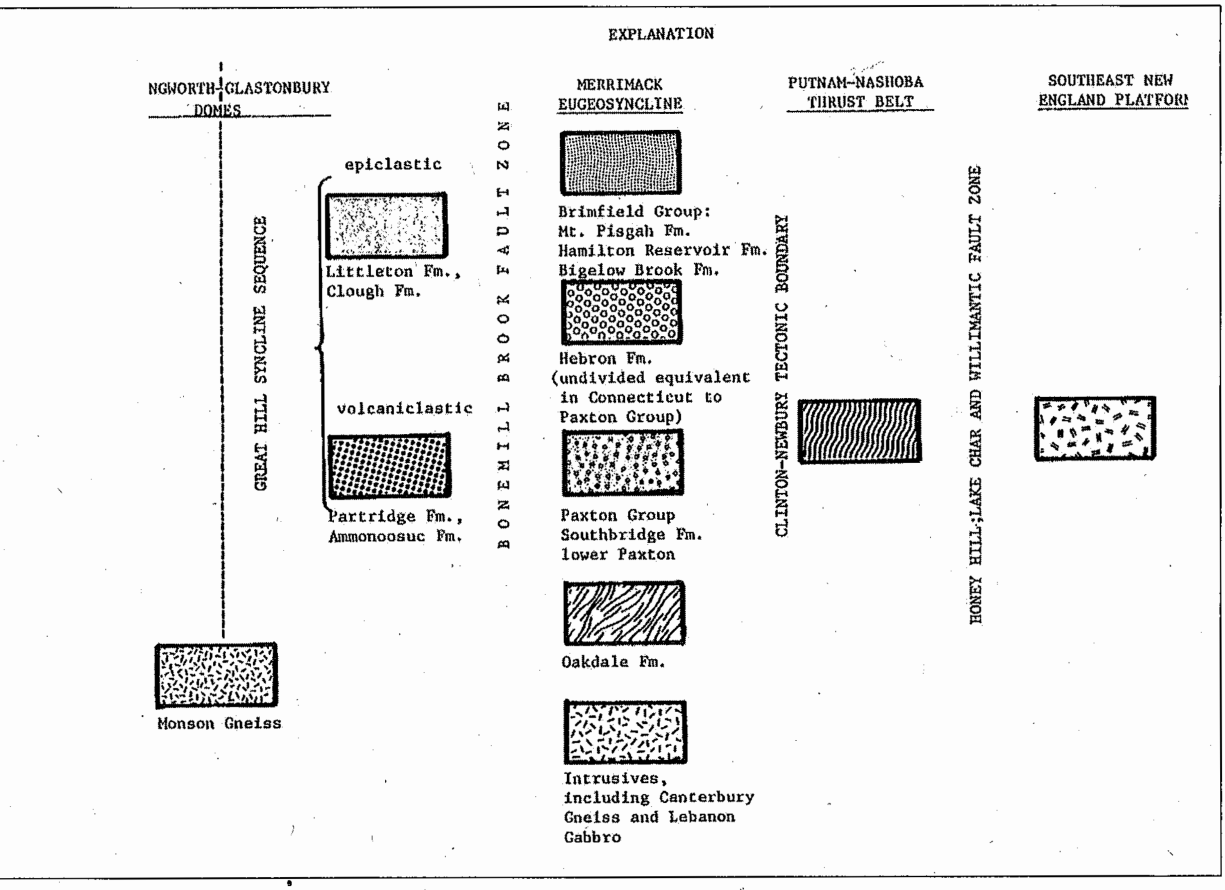


FIGURE 2-13. Map of eastern Connecticut and adjacent areas showing structure of the eastern Sturbridge Terrane and its relations with the Nashoba and the Southeast New England Batholith terranes. Sections A-A′ and B-B′ are shown in Figures 2-14 and 2-15, respectively.

Units 1 to 4 (Smith & Barosh, 1981). The exposed base is white quartzite, which is overlain by well-bedded, thin-bedded and graded-bedded dark-gray siltstone to mudstone. Some medium-bedded sandstone with staurolite occurs in the upper part. These deposits are formed on a submarine slope, distant from their source, by turbidity currents and, in some cases, slumps. The Eliot Formation of southern Maine (Katz, 1918; Hussey, 1962) correlates with Unit 2 of the sequence (Peck, 1976). Unit 2 has interbedded siltstone and



mudstone that is commonly highly folded apparently due to contrasting rock strength in slipping while soft and the folds do not extend into the adjacent strata. Similar mudstone with intervals containing pebbles of siltstone and quartzite is known as the Harvard Conglomerate, which seems to fit between Units 1 and 2 and represents a slump deposit. This conglomerate is a pendant within the apparently Late Ordovician Bare Hill Pond Granite in Harvard, Massachusetts (Barosh & Alvord, in press). Another adjacent unit in Clinton, Massachusetts, consists of altered dark-gray basaltic ash (Peck, 1975).

Similar strata occur in local fault troughs along strike across the New Hampshire and Maine coastal region and into New Brunswick (Ludman, 1991; Fyffe *et al.*, 1991). The large Fredericton Trough on the Maine-New Brunswick border contains a near identical section as the Nashua Trough, with a basaltic formation below, as that at Clinton (Barosh, 1999b). Some strata in Maine and those in the Fredericton Trough are fossiliferous and show the volcanic base to be Cambrian and the turbidic sequence to be Ordovician in age. No fossils have been found in place in the Massachusetts section, although trilobite fragments were seen in float (Peck, 1976), but the close lithologic correlation shows them to be the same age (Barosh, 1999b). Although these pre-Silurian strata cannot be correlated across the Sturbridge-Nashoba Terrane boundary, Silurian-Devonian strata can (Gates, 1969; Barosh *et al.*, 1977a). Some small blocks of younger Paleozoic rock are present and others may exist. A small fault block of slightly metamorphosed Devonian limestone occurs at the north end of the Hartford Graben in Massachusetts (Hitchcock, 1871).

The Sturbridge strata structurally overlie parts of both the Nashoba and Southeast New England Batholith terranes (see Figures 2-13 & 2-14) that are exposed in windows locally (Pease, 1982 & 1989). The Willimantic Dome in eastern Connecticut displays a thin slice of the

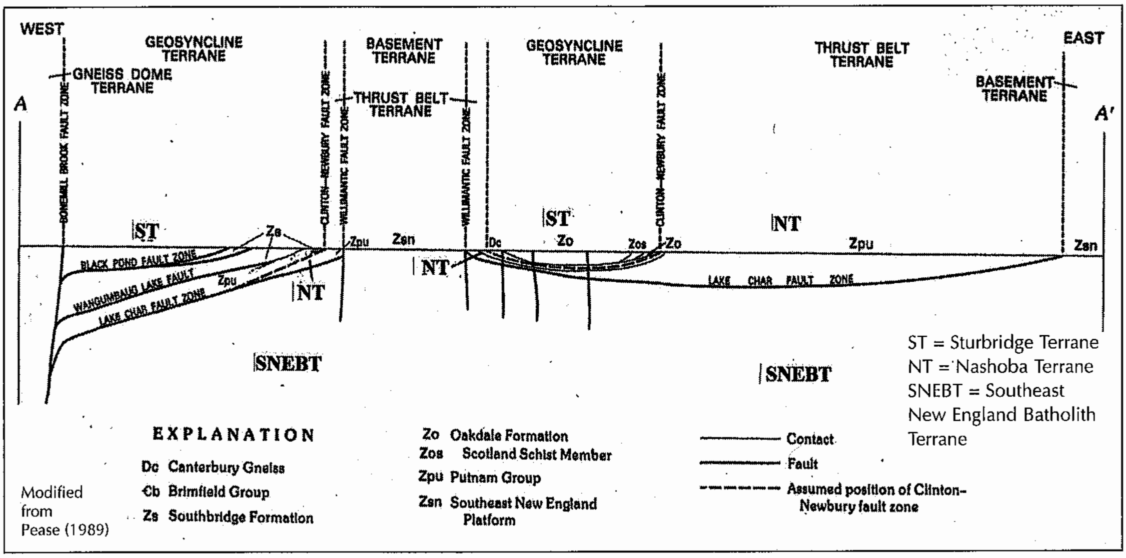


FIGURE 2-14. Section through eastern Connecticut showing structural relations of different terranes. Location is shown as A-A′ on Figure 2-13.

Nashoba rock over that of the Southeast New England Batholith (Pease, 1989). The linear Bronson Hill uplift, to the east of the Connecticut River Valley, also shows rock of the Southeast New England Batholith along with probable Ordovician granite and strata. The assignment of the highly deformed metamorphosed strata exposed in the underlying Waterbury dome of southwestern Connecticut is not yet clear.

The structure of the region was thought to represent several complexly folded anticlinoria (arches) or synclinoria (swales) that ran the length of New England by Billings (1956). These features were interpreted without support from field data. No stratigraphic or structural relations indicated that there were such features. The part across eastern Connecticut, east-central Massachusetts and southeastern New Hampshire is referred to as the Merrimack Synclinorium between the Rockingham Anticlinorium to the east and the Bronson Hill Anticlinorium on the west (Billings, 1956). Smaller hypothetical folds within these large

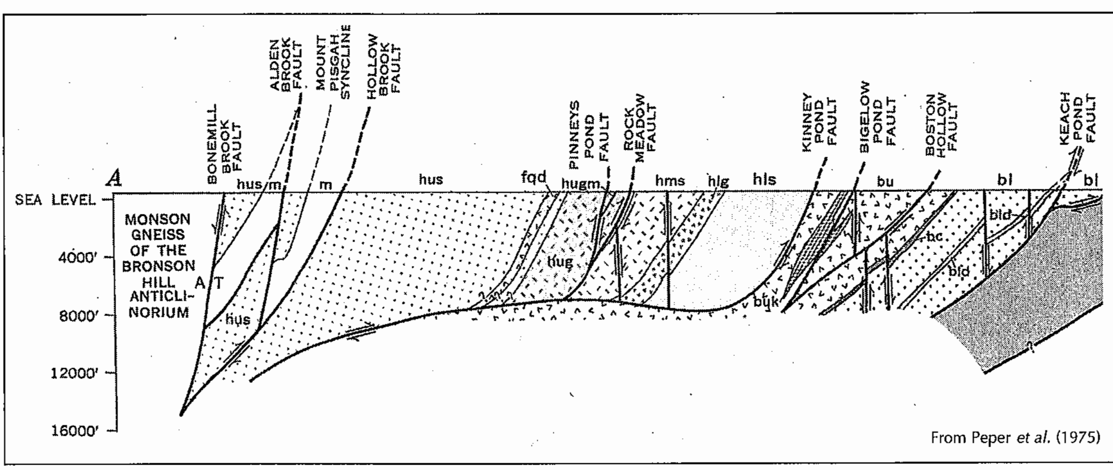


FIGURE 2-15. Section through the Brimfield area along the Massachusetts-Connecticut border. Detail of westernmost edge of Figure 2-7. Location is shown as B-B′ on Figure 2-13.

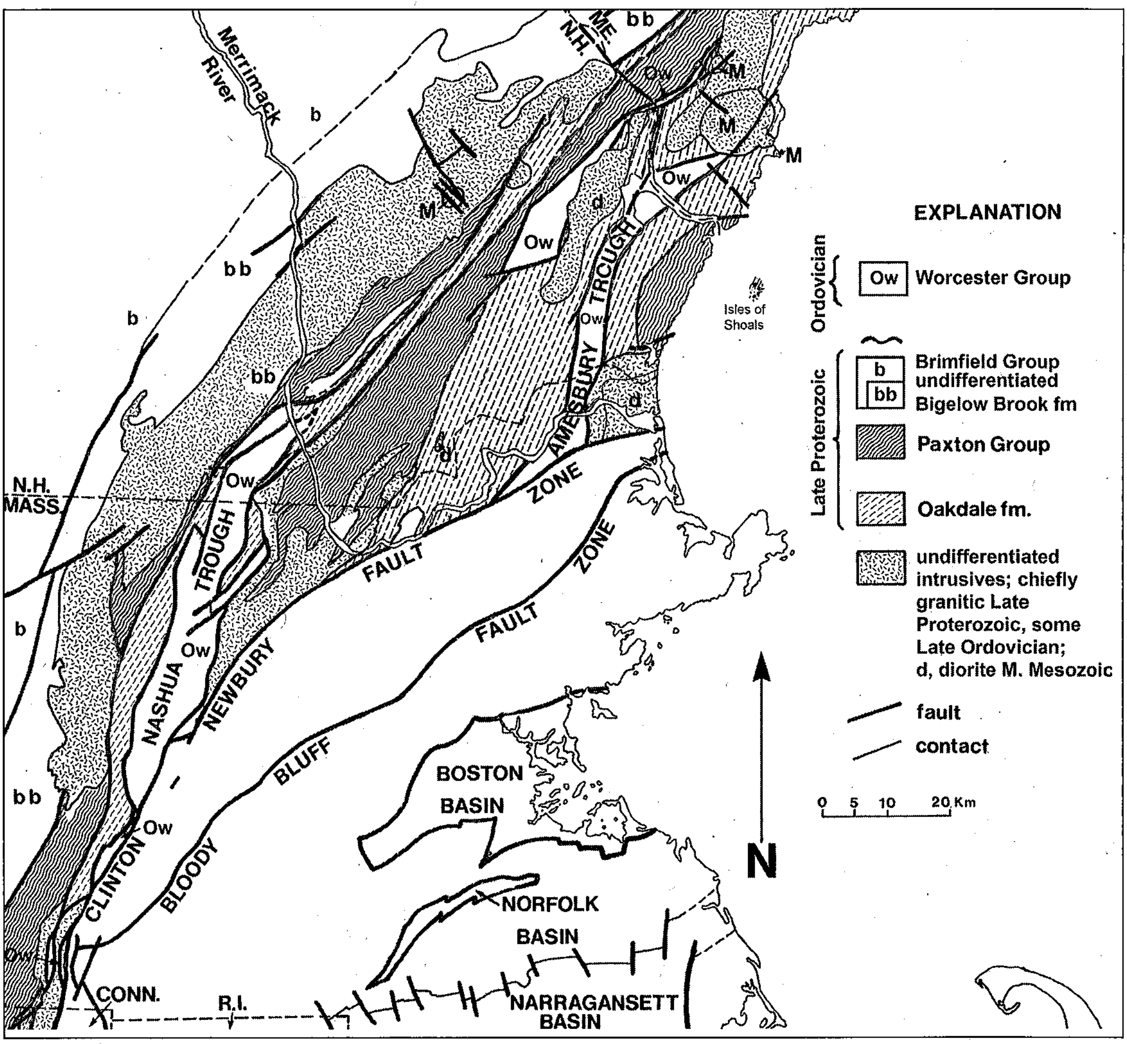


FIGURE 2-16. Map of northeastern Massachusetts to southern Maine showing the geology of part of the Sturbridge Terrane.

structures then were drawn by Robinson (1963), Thompson *et al.* (1968), Dixon and Lundgren (1968), Robinson and Hall (1980) and Zen (1983). However, more information became available from detailed mapping of stratigraphy along the Connecticut-Massachusetts border (Pease, 1972 & 1989; Peper *et al.*, 1975; Pomeroy, 1975; Moore, 1976; Pease & Barosh, 1981; Barosh, 1974 & 2005; Barosh & Moore, 1988). In addition, more information from mapping the bedrock in the Wachusett water diversion tunnel across the region to the north (Callaghan, 1931) also became available. All this information demonstrated that such hypothetical folds were not supported by field evidence. Few folds are observed in the region, except for drag folds along thrust faults (such as the large one along the west edge of the Nashua Trough). The Sturbridge Terrane is a large slab that underthrusts the Grenville Terrane to the west and is itself underthrust by the terranes to the east, which are seen to underlie it along its eastern and southern borders and in windows. Both the Oakdale and the Paxton are cut out to the west against the basal thrust zone. Internally, the slab essentially consists of west- to northwest-dipping strata sliced by a series of early approximately bedding-plane thrust faults, which are offset by various later smaller

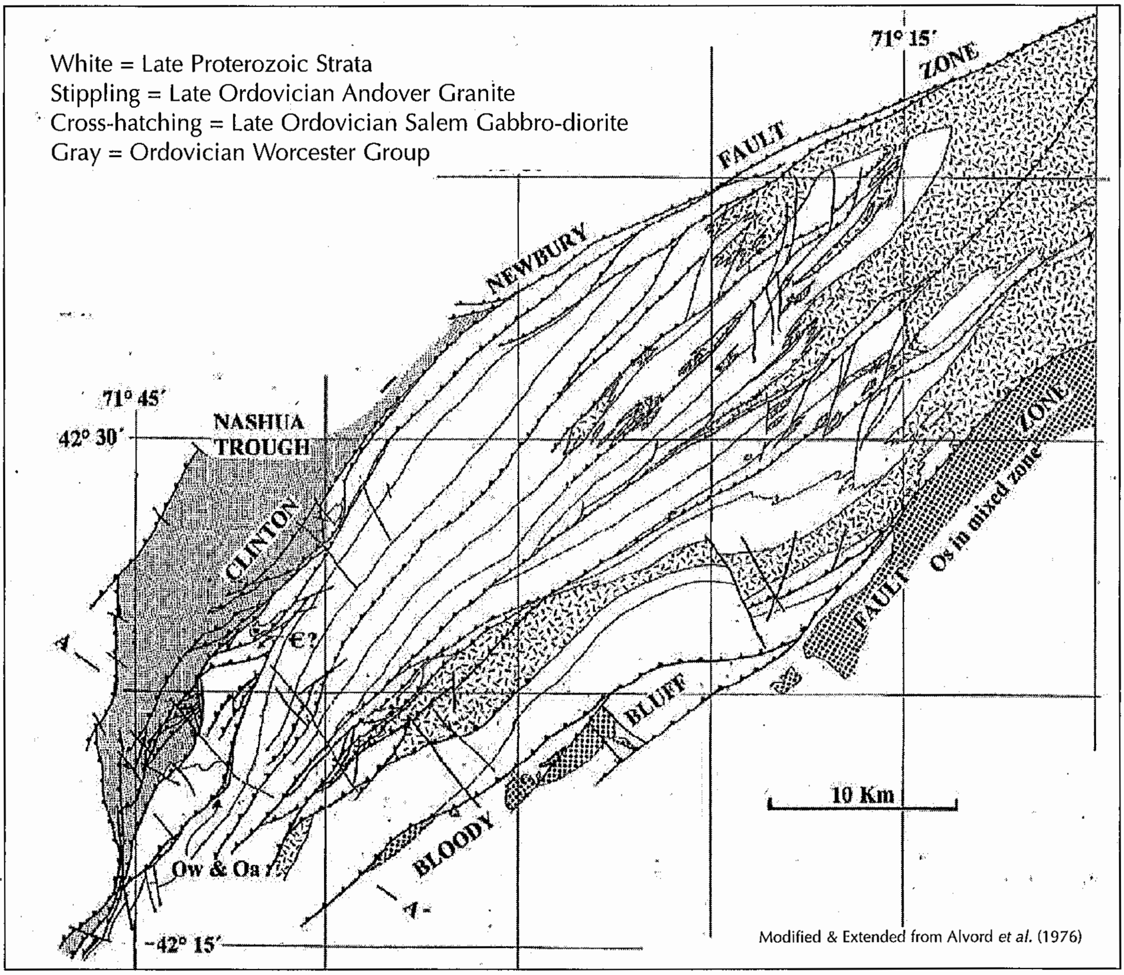


FIGURE 2-17. Structural map of the Nashoba Thrust Belt northwest of Boston, Massachusetts. Section A-A′ is shown in Figure 2-18.

faults. The eastern part, between the Nashoba Terrane and the Bonemill Brook fault, which borders the Bronson Hill uplift, has complex overlapping thrust sheets near its southern edge in Connecticut (Pease, 1989). These thrust faults decrease in both number and offset northward into central Massachusetts, where a few very gentle folds are present (Callaghan, 1931) between more widely spaced thrust faults. In other words, the rocks are more squeezed and deformed to the south nearer the base of the terrane. Reactivation of some thrust faults in eastern Massachusetts caused the repetition of the Oakdale and Paxton (see Figures 2-12 & 2-16) and caught younger, less metamorphosed rock between steeply west-dipping faults in the Nashua and Amesbury Troughs (Smith & Barosh, 1981 & 1982). The offset along the thrust faults is west-over-east, with a right-lateral strike-slip component. One example of this configuration is the northeast-trending Eastford Fault in northeast Connecticut, which has 4 kilometers (2.5 miles) of right-lateral offset and bends northward to end as a thrust in the Webster area (Barosh, 1974 & 2009).

Nashoba Terrane. The Nashoba Terrane forms a plate collision zone of closely spaced west-dipping thrust faults (Bell & Alvord, 1974), called the Nashoba Thrust Belt, which separates the Southeast New England Batholith Terrane from the Sturbridge Terrane in eastern Massachusetts and Connecticut (see Figures 2-12, 2-17 & 2-18). The rock and struc-

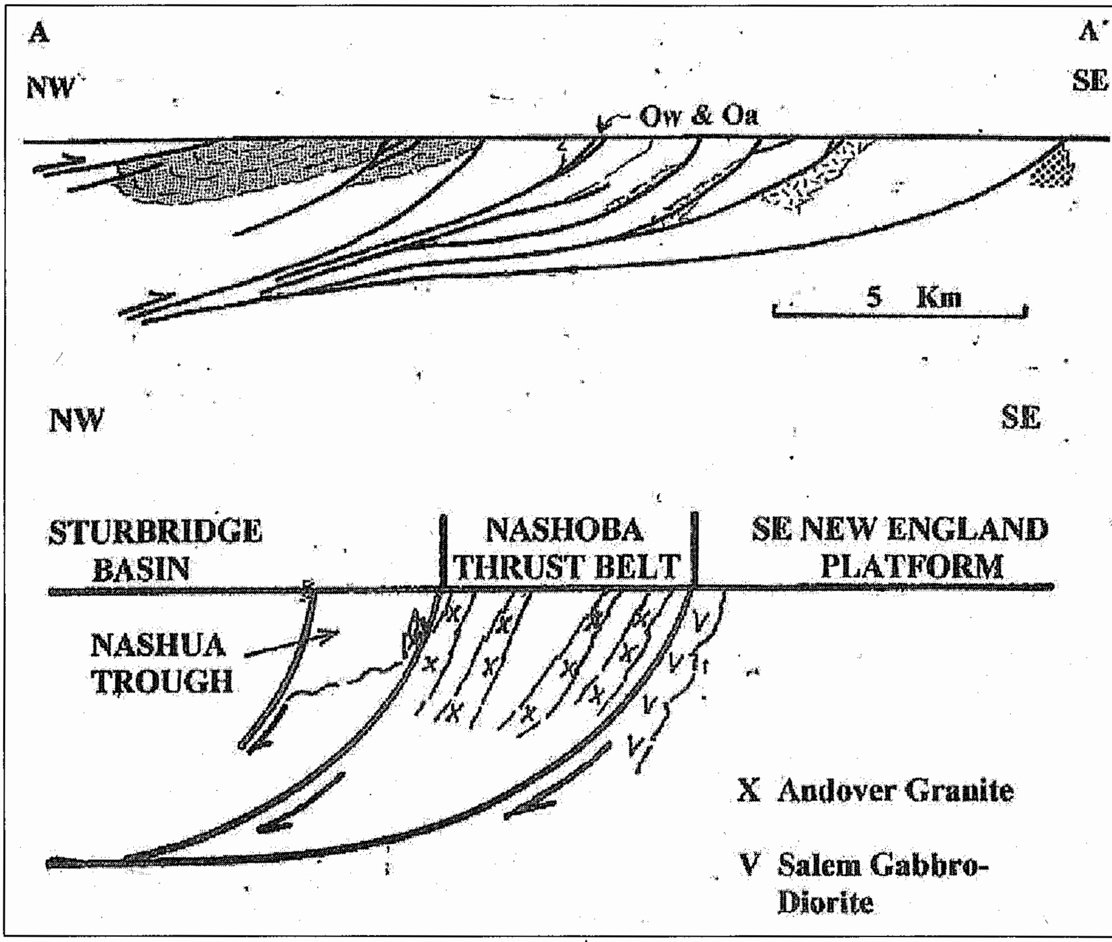


FIGURE 2-18. Section through the Nashoba Thrust Belt; location marked in Figure 2-17. Upper section shows actual scaled section with fault slice of Ow (Ordovician Worcester Group) and Oa (Andover Granite). Lower section is sketch showing structural relations.

ture of the adjacent terranes terminate against it. No stratigraphic correlation has been possible between the pre-Silurian strata of these fault bounded terranes (Barosh *et al.*, 1977a), and the early rock composing them apparently formed at considerable distances from one another. These fault slices are particularly prominent in the aeromagnetic data (Bell, 1972; Alvord *et al.*, 1976; Barosh, 1972; Barosh *et al.*, 1974 & 1977b).

The terrane contains a high-grade metamorphic volcaniclastic sequence over 18 kilometers (11 miles) thick where it was measured and described northwest of Boston (Bell & Alvord, 1976; Alvord, 1975). The moderately to well-bedded, mostly thin-bedded sequence consists mainly of varying proportions of light-gray gneiss, schist, amphibolitic gneiss, amphibolite and marble lenses with a sillimanite-muscovite schist at the top. These strata were formed from sand that was derived from andesitic and basaltic debris, silt and both aluminous and limey mud. The units, from the base upwards are: Marlboro Formation, Shawsheen Gneiss, Fish Brook Gneiss, Nashoba Formation and the Tadmuck Brook Schist. The Marlboro and Nashoba formations extend into Connecticut where they were named the Quinebaug and Tatnic Hill, respectively (Dixon, 1964; Barosh, 2005 & 2009). The Fish Brook Gneiss gave a date of 730 million years ago (Zartman & Marvin, 1987). Strata of the Nashoba Terrane are invaded by several types of intrusive rock.

Moderately foliated Assabet Quartz Diorite, of apparent Late Proterozoic age, forms elongate bodies paralleling the structure in Massachusetts and are apparently controlled by the thrust faults. The abundant slight to nonfoliated Andover Granite has a Late Ordovician best date of 460 million years ago (Zartman, 1976). The granite has intruded along the thrust faults and other structures, but also cuts across the structure in Massachusetts and very locally extends into Ordovician strata of the Sturbridge Terrane (LaForge, 1932). The Andover Granite occupies much of the northeastern part of the terrane and fingers out to the southwest. A large foliated granite body known as the Canterbury Gneiss formed along the Clinton-Newbury Fault Zone in Connecticut and obliterated the mylonite from its early movement (Pease, 1989).

A few later small, nonfoliated, generally circular plutons invaded the terrane in the Silurian and Devonian periods. The Silurian Preston Gabbro crosses the structure in southeastern Connecticut (Dixon & Felmlee, 1986), a smaller circular one of perhaps the same age is in Concord, Massachusetts (Barosh, 1979c), and the Millstone Granite, which is dated as Devonian, is at Worcester. Some Devonian ages are reported from the Canterbury Gneiss that appears to be much older, but could include younger intrusions. The Silurian and Devonian plutons may have served as feeders to volcanic deposits such as the Newbury Volcanic Complex (described below) and accompanied a period of mild regional metamorphism suggested by Pease (1989) or local contact metamorphism that extended from the Early Silurian to the Early Devonian in Connecticut. Pink pegmatite dikes of apparent Permian or Middle Triassic age also occur locally.

A fault block containing the unmetamorphosed Late Silurian-Early Devonian Newbury Volcanic Complex is dropped into the terrane in northeastern coastal Massachusetts (see Figures 2-12 & 2-19). It aggregates more than 4,400 meters (14,432 feet) of interbedded basaltic, andesite and rhyolitic flows and ash, red mudstone and siltstone, and gray calcareous mudstone (Shride, 1976). Enclosed fossils indicate a specific correlation to one unit in the coastal volcanic sequences of northeastern Maine and others are temporal equivalents. These fauna are of Baltic-British affinity rather than Appalachian (Gates, 1969; Shride, 1976). The Maine strata overlie the Sturbridge Terrane. These two sections and a small patch of the Newbury on the nearby Southeast New England Batholith Terrane (Bell *et al.*, 1977, 1993; Dennen, 1981) demonstrate that the Siluro-Devonian volcanic sequence overlaps all three terranes. The Maine strata extend down to the Early Silurian (Gates & Moench, 1981). A sliver of smashed and slickensided Pennsylvanian strata occurs at the west side of the thrust zone adjacent to the Clinton-Newbury Fault Zone in Worcester, Massachusetts. This mildly metamorphosed Pennsylvanian carbonaceous siltstone constitutes the so-called "Worcester Coal Mine" (Perry, 1885; Kemp, 1887; Grew, 1973) and correlates with identical strata at Cranston, Rhode Island, at the west side of the Narragansett Basin farther east (Emerson, 1907). Apparently it is a remnant of more widespread Pennsylvanian strata over the region.

The thrust belt is bounded on the northwest by the Clinton-Newbury Fault Zone, which is the largest fault known on the East Coast, and on the southeast by the Bloody Bluff Fault Zone that joins the Lake Char Fault in northeastern Connecticut (Cupples, 1961; Dixon, 1974; Barosh, 1984b, 1996a & 2005) and the Honey Hill Fault in southeastern Connecticut (see Figure 2-19). The regional northerly structural tilt brings such a cross-section into view and demonstrates that the thrusts flatten and merge downward. The faults are near vertical in northeastern Massachusetts, and then shallow to a 20-degree west dip at the Connecticut border and flatten out in southeastern Connecticut, where the thrust faults in the zone merge into the basal Honey Hill Fault above the Southeast New England Batholith Terrane (Pease, 1989). The basal thrust also is exposed in the Sturbridge Terrane in a window that forms the Willimantic Dome where it is called the Willimantic Fault Zone (see Figures 2-13 & 2-14). The thrust belt is squeezed more and drastically thinned by thrust faults to the southwest across Massachusetts. This condition results in the lower formations being progressively reduced from its 26 kilometer (16

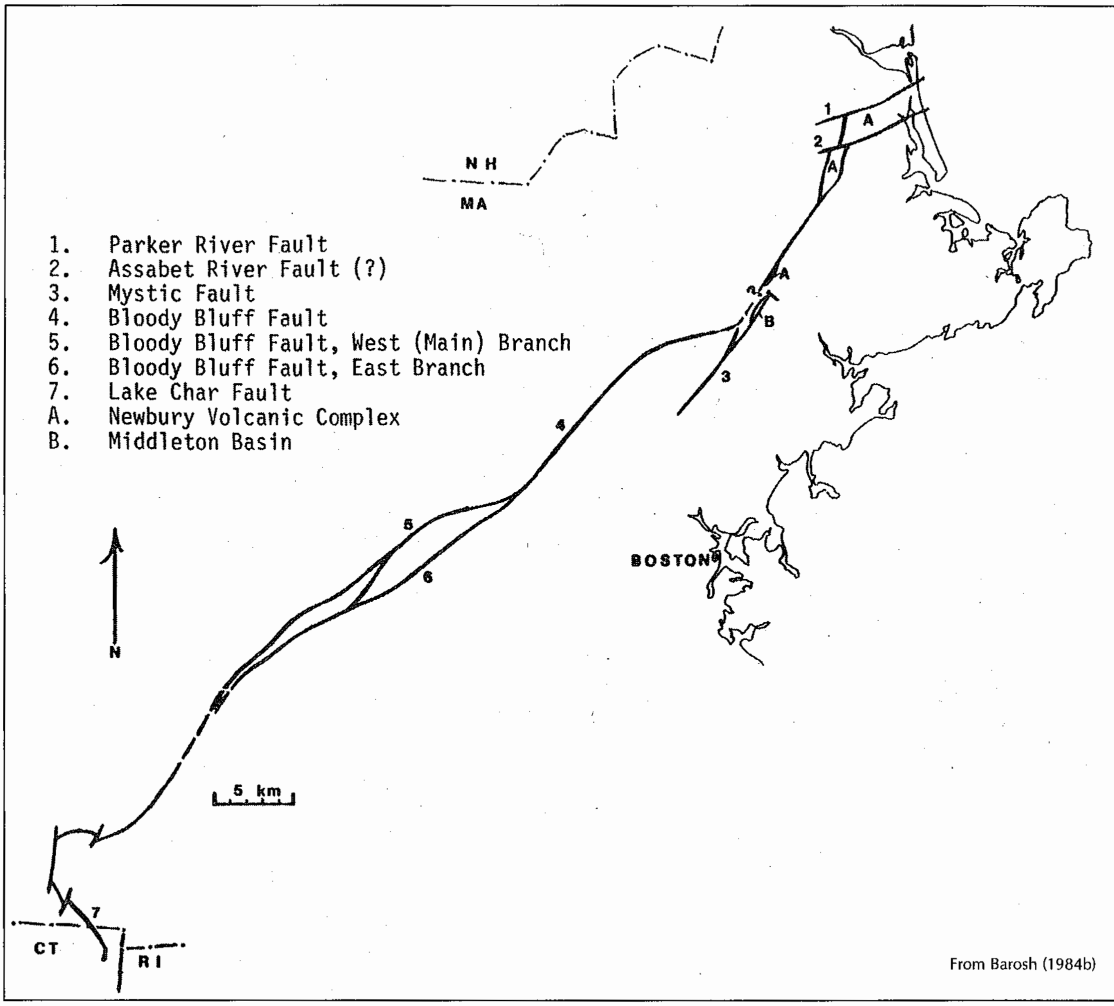


FIGURE 2-19. Map of eastern Massachusetts showing the Bloody Bluff Fault system.

mile) width northwest of Boston to only about 100 meters (328 feet) wide near the Connecticut border (Barosh, 1974, 2005 & 2009). The Tadmuck Brook Schist, at the top, is gradually cut away by the Clinton-Newbury Fault Zone until it pinches out just north of Connecticut (Barosh, 2005 & 2009). Farther south in Connecticut, the zone widens again and a partial section re-emerges. This section thins again against the basal thrust, as can be seen (see Figure 2-14) along the Honey Hill Fault Zone and in the Willimantic Dome (Pease, 1989). The observed displacement across the thrust belt along the Honey Hill Fault Zone measures about 150 kilometers (93 miles) and this displacement is probably only a fraction of the total. However, the direction and type of movement have changed with time. The early movement along the thrust faults is west over east, but later it shifted to northwest over southeast as the collision zone closed at the end of the Ordovician. A right-lateral strike-slip component appears to have increased with time as adjacent extensional features formed in the Mid-Paleozoic and then ceased near its end.

Southeast New England Batholith Terrane. The Southeast New England Batholith Terrane is one of the most variable, complicated and geologically interesting regions in the eastern United States (see Figure 2-1). The terrane consists of remnants of an ancient volcanic pile that had been invaded by a Late Proterozoic batholithic complex, which was later the site of

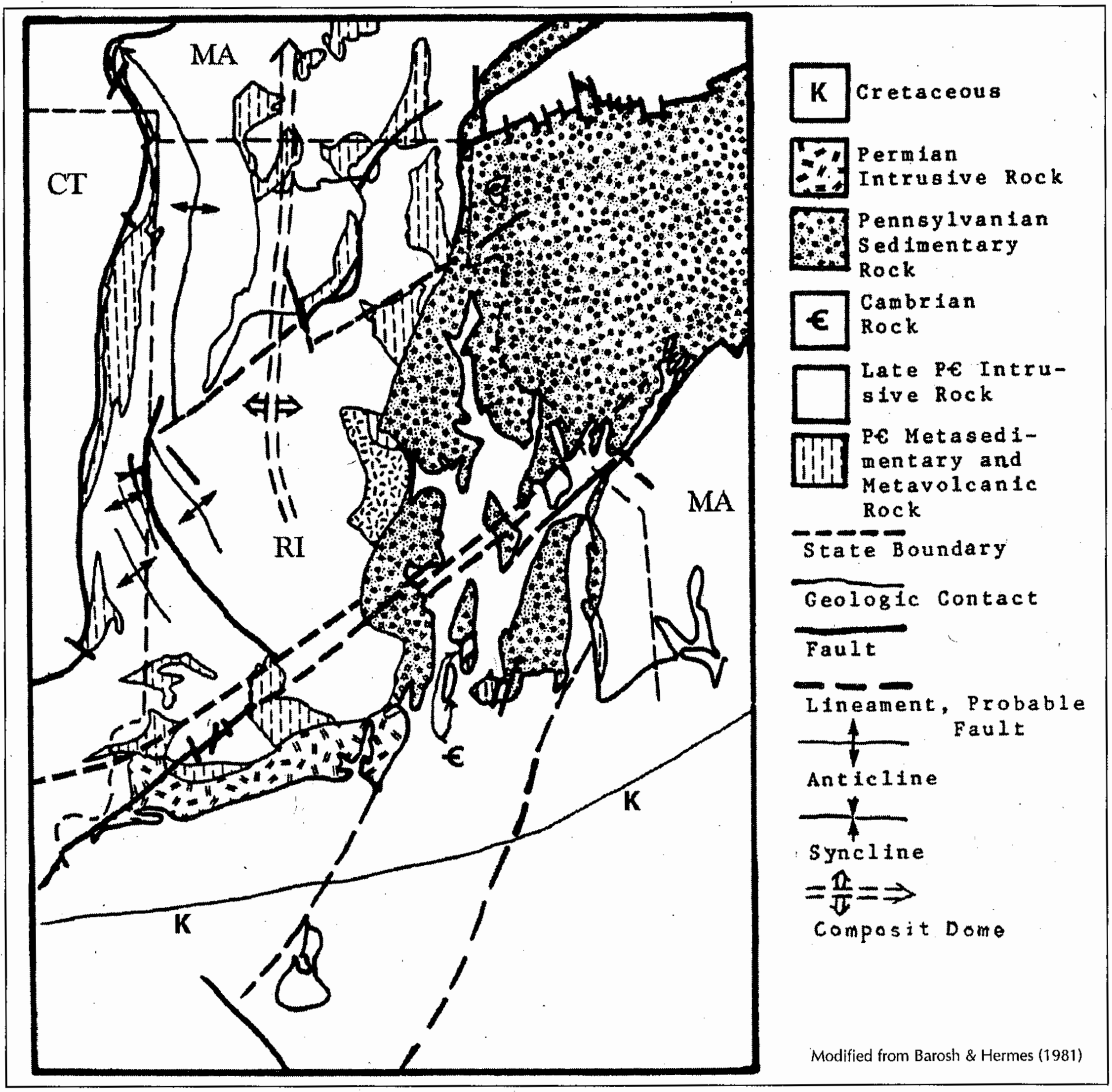


FIGURE 2-20. Sketch map of Rhode Island and vicinity showing major structural features.

volcanic centers and intrusions of different ages, and partially covered by sediment of a wide variety of ages. The sediment occurs chiefly in fault basins that include the latest Proterozoic Boston Basin, the Pennsylvanian Narragansett, Norfolk, North Scituate and Woonsocket basins, and various Mesozoic basins (see Figure 2-12). Remnants of Cambro-Ordovician overlap deposits and minor Siluro-Devonian redbeds, which may lie in another basin, also are present. Rock of this general age and type occurs in the Avalon Peninsula in Newfoundland as well, and the Southeast New England Batholith has been grouped with the Avalona Peninsula by some as the "Avalon Zone" or as a remnant of an ancient continent called "Avalonia." However, the granite and its relations are similar to Pan-African granite and this term is more explicit and can be used where a larger context is needed.

The volcanic pile is represented by moderate- to high-grade meta-sedimentary and meta-volcanic strata, which remain as xenoliths, large pendants and as a border of the batholithic complex. The border zone is chiefly developed around a semi-domal structure (see Figure 2-20) centered over western Rhode Island (Barosh & Hermes, 1981). The zone is narrow along southeastern and eastern Connecticut where it is cut off to the west by the Lake Char-Honey Hill fault zones, but it widens and spreads out across northeastern Massachusetts north of the Boston Basin. These strata grade upward from an intruded base of quartzite and interbedded quartz schist into a thick sequence of mafic volcanic rock. The quartzitic basal portion is mapped as the Plainfield Formation, Westboro Formation or lower Blackstone Series in Connecticut, Massachusetts and Rhode Island, respectively (Bell & Alvord, 1976; Barosh, 2005). This near-shore, laminated, thin-bedded light-gray to tan quartzitic unit is succeeded by a dark to light-gray metamorphosed sequence of amygdaloidal (filled almond-shaped vesicles) and massive mafic and minor felsic flows, pillow lavas, mafic pyroclastic deposits and ash-fall tuffs that form the Middlesex Fells Volcanic Complex in Massachusetts and, in Rhode Island, the upper Blackstone Series, which also contains a marble unit (Shaler *et al.*, 1899; Bell & Alvord, 1976; Quinn, 1971; Dennen, 1981). These strata are overlain northwest of Boston by an additional northwest-dipping sequence that wedges in southeast of the Bloody Bluff Fault Zone. It consists of an unnamed fine-grained volcaniclastic unit, the Greenleaf Mountain Formation of mostly amphibolite, and the Burlington Formation of impure quartzite, gneiss and amphibolite with some capping metaconglomerate (Bell & Alvord, 1976). The top is truncated by the Bloody Bluff Fault. The aggregate thickness of the total section (Bell & Alvord, 1976) northwest of Boston is 3,325 meters (11,000 feet), and at least 4,600 meters (15,000 feet) to perhaps more than 6,100 meters (20,000 feet) is preserved in Rhode Island (Quinn, 1971).

The Late Proterozoic batholithic complex that characterizes this region ranges from quartz-rich alaskite to diorite or gabbro (Quinn, 1971; Hermes *et al.*, 1981b). Light-colored granodiorite and quartz monzonite are the most common. The gabbro and diorite formed early and are present chiefly east of Milford where they show up as xenoliths and large pendants in the granitic rock (Crosby, 1904). They were locally mislabeled by Chute (1966 & 1969) south of Boston as the younger Salem Diorite. The granitic rock consists of a number of large bodies. The Northbridge Granite and Dedham Granodiorite form the extensive large bodies near Boston and several others are widespread in Rhode Island and adjacent Massachusetts and Connecticut (Quinn, 1971; Barosh *et al.*, 1977a; Barosh, 2005). These bodies may have a confusing number of names. The Northbridge, for example, was called provisionally the Ponaganset Gneiss in Rhode Island by Quinn (1971) and mistakenly the Milford Granite west of the Boston Basin by Emerson (1917). The granites tend to become finer grained toward their borders and may have locally preserved aplitic border zones, which have been described as separate plutons in places. The Dedham has undergone alteration of the original light-gray rock in most places, and consequently has developed a pinkish to salmon cast or pink and green mottling. Flow foliation and lineation increase toward the borders. Moderate to very strong flow foliation is found adjacent to the Nashoba Terrane, especially in Connecticut and Rhode Island, but to the east most granite is nonfoliated and can be fresh looking. The foliation is syntectonic, being the result of deformation while the granites formed and serves to demonstrate their close ages.

The granites are known to be pre-Cambrian from the overlying Cambrian strata and are older than the latest Proterozoic fill of the Boston Basin. Rock of the batholithic complex yield ages that generally range from 600 to 620 million years ago (Zartman & Naylor, 1984; Galloway 1973; Smith 1978; Hermes *et al.*, 1981b), but older ages occur and the ages are most likely between 620 and 630 million years ago (Zartman, 1976). However, experience has shown that dating these granites can prove difficult, as was the case of granites west of Boston that when dated (Thompson *et al.*, 1996) actually produced results nearly opposite the known sequence.

The batholith is overlain by scattered remnants of a transgressive overlap assemblage of lower Paleozoic strata described by Walcott (1891a & 1891b). Much of these remnants of Lower to Upper Cambrian strata of mostly argillite and siltstone are preserved at several locations around the Boston Basin. Also, altered shale and limestone with a thin basal quartzite occur over the granite near the northeast corner of Rhode Island (Shaler *et al.*, 1899). Additional shale with interbeds of siltstone, now metamorphosed to argillite or schist due to nearby Permian granite, is present at Jamestown, Rhode Island, in southwestern Narragansett Bay, where fossils were found by Trem Smith (Skehan *et al.*, 1977). A thick, white quartzite bearing Ordovician inarticulate brachiopods had formerly covered the Cambrian, but was almost all stripped off during Pennsylvanian time and now forms clasts in conglomerate of that age or reworked into Pleistocene and Holocene deposits.

The Cambrian strata also overlap the easterly trending fault trough forming the Boston Basin (see Figure 2-12). The basin contains a thick, barely altered, very Late Proterozoic section with a volcanic unit resting over the batholithic granite at the base and overlain by conglomerate that passes upward through an interfingering sequence into thin-bedded argillite, which contains minor quartzite and tuff beds near the top. The volcanic and conglomeratic rock is mostly terrestrial and the argillite marine in origin.

Late Ordovician (461 to 444 million years ago) alkalic granite plutons and a variety of associated rhyolitic flows and tuff mark a volcanic chain, extended north-northeastward across the region from Rhode Island to at least Cape Ann, north of Boston (see Figure 2-21). Another line of basic plutons extends northeast along the southeast side of the Bloody Bluff Fault Zone from west of Boston to Cape Ann, forming a lesser chain of basaltic cones (see Figure 2-17). The intrusive rock is not metamorphosed, only has flow foliation locally at its borders and tends to form circular bodies of several phases. The largest center is about Cape Ann, formed of Cape Ann Granite, which consists of several phases of quartz monzonite, and the approximately contemporaneous and highly-variable Salem Gabbro-Diorite (Toulmin, 1964; Bell & Dennen, 1972; Dennen, 1976, 1981, 1991a, 1991b & 1992). The several bodies of Salem Gabbro-Diorite that lie along the east side of the Bloody Bluff Fault Zone to the west of Boston display none of the intense flow foliation and shearing near the fault that is present in the older batholithic rocks (Barosh, 1977a, 1977b & 1984b). The associated volcanic rock comprises the Lynn Rhyolite, formerly called the Lynn Volcanic Complex or Series (Dennen, 1981 & 1991a), found around Lynn and Marblehead on the south side of Cape Ann (Warren, 1913; Dennen, 1981 & 1991a). The Lynn complex is composed of a wide variety of flow, ash-flow, tuff and agglomerate of intermediate to sialic composition, but chiefly rhyolite. The Lynn Volcanic Complex rests unconformably (Clapp, 1921) on the batholithic rock and has an estimated thickness of 600 meters (2,000 feet). Similar rhyolitic ash-flow tuff and flows are preserved around the Quincy Granite at another volcanic complex in the Blue Hills, which border the south side of the Boston Basin (Chute, 1969; Sayer, 1974; Kaktins, 1976; Naylor, 1981; Kaye, 1982a). These formations are described with the Boston Basin rock. Some siliceous pyroclastic tuff, which occurs to the southwest in Medfield (Volckmann, 1977) may be part of it or possibly correlate with the latest Proterozoic Boston Basin volcanic fill. An additional volcanic center to the southwest forms the circular Rattlesnake pluton that is composed of different intrusive phases, but has lost its cover of volcanic rock (Lyons & Krueger, 1976).

Similar small granite plutons occur in northeastern Rhode Island, and the East Greenwich Group forms a much larger complex in west-central Rhode Island (Quinn *et al.*, 1949; Quinn & More, 1968; Quinn, 1971). The group consists of rhyolitic flows, tuff and breccia around a center of Cowesett Granite and related granite. These granites contain only a minor amount of riebeckite, but are otherwise similar to the riebeckite-bearing Cape Ann and Quincy granites. The Cape Ann Granite dates at 450 (±25) million years ago, which is the Middle-Late Ordovician boundary, and the Quincy Granite has a similar 430-457 million years ago age, which places them in the Late Ordovician (Zartman, in USGS, 1967; Zartman & Marvin, 1971; Dennen, 1991a). These findings are consistent with their relations with fossil-bearing stratigraphic units. The Cowesett Granite, and associated volcanic rock in Rhode Island, have been dated as Devonian by Hermes *et al.* (1981b);

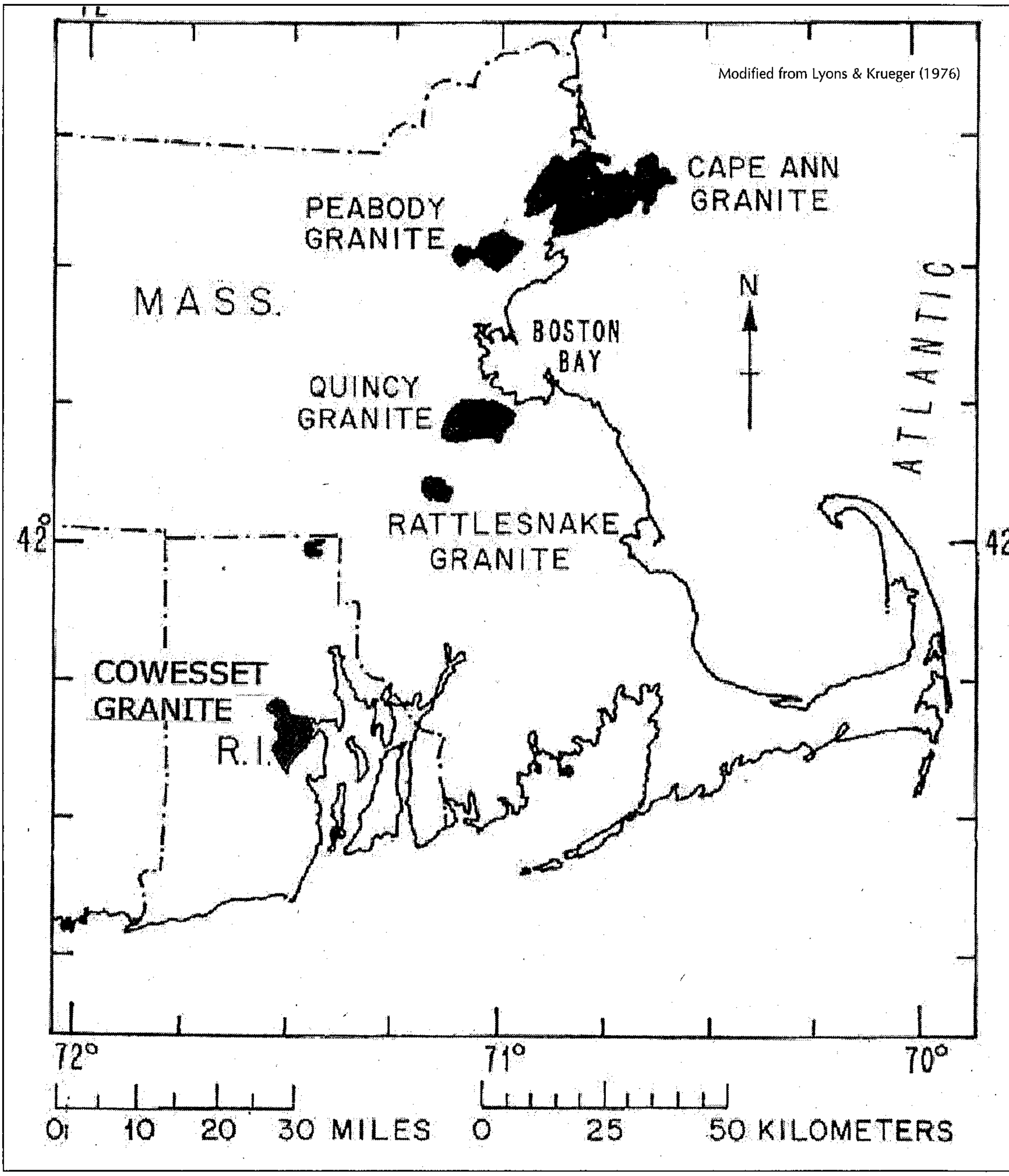


FIGURE 2-21. Areal distribution of Late Ordovician alkalic granite in southeastern New England.

however, they also dated the nearby Scituate Granite as Devonian. This foliated granite is clearly part of the Late Proterozoic batholith, so the dating or sampling is in error. Other batholithic granite in southwestern Rhode Island that was previously dated as Devonian (Moore, 1959) is found to consist of a mixture of Late Proterozoic and Permian rock (Hermes *et al.*, 1981a).

The unmetamorphosed Late Silurian-Early Devonian (423 to 416 million years ago) volcanic-redbed sequence, present in the Newbury Basin in the Nashoba Terrane, also is represented in this terrane by the small remnant mentioned in northern Massachusetts (Bell *et al.*, 1977 & 1993) that Dennen (1981) thought was a fault basin. Volcanic rock in the Norfolk Basin, south of Boston, has been dated as Devonian (Maria & Hermes, 2001). However, these rhyolite and basalt flows are interbedded with terrestrial red mudstone, siltstone, sandstone and conglomerate of the Wamsutta Formation, which is part of the fossiliferous Pennsylvanian sequence (Knox, 1944; Lyons *et al.*, 1976). Until stratigraphic studies separate this rock from the Pennsylvanian strata, the Devonian dating remains very doubtful. In any case, the Wamsutta is an early fill in the Norfolk Basin.

The fault-bounded Norfolk and Narragansett basins south of the Boston, along with the smaller North Scituate and Woonsocket basins to the west of them (see Figure 2-22), are filled with a thick succession of terrestrial conglomerate, sandstone, shale and some coal of Pennsylvanian age (Shaler *et al.*, 1899; Quinn & Oliver, 1962; Oleksyshyn, 1976; Lyons, 1978; Lyons *et al.*, 1976). The sequence has been described as a basal Pondville Conglomerate (Bellingham Conglomerate in the western basins), overlying redbeds of the Wamsutta Formation, followed by the Rhode Island Formation of generally gray shale and sandstone with some coal and great lenses of a higher Purgatory Conglomerate, and topped by the Dighton Conglomerate. The Pondville consists of interfingering lenses of conglomerate and sandstone. And at least some of the higher conglomerate is fault repetition, indicating a much more detailed study of the structure and stratigraphy is needed. The total thickness is estimated (Shaler *et al.*, 1899) to be about 3,660 meters (12,000 feet), but the evidence for this estimate is weak (Quinn, 1971).

The conglomerate was shed into the basin from the rising borders to interfinger with the finer deposits formed along southwest-flowing rivers and backwaters in a valley system similar to and contemporaneous with ones in basins in Maritime Canada (Ballard & Uchupi, 1975; Oleksyshyn, 1976; Lyons *et al.*, 1976, Towe, 1959). The Canadian basins lie along the same trend to the northeast and there may be considerable intervening offshore basins. The basin fill in Canada began earlier in the Pennsylvanian (Lyons *et al.*, 1976) and has similar underlying Mississippian deposits. This evidence suggests that southeastern New England was either higher or eroding in the Mississippian or that the deposits are buried below the Pennsylvanian strata. The Narragansett deposits had far more extensive distribution in the past, and extend westward into the Sturbridge Terrane where the Worcester exposure lies.

The southwestern shore of Rhode Island, adjacent Connecticut and eastern Long Island are underlain by the nonfoliated Narragansett Pier Granite and by its late dike phase, the Westerly Granite and pegmatite dikes (Quinn, 1971). Late pink pegmatite dikes, identical to the late-stage pegmatite associated with this granite, are found scattered northward across the region into New Hampshire (Barosh, 1984a; Hermes *et al.*, 1981a) and westward to beneath western Long Island (Barosh, 1991). Southern Rhode Island has suffered more erosion than to the north and shows the irregular roof of the granite to dip gently to the north. These granites intrude Pennsylvanian strata and are generally considered Permian in age, yet yield a variety of radiometric dates that range from Early Permian to Late Triassic (Quinn, 1971). Note is made that K/Ar radiometric dates can be restarted by high temperatures. No related volcanic rock is known.

The Carboniferous strata (see Figure 2-4) are metamorphosed to upper amphibolite facies in the southwestern part of the basin adjacent to the Permian Narragansett Pier Granite (Shaler *et al.*, 1899; Quinn, 1971; Hermes *et al.*, 1981a; Hepburn & Rehmer, 1981). The grade of metamorphism decreases to the north away from the granite (Shaler *et al.*, 1899; Quinn, 1971) and represents a complex contact metamorphism during which two separate thermal events may have occurred (Hepburn & Rehmer, 1981). All of Rhode Island and eastern Massachusetts were heated enough to reset K/Ar dates to about 240 million years ago, which is Middle Triassic (Zartman *et al.*, 1970; Day *et al.*, 1980; Dallmeyer, 1981), far beyond where the rock is noticeably altered. The metamorphism and intrusion are undoubtedly part of the same event with the high temperature just preceding the granite.

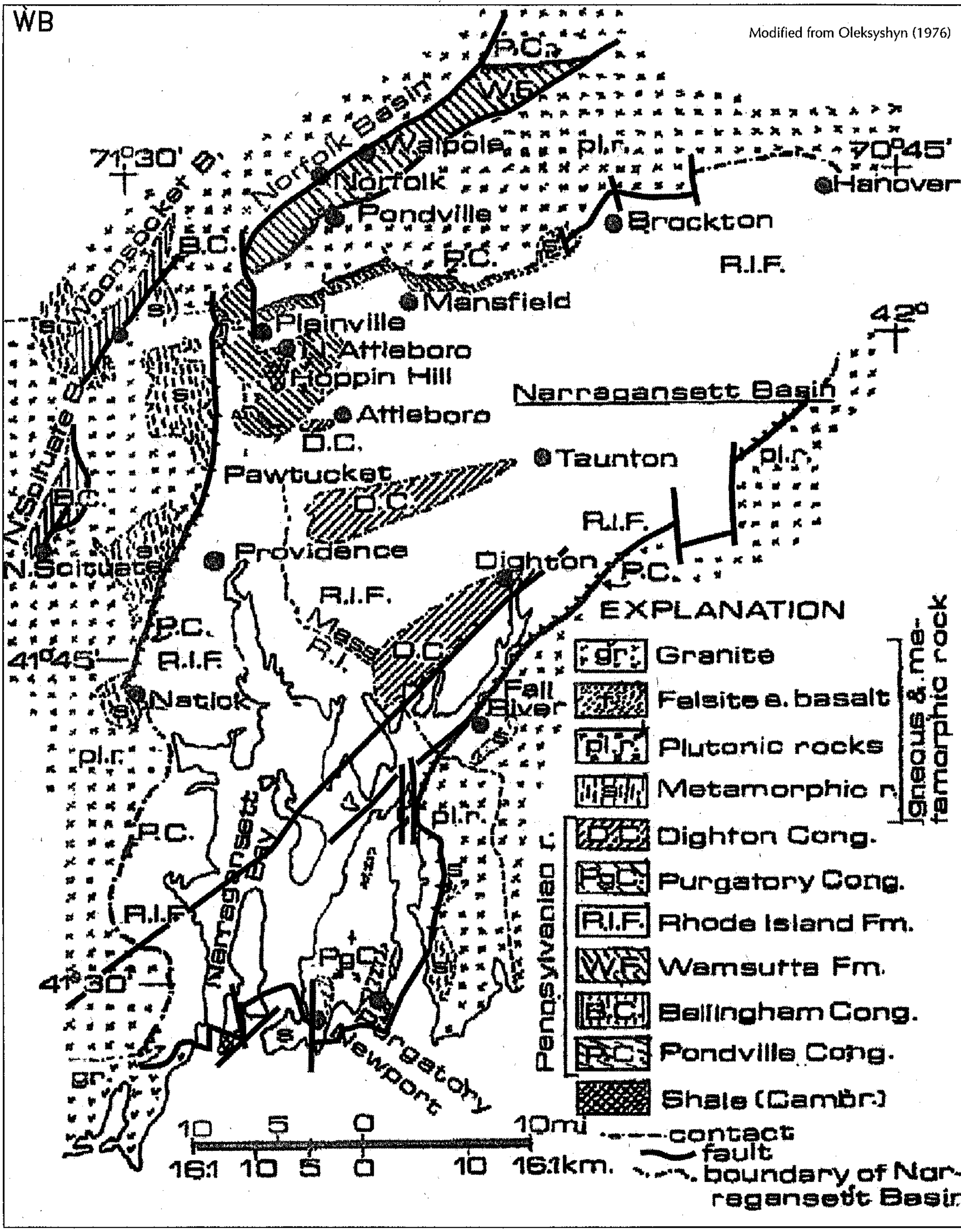


FIGURE 2-22. Map showing basins of Pennsylvanian terrestrial strata in Rhode Island and adjacent Massachusetts.

Some complexities are probably mainly due to irregularities along the shallow northward-dipping surface of the granite.

The structure of the area is varied and complex. The Southeast New England Batholith is syntectonically folded along its northwest side

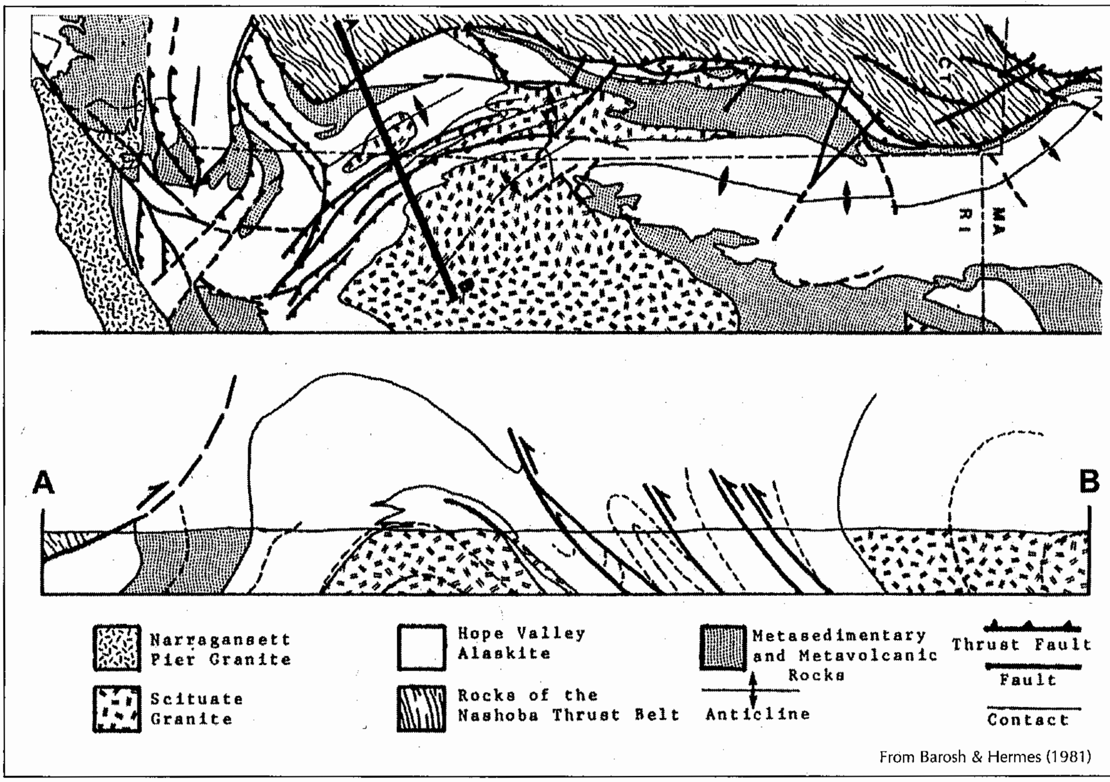


FIGURE 2-23. Sketch map and section of the West Rhode Island Fold Belt.

against the Nashoba Thrust Belt in Rhode Island and Connecticut (see Figures 2-12, 2-20, 2-21, 2-22 & 2-23) and the rock is strongly foliated, sheared and folded adjacent to the Bloody Bluff-Lake Char-Honey Hill Fault System (Feininger, 1965; Barosh *et al.*, 1977a; Barosh & Hermes, 1981; Barosh, 2005 & 2009; Smith & Barosh, 1983). A series of north-trending, north-plunging syntectonic folds, designated the West Rhode Island Fold Belt (Barosh 1972 & 1976b; Barosh & Hermes, 1981; Hermes *et al.*, 1981a), lie along the Connecticut-Rhode Island border (see Figures 2-23 & 2-24). These folds are broad and open in the north, but become progressively more compressed to the south where they are overturned and broken by thrust faults, which tend to cut out the synclines (Feininger, 1965; Barosh, 1972). One of these faults that was mapped by Barosh *et al.* (1974 & 1977b; Barosh & Hermes, 1981) was proposed to be a plate boundary called the "Hope Valley shear zone" (O'Hara & Gromet, 1985), but all the mapping shows it to have the same rock on either side and the fault dies out to the north at the southern edge of Massachusetts (Barosh, 2005) and terminates southward against a fault in southwestern Rhode Island. The western part of the fold belt swings southwest and west approximately parallel to the Honey Hill Fault Zone in southeastern Connecticut where the folds are all overturned and dip to the northwest. The eastern part swings to the southeast across southwestern Rhode Island where the folds are overturned and dip to the northeast. Both the northwest- and northeast-dipping overturned folds and associated thrust faults merge northward and apparently formed at the same time. The folds are described by both the flow foliation in the granite and the bedding of the invaded metasediment (Feininger, 1965; Barosh, 1972 & 2005), demonstrating both rocks deformed together against the underside of the thrust belt as the granite formed in the Late Proterozoic. The folds broke with further compression in the latest Proterozoic and Ordovician. The degree of metamorphism and deformation increases to the south where the

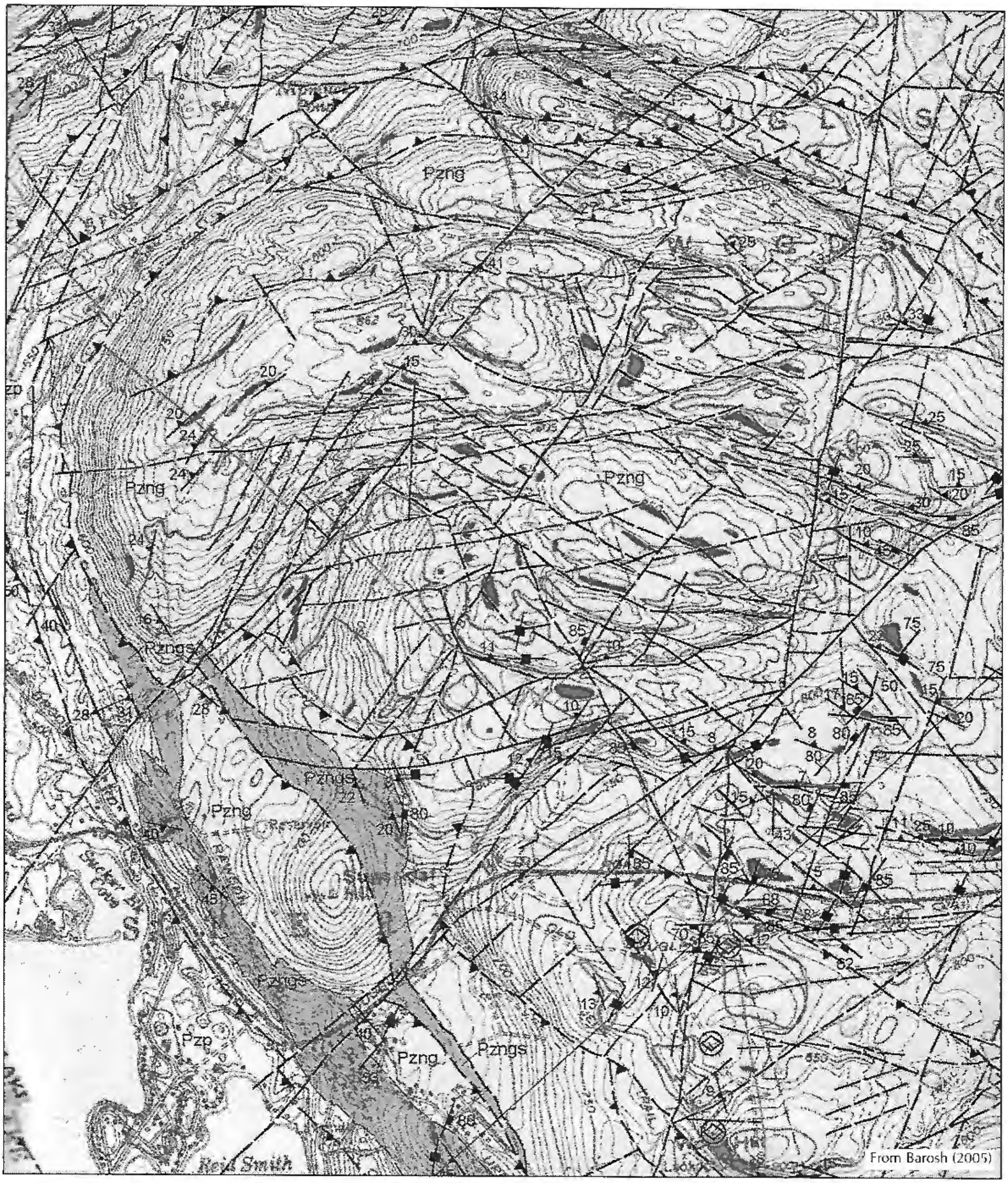


FIGURE 2-24. Anticlinal nose at the north end of the West Rhode Island Fold Belt consisting of highly faulted Late pre-Cambrian Northbridge Granite and intruded metamorphic strata, southern Massachusetts just north of the northwest corner of Rhode Island.

rock was originally deeper. The gentle north plunge of the lineation in the granite that formed parallel to the fold axes also shows the present north tilt of the structure. The West Rhode Island Fold Belt ends to the north just inside Massachusetts, where the Nashoba Thrust Belt changes direction from the north to the northeast (see Figures 2-1 & 2-12). This shift is apparently due to later overlap of the folds northward by relative southeast move-

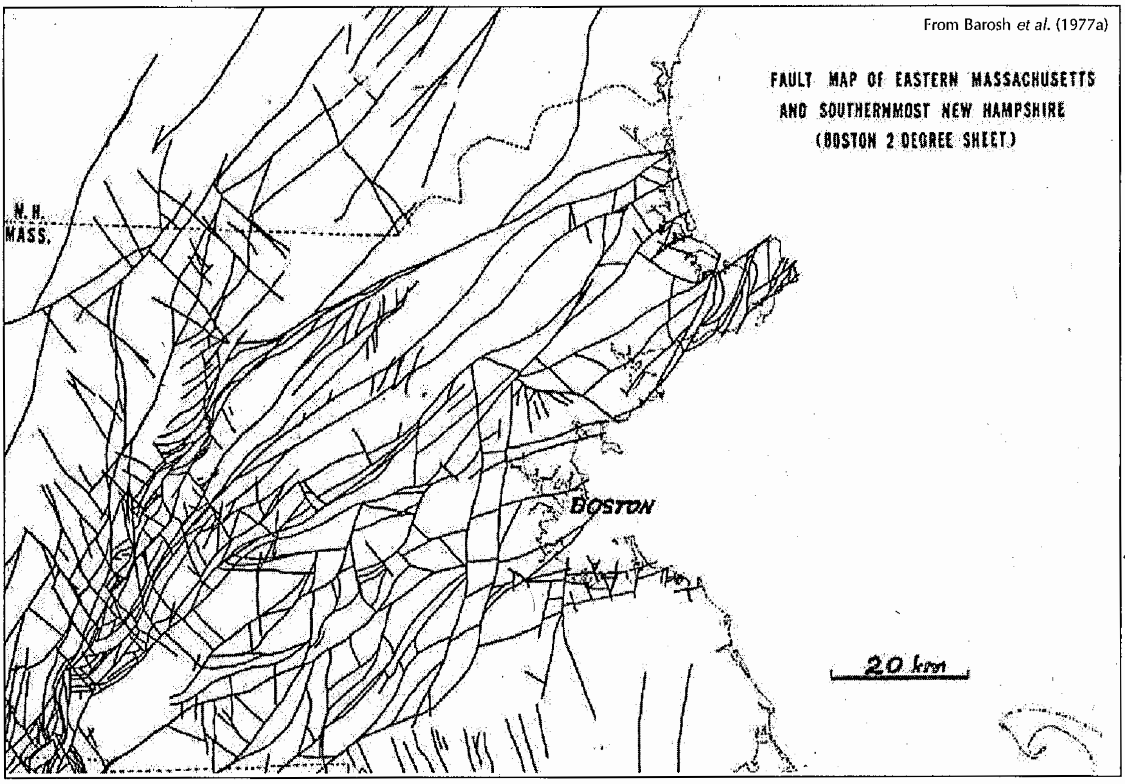


FIGURE 2-25. Map of eastern Massachusetts and southern New Hampshire showing mapped faults.

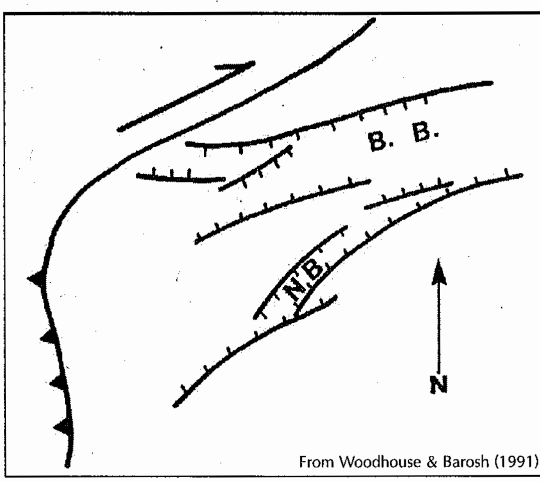


FIGURE 2-26. Sketch map showing structural relations of the Boston (B.B.) and Norfolk (N.B.) basins with the eastern edge of the Nashoba Thrust Belt.

ment along the Bloody Bluff Fault Zone during the Ordovician. Farther north, the batholithic complex is foliated and sheared adjacent to the thrust belt rather than folded, and less deformed in general.

Several northeast-trending fault zones are indicated to cross the Rhode Island Dome by coinciding topographic, aeromagnetic and gravity lineaments (Barosh, 1972 & 1986a; Schwab & Frohlich, 1979). The distribution pattern, attitudes and magnetic characteristics of the Blackstone Series where crossed by these fault zones suggest each has a few kilometers of right-lateral offset and the southernmost one, the Queen River fault, extends from southeastern Connecticut and cuts off the domal structure to the south (see Figure 2-20). The aggregate number of these and later faults results in the Proterozoic basement being extremely faulted. At least seven fault sets are seen to cut well exposed rock (see Figure 2-24) near the northwest corner of Rhode Island into small blocks (Barosh, 2005) similar to the mosaic of faults cutting the Nashoba Terrane to the north (Bell & Alvord, 1976) and where there is structural control in the Boston Basin and good exposures on the surface (Crosby, 1880; LaForge, 1932; Kaye, 1980a; Ross & Bailey, 2001) and in tunnels (Barosh & Woodhouse, 1990; Stone & Webster, 1995).

Several east-northeast- to northeast-trending fault basins are dropped into the eastern portion of the terrane and more are indicated offshore (Ballard & Uchupi, 1975). They may be part of an early fault system that reactivated at different times. The controlling faults end to the west (Barosh, 1977a) against the Bloody Bluff-Lake Char fault zones (see Figure 2-25). Their orientation may have been controlled by right-lateral movement (Barosh, 1984a) along the Nashoba Terrane (see Figure 2-26) or by the earlier east-west oriented collision. Extension across such faults apparently controlled the early volcanism in the Boston Basin and also may have possibly controlled the later nearby Late Ordovician granite plutons.

Faults of the northeast-trending Norfolk Basin to the south merge with those along the southeastern side of the Boston Basin and could be reactivated ones (Barosh, 1995). The Norfolk and the North Scituate, Woonsocket and Narragansett basins all appear to have their greatest offset along their southeast sides. The northeast side of the Narragansett Basin is a faulted depositional contact. Some of the faults in the basin have Mesozoic movement and the degree to which they represent reactivation of original basin faults is unknown. The northern part of the Narragansett Basin exhibits (Shaler *et al.*, 1899) a few broad east-northeast-trending bands of strata interpreted as large open folds (see Figure 2-22), but gravity profiles (Sherman, 1978) and evidence of faults (Barosh, 2006b & 2006c) indicates some if not all are fault blocks. Small isoclinal to recumbent north-northeast-trending folds, some of which are overturned, occur locally in the southern part of the basin. These folds have been interpreted by some workers to represent multiple episodes of regional deformation (Burkes, 1981). However, the folding appears to be highly irregular, local and not to affect the adjacent older rock. Also, the style of the regional Permian-Triassic Narragansett Pier Granite intrusion into these rocks does not indicate any regional compression (Hermes *et al.*, 1981a). Furthermore, the rock in the basin exhibits considerably soft sediment deformation and there is evidence for a great deal of sliding along the coal seams in this area (Rabin, 1981). Most folds can thus be accounted for by internal movement in gliding along the coal seams. However, the deformation shown by the stretched clasts in the conglomerate and some broad folds at the southwestern edge of the Narragansett Basin is compressional. The strike of the stretched pebbles and small faults around southern Middletown, Rhode Island, trends northerly and they show west over east movement, as do a few small thrust faults to the east. These structures pre-date the Narragansett Pier Granite.

Mesozoic & Cenozoic Geology

A new system of structures and basins developed across the terranes as the North Atlantic Basin was initiated about 235 million years ago and developed later in the Mesozoic as Pangea broke up. These structures transcended the terrane divisions discussed above and the region behaved as a single unit. Normal faults, graben basins and dikes, largely controlled by earlier faults, formed in the Late Triassic-Early Jurassic under the initial extension and under north-south compression. Then fresh systems of faults and basins developed as the new edge of the present North American continent formed and sagged downwards. The changes reflect the early faults rotating out of the line of the active stress system as the Atlantic widened and were replaced by new more compatible structures (see Figure 2-27). Some of the zones of these later faults are the landward extensions of structural adjustments within the North Atlantic that control a late Mesozoic volcanic chain and present-day earthquakes. Southeastern New England presents the best expression of these post-Paleozoic features on the East Coast.

Many Late Triassic-Early Jurassic terrestrial basins are present onshore and offshore as part of a northeast-trending system connecting those of the Mid-Atlantic (Ballard & Uchupi, 1975; Kaye, 1983a) with the Fundy Basin of Nova Scotia (see Figures 2-12 & 2-28). Most of the onshore basins are small north-

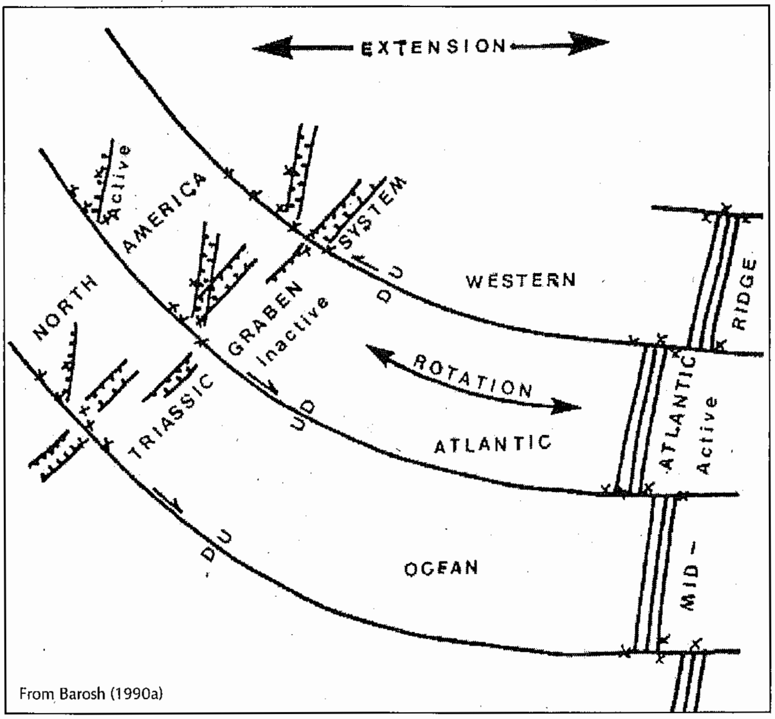


FIGURE 2-27. Diagrammatic sketch showing relations of the Triassic grabens with the plate boundary at the Atlantic Ridge and the later Jurassic and younger grabens that developed due to rotation of the North American Plate. X marks the location of an earthquake.

east-trending ones (see Figure 2-29). The large north-trending Hartford Graben is a prominent exception, due to control by an older fault along the west side of the Bronson Hill uplift, although the great majority of the numerous small faults within the graben trend to the northeast. The displacement in the Hartford Graben is mainly along its eastern side and is essentially a half graben as are some of the others. The other basins are controlled by older faults as well, such as the small Middleton Basin northwest of Boston where red conglomerate, sandstone and siltstone form a fault sliver within the Bloody Bluff Fault Zone (Kaye, 1983a; Barosh, 1984b) northwest of Boston (see Figure 2-29). Other such small basins probably lie undiscovered. The fill of the Hartford Graben, as in the others, consists of chiefly red to chocolate brown mudstone, siltstone, sandstone and minor pebble conglomerate. A volcanic vent against the southeast side of the graben fed three composite basalt flows that mark the basal Jurassic part of the section. These basalts flowed generally eastward (Gray, 1982) toward the active border fault. Graben basins of Late Triassic to Early Jurassic red clastic rock and basalt lie offshore buried beneath the thick glacial outwash sands and gravels of Cape Cod and coastal plain deposits (Ballard & Uchupi, 1975) and have been reached by drill (Folger *et al.*, 1978) on Nantucket Island (see Figures 2-12 & 2-30). Similar grabens lay farther offshore to the north and northeast. These basins were contiguous with a similar cluster of basins off Morocco (see Figure 1-2). Pollen and spores date the Hartford Graben deposits from early Late Triassic to at least middle Early Jurassic, approximately 227 to 195 million years ago, although the Fundy Basin to the northeast may have begun in the latest Middle Triassic (Traverse, 1987).

Other northeast-trending normal faults in the region and earlier thrust faults, which reactivated as normal faults, are apparently also of this age. One of these zones, the Watch Hill Fault Zone that extends from eastern Long Island to Cape Cod Bay, has been mapped in detail (see Figure 2-23) through southwestern Rhode Island (Moore, 1967; Smith & Barosh, 1981; Frohlich, 1981; Hermes, *et al.*, 1981a). Red sandstone float has been found near the Watch Hill Fault Zone on Long Island and it can be dated to early Mesozoic as it cuts Permian or Triassic granite and is offset by many later Mesozoic or younger faults. The fault continues as a zone of *en echelon* segments northeastward across Narragansett Bay, through Fall River, Massachusetts, and along the southeast side of the Narragansett Basin. The bay changes both

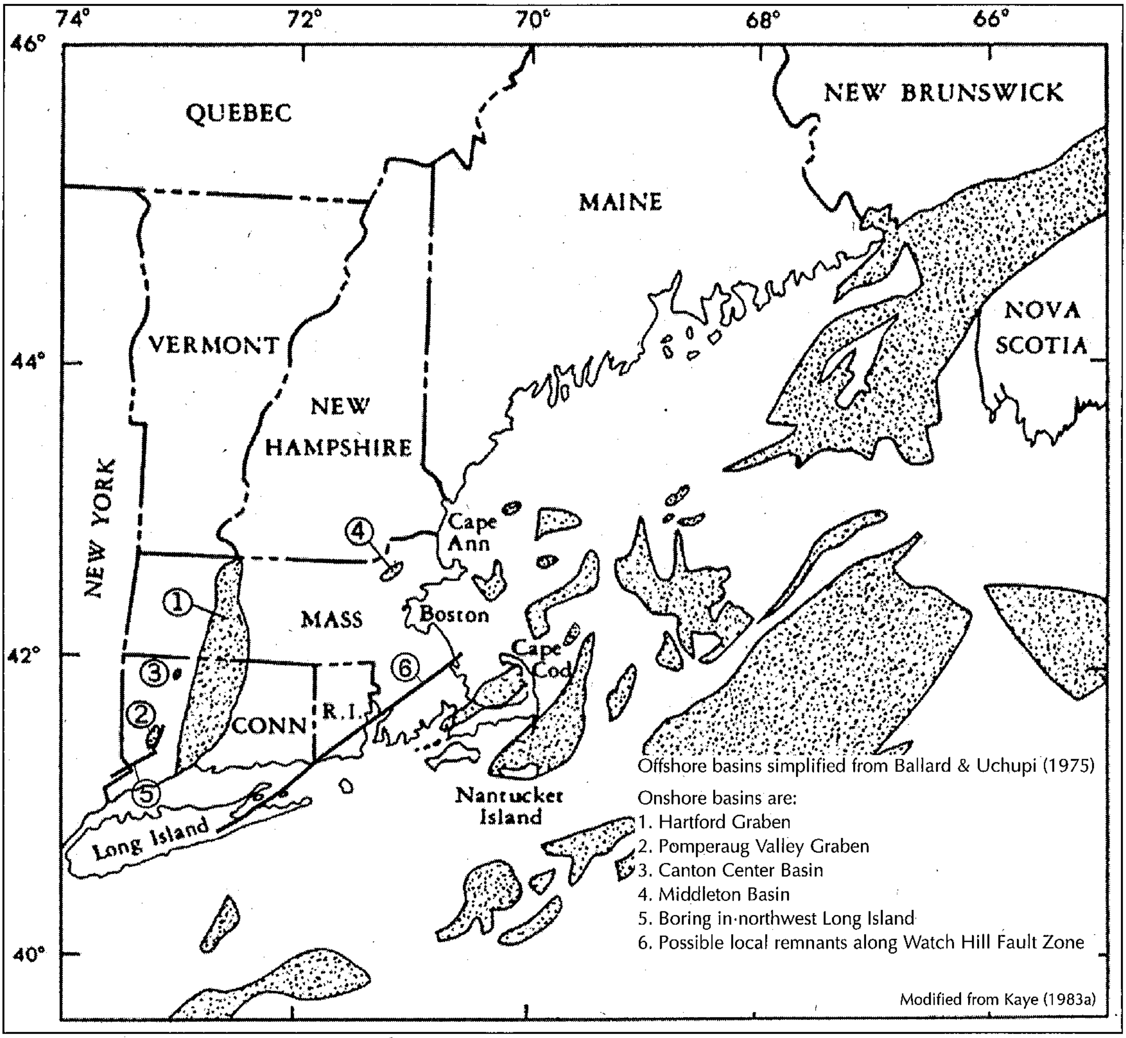


FIGURE 2-28. Map of New England showing locations of basins containing the Upper Triassic-Lower Jurassic Newark Group (stippled) and Watch Hill Fault Zone.

shape and trend where it is crossed by the fault (see Figure 2-22), which is expressed by a zone of geophysically defined faults (Collins & McMaster, 1978). A horst of Proterozoic granite, within the Pennsylvanian strata, lies between the overlapping ends of two en echelon segments (Barosh, 2006a & 2006b) in Bristol, Rhode Island (see Figure 2-30). The Pennsylvanian Dighton Conglomerate in the basin is repeated by the Watch Hill Fault Zone (see Figure 2-22).

Additional northeast-trending faults that cut the Pennsylvanian strata of the Narragansett and Norfolk basins appear to have Mesozoic movement as well. The northeast-trending faults indicated by the aeromagnetic trends in the largely covered region southeast of the Narragansett Basin (Barosh *et al.*, 1977b) also may have moved then. A fault cutting the northwestern side of the Norfolk Basin continues northeastward into Boston Harbor. This fault and the Watch Hill Fault to the south bracket the Pennsylvanian strata and appear to be the southwestern counterpart of the Fundian Basin to the northeast (see Figures 2-22 & 2-28).

A new set of north-trending normal faults and grabens developed across the region in the mid-Mesozoic and cut the earlier northeast-trending faults, but lack onshore deposits. Several of the grabens form a zone

(see color version on page 450)

FIGURE 2-29. Fault slice of Late Triassic redbeds, the Middleton Basin, in the Bloody Bluff Fault Zone, bordering dark Late Proterozoic volcanic rock mined in the SanVal Quarry, Middleton.

from Lake Champlain to Lake George. The Narragansett Bay Graben (Collins & McMaster, 1978; McMaster *et al.*, 1980), shown in Figure 2-31, and the Assawompset Graben to the east (Koteff, 1964a) formed onshore in southeastern New England and the north-trending Hartford Graben may have reactivated. Some of these extension faults have very wide silicified zones, such as those along the Thames River in Connecticut (Goldsmith, 1985), Diamond Hill at the northwest side of the Narragansett Basin and the east side of Bristol, Rhode Island (Quinn, 1971), besides numerous small en echelon zones, with staggered alignment, within Narragansett Bay. The islands and channels in Narragansett Bay reflect the horst and graben system well. A clear example is the Sakonnet Channel of eastern Narragansett Bay where drilling shows a submerged down-dropped block of Pennsylvanian strata within Proterozoic granite (see Figure 2-32), which is exposed onshore (Upson & Spencer, 1964; Barosh, 2006c).

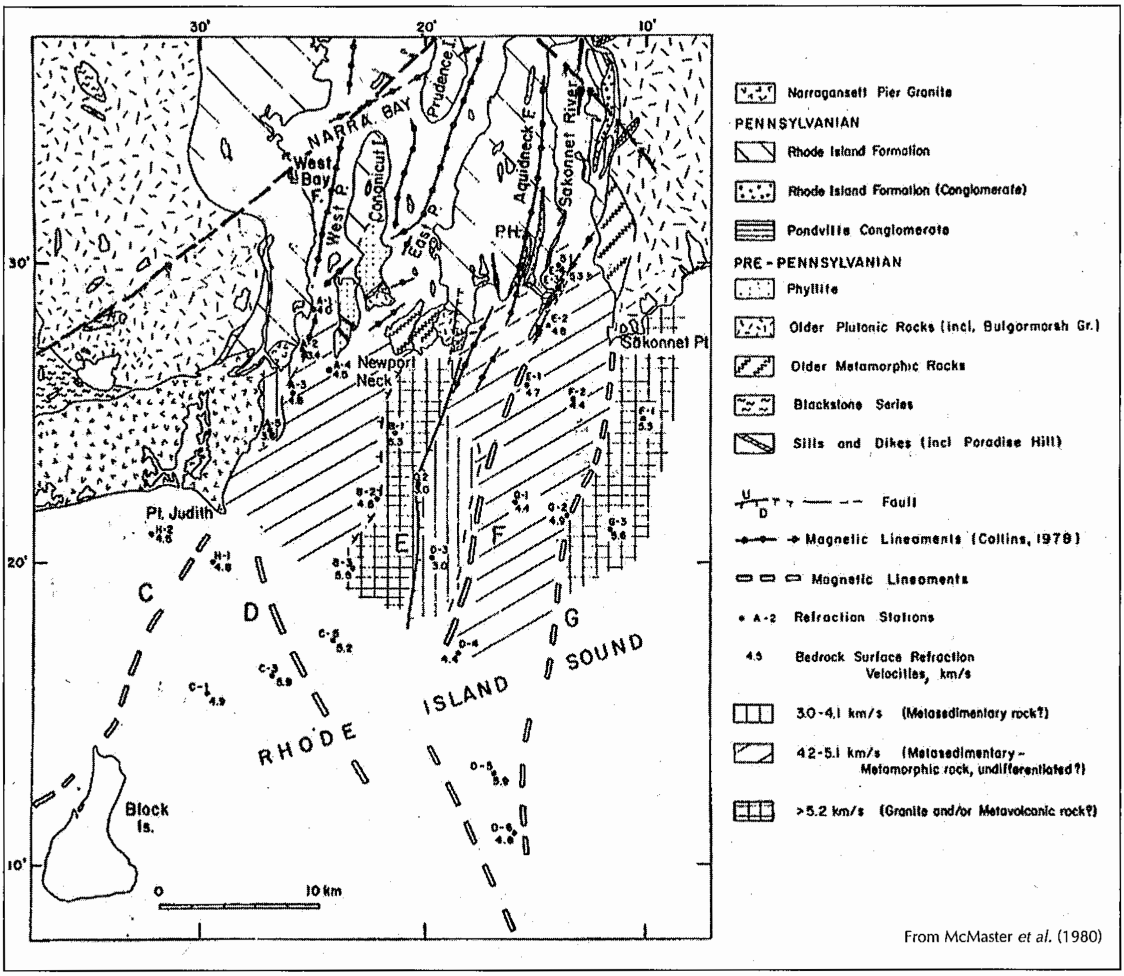
Both of these fault trends control dike emplacement across the region. Small Mesozoic diabase dikes are ubiquitous in the region and lamprophyre dikes are found locally. Generally, they are poorly exposed, but the large ones are well expressed by their magnetic properties (Snyder, 1970) and are commonly seen in tunnels (Crosby, 1904). A long northeast-trending dike system, the Higganum Dike, contains diabase up to 30 meters (100 feet) thick and extends from the southeast side of the Hartford Graben northeastward to New Hampshire. It has been dated to 200 million years ago and is similar in age to the flows in the graben. The Higganum Dike apparently follows a deep structure, but there is little evidence that it follows any significant surface fault zone. Numerous small northeast-trending diabase dikes are found across eastern Connecticut and central Massachusetts, but farther eastward northerly trends are the most common. A large mafic intrusion of possible Mesozoic age with a northward elongation is interpreted from gravity and magnetic data to underlie the western side of Cape Cod, and magnetic highs indicate that there are many other large north-trending dikes onshore, as well as offshore of southeastern Massachusetts (Barosh, 1976a; Barosh *et al.*, 1977b). These include the diabase encountered by deep drilling on Nantucket (Folger *et al.*, 1978). These fresh diabase dikes are seen in tunnels around Boston where they follow north-trending faults and may suffer from later fault offset (Crosby, 1904; Kaye, 1982b; Barosh & Woodhouse, 1990). Several diabase dike sets of various trends occur in central New England northwest of Boston (McHone, 1978, & 1984; McHone & Butler, 1984).

High-angle northwest-trending faults developed both about the same time and later than the north-trending ones and these two sets are the youngest ones found in New England (Barosh, 1986c & 1992). Numerous small faults of these two sets occur throughout the region. Many appear to cut the Higganum Dike (Sawyer & Carroll, 1979), more offset the Watch Hill Fault Zone (Frohlich, 1980 & 1981;

FIGURE 2-30. Map of Mount Hope Bay in northeastern Narragansett Bay showing Mesozoic faults, including northeast-trending segments of the Watch Hill Fault Zone and other north- and northwest-trending faults.

Barosh, 2006b) and some apparent Jurassic structures northwest of Boston (Kaye, 1984a). A few scattered east-west Mesozoic faults also are present in the region, but these may be slightly older.

Nonfoliated circular granitic plutons and associated volcanic rock form remnants of a northwesterly trending volcanic chain that developed along eastern New Hampshire and in southwest Maine during the Jurassic and Early Cretaceous (Eby, 1987). A few related felsic dikes occur in northeastern Massachusetts and the southernmost volcanic neck of this chain may lie just offshore of Cape Ann (Boston Edison Company, 1976a; Barosh, 1992). These plutons occur at intersections of the northwest and north-trending faults (see Figure 2-33), interpreted from aerial photographs, in southern Maine and New Hampshire (Barosh, 1986f & 1992) and are cut by them as well (Freedman, 1950). This volcanic chain apparently is related to the plutons forming the New England Seamounts farther offshore to the southeast (see Figure 2-8).



From McMaster *et al.* (1980)

FIGURE 2-31. Geologic map of southern Narragansett Bay and adjacent offshore area.

When the Late Triassic grabens subsided to the east as the Atlantic Basin grew, they first received saline deposits and then were overtopped by a seaward thickening wedge of late Mesozoic and Tertiary deposits, which lie just offshore and are part of the submerged northeast extension of the Atlantic Coastal Plain (see Figure 2-34). A nearly continuous sequence from Middle Jurassic to upper Tertiary is present offshore (see Figure 2-35), but where it laps onto the coast it is interrupted by many unconformities due to many fluctuations of the shoreline (Gibson *et al.*, 1968; Jansa *et al.*, 1979; Valentine, 1981; Grow, 1981), which creates an irregular partial sequence at the inner edge. The inner edge of the strata turns eastward in Raritan Bay at New York City to run beneath northern Long Island under thick glacial deposits. The Upper Cretaceous deposits lie just offshore of Rhode Island where their inner margin forms a northward-facing *cuesta* (O'Hara, 1980). This inner contact swings northward across western Cape Cod beneath a cover of glacial outwash and continues to north of Cape Ann, where the deposits become thin and patchy off New Hampshire (Weed *et al.*, 1974). Cretaceous clays and sands are exposed at a few places on Block Island where they may be in place, and Cretaceous and Tertiary deposits are exposed at Martha's Vineyard to the east where they have been thrust up by glacial action (Kaye, 1964a & 1964b). Small areas of Eocene and Miocene sand and silt occur onshore near the coast in the vicinity of Marshfield, south of Boston. These areas remain the only Tertiary outcrops known on the mainland; those near

Scituate correlate with the Gardiner's Clay in New York (Kaye, 1983b).

These changes in direction of the inner contact of the coastal plain deposits are at least partially structural. Broad transverse arches and swales across the Coastal Plain have long been recognized south of New England by the relative thickening and thinning of the deposits along strike and changes in the coastline. The swales cause the coast to be embayed and the embayments at Raritan Bay and the New Hampshire coast also show evidence suggesting that there is relatively more local down-warping (Barosh, 1986b). Also, the outward curve across Cape Cod may be enhanced by arching. The boundaries between the arches and embayments are aligned with northwest-trending fracture zones offshore and differential movement appears to be taking place across their landward extensions, which tend to be earthquake prone (Barosh, 1986c & 1990a). These northwest-trending fracture zones are referred to as transform fracture zones in the North Atlantic Basin and are due to spatial adjustments as the ocean basin widens.

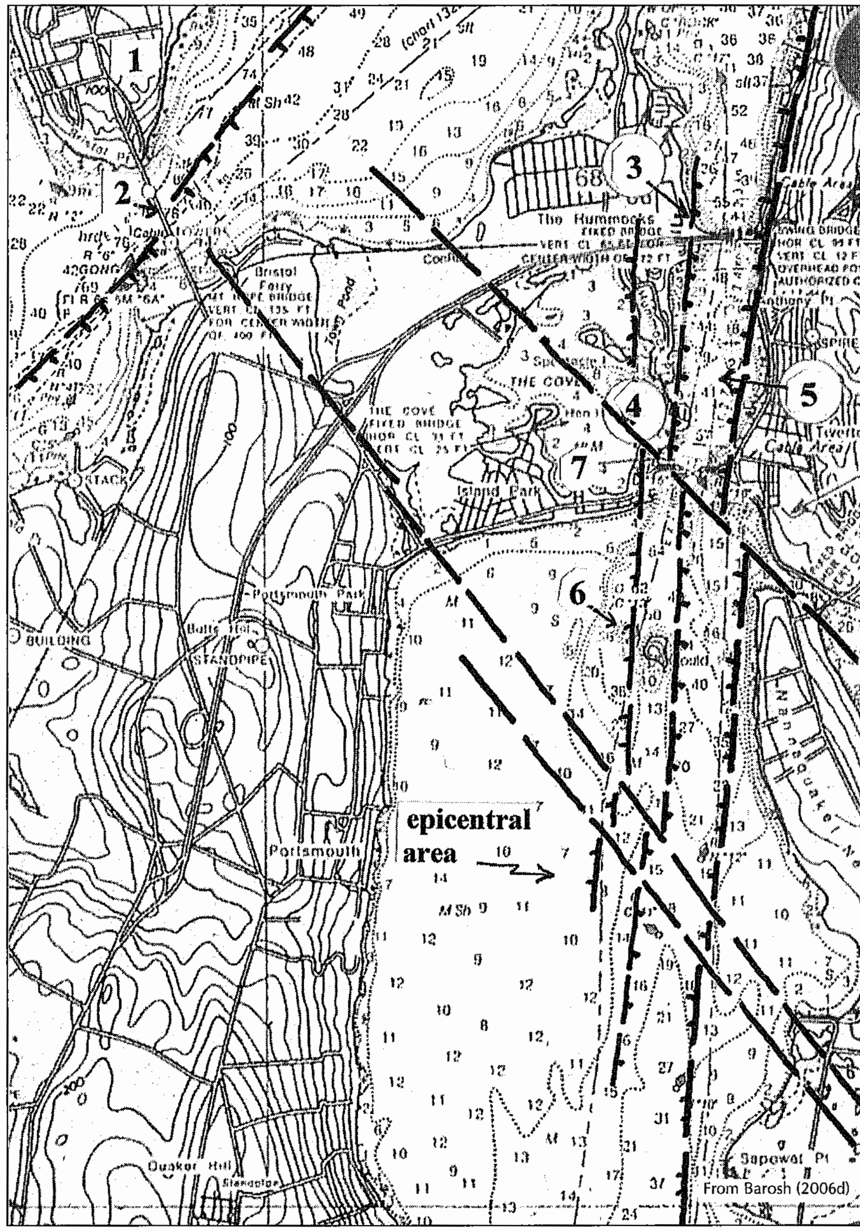


FIGURE 2-32. Map of the Sakonnet River, eastern Narragansett Bay, showing the epicentral area of the 2001 Sakonnet earthquake, the north-trending Sakonnet Graben and the northwest-trending Four-Corners Fault Zone, which is indicated to be active.

The Cretaceous strata are cut by a north- to northwest-trending fault, the New Shoreham Fault, offshore south of Rhode Island (McMaster, 1971) and faults of similar trends onshore (Hermes *et al.*, 1981a) and in lower Narragansett Bay (McMaster *et al.*, 1980) are probably related (see Figures 2-20 & 2-31). The

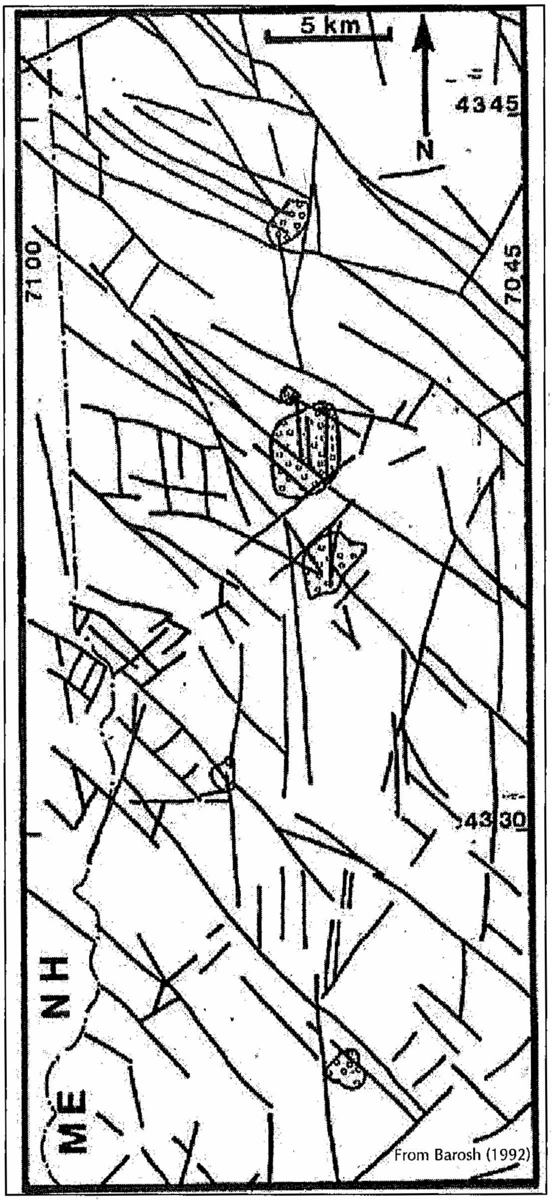


FIGURE 2-33. Map of the New Hampshire-central-west Maine border showing topographical lineaments, which result from at least small Mesozoic faults, and Mesozoic plutons.

New York Bight Fault, farther west, south of western Long Island, cuts Tertiary deposits (Hutchinson & Grow, 1982). Some of the high-angle faults that cut the Tertiary deposits at Marshfield and on Martha's Vineyard appear tectonic in origin and are not due solely to glacial action (Kaye, 1983c).

Repeated Pleistocene glaciations smoothed the general landscape while etching out the fault-controlled valleys and leaving behind a complex cover of till, glaciofluvial and glacio-lacustrine deposits. However, these deposits were eroded by each subsequent glaciation and the record is generally restricted to those of the last event. The last Wisconsin ice sheet covered the entire region and extended off-shore to the east. Extensive outwash plains and moraines developed across Cape Cod and nearby islands near its southern terminus (see Figure 2-36). The southernmost stand resulted in a thick outwash laid down across the edge of the Coastal Plain deposits of Long Island and the islands to the east while the shoreline was farther off to the south (see Figures 2-37 & 2-38). An ice front melted back in stages and a stand in Cape Cod Bay deposited outwash deposits of several hundred feet thick on outer Cape Cod and a significant thickness over southeastern Massachusetts as well. A further retreat to coastal Connecticut-Rhode Island left a depression in Long Island Sound that filled to form a great freshwater lake that drained to the east. Thereafter, as the ice melted back, a complex and often bewildering variety of till, drumlin, esker, outwash, delta and lake clay, sand and gravel deposits were laid down. Each pause in the ice front as it melted and retreated northward resulted in sequences of many types of outwash, delta and lake deposits forming in the shallow valleys (see Figure 2-39) while marine clays were deposited along the shore. Usually the deposits are thin, although they are quite variable in thickness onshore. Little geologic change other than man's activities and the filling of many lowland areas by lake and swamp material has affected the area since the retreat of the ice. This situation makes for highly variable ground conditions that may change over short distances and be full of surprises. For example, occasional readvances might reshape a variety of deposits into drumlins, such as the large drumlin of outwash sand at Walpole, Massachusetts, and the mixed deposits of the Beacon Hill drumlin in Boston. (These very complex glacial deposits due to the interplay of glacial events and sea-level

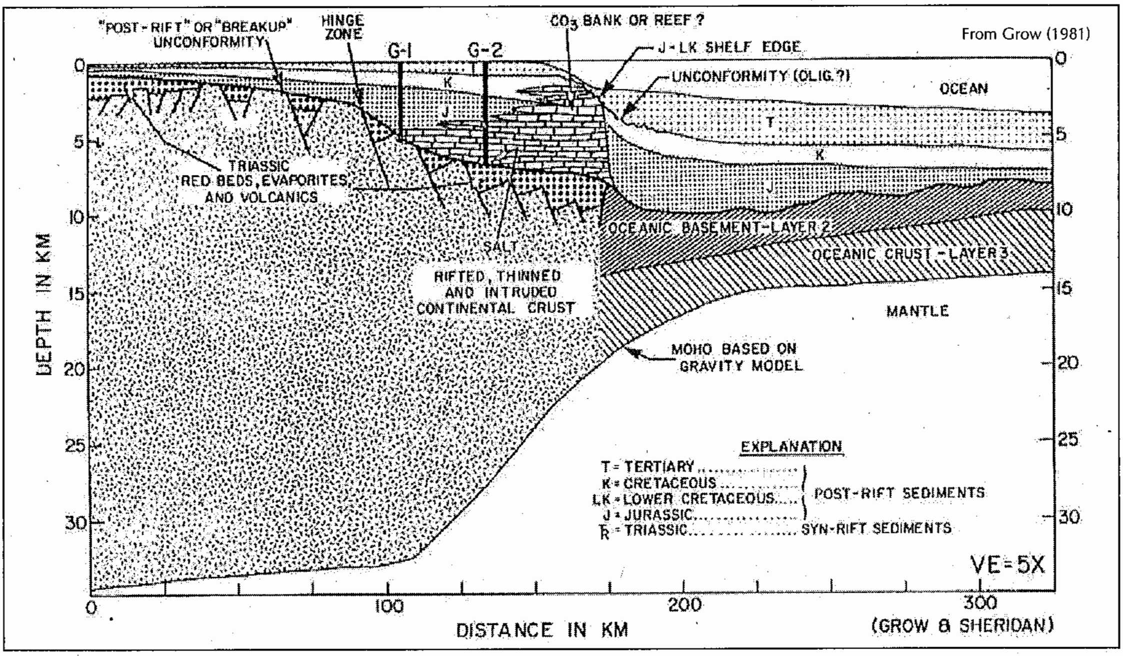


FIGURE 2-34. Composite geologic section across the southwest end of Georges Bank offshore of southeastern New England.

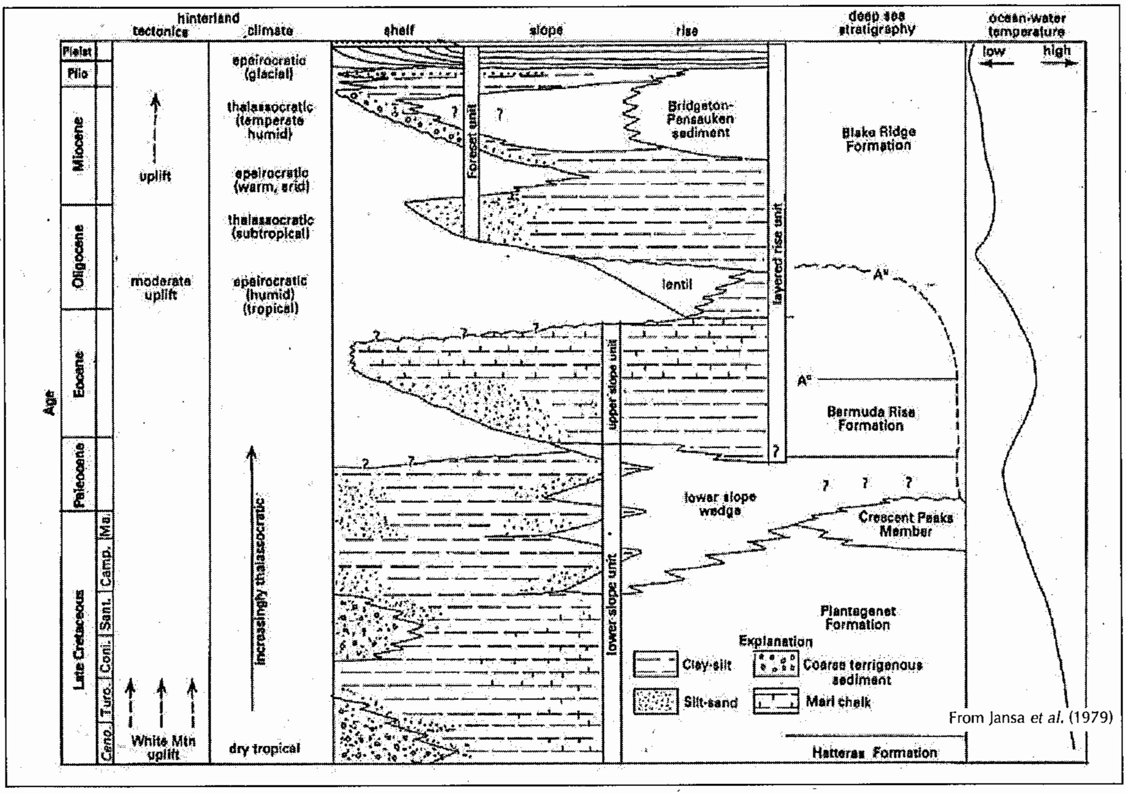


FIGURE 2-35. Schematic stratigraphic relations of Cretaceous and Tertiary strata offshore of New England and the Boston Coastal Plain Margin.

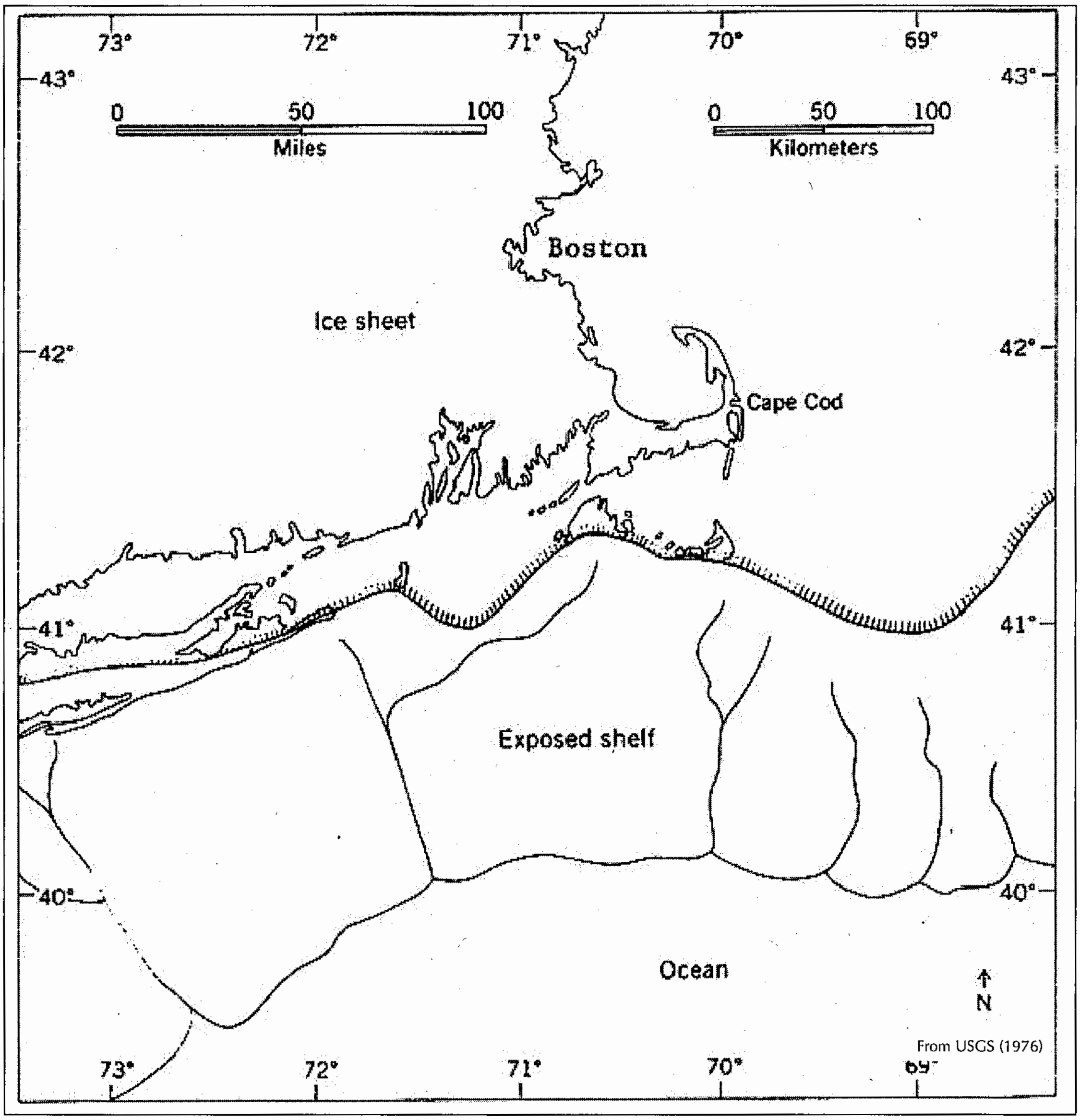


FIGURE 2-36. Map of southeastern New England showing the maximum southward extension of the glacial ice, outwash deposits and shoreline between 18,000 and 25,000 years ago.

changes in the coastal region are described in a section on the Boston Basin.)

Neotectonic Movement & Seismicity

The tectonic activity initiated in the Mesozoic continues to operate, albeit at a lesser magnitude than in the past, and the East Coast is affected by neotectonic movement causing earthquakes. The common labeling of the region as the "passive" edge of the continent in contrast to the Pacific side is a misnomer because it remains tectonically active. This movement is related to the continued opening of the North Atlantic Basin along the Mid-Atlantic Ridge and clearly seen where it is exposed in Iceland. The crust is spreading at an average rate of about 2.5 centimeters (1 inch) per year along the ridge (Kiou & Tilling, 1996) where much of the movement is extensional (Kristansson, 1974), but some lateral, as well as vertical, movement occurs along the oceanic fracture zones, which are transverse

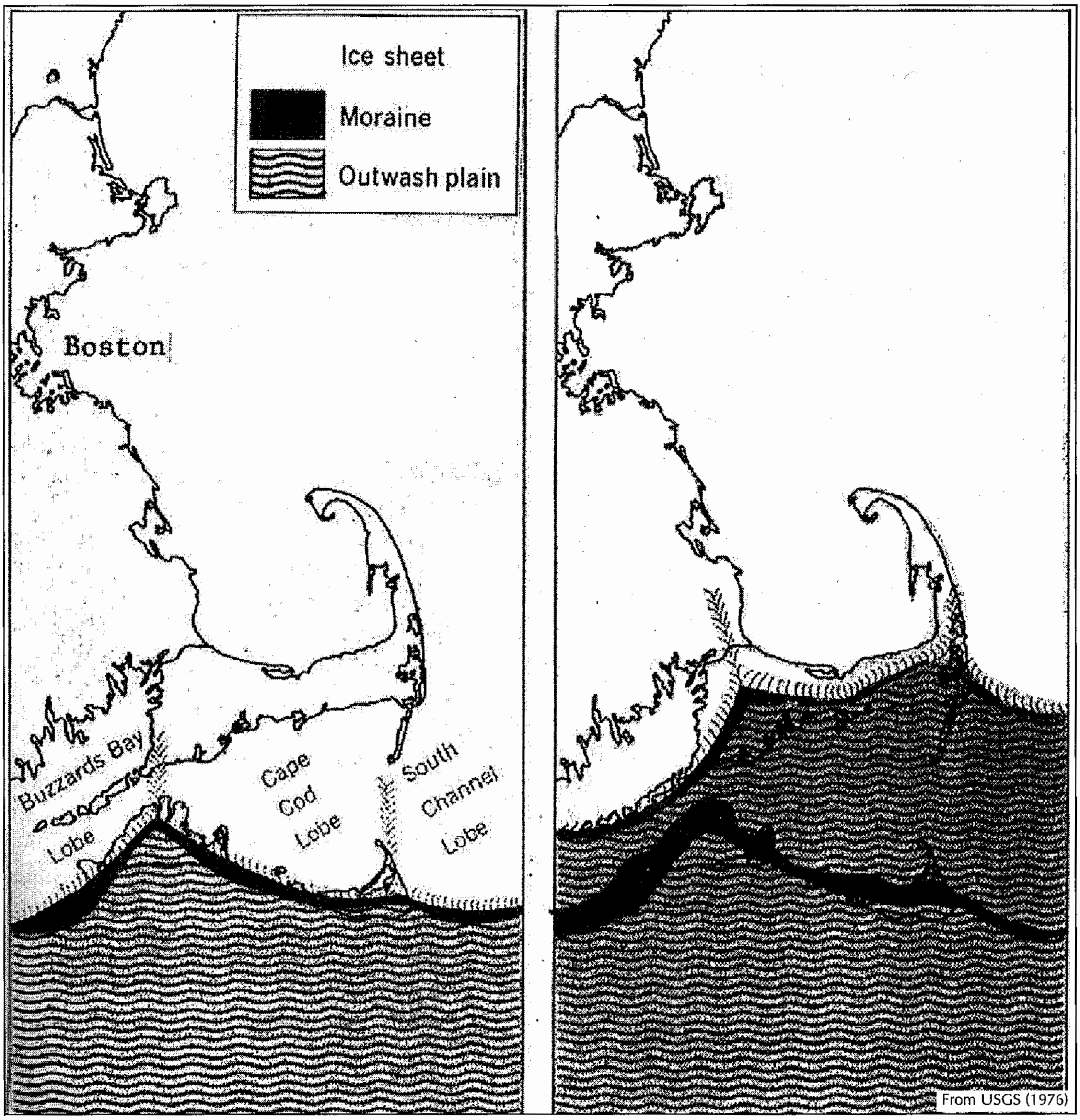


FIGURE 2-37. Map of southeastern Massachusetts showing the last glacial retreat and the moraines formed on Martha's Vineyard, Nantucket and Cape Cod.

structural zones, along which adjustments are made in response to the spreading (see Figure 2-7). The landward response to this movement in New England is activity along many of the northwest-trending zones of faults, although thus far only rare specific active faults are identified (Barosh, 2006b & 2006c).

The current crustal movement in New England is a composite of several causes that need be sorted out, and single measurements or approaches provide scant information. The recognized causes are (see Figure 2-40): regional tilt, transverse arching and subsidence, sagging of the continental edge, and fault offset (Barosh, 1989 & 1991). However, glacial rebound is over in this region. Unraveling these different causes is further confused by sea-level rise from the melting of ice and thermal expansion, residual strain release, and freezing and thawing.

The most obvious recent changes in eastern Massachusetts are due to the general rise in

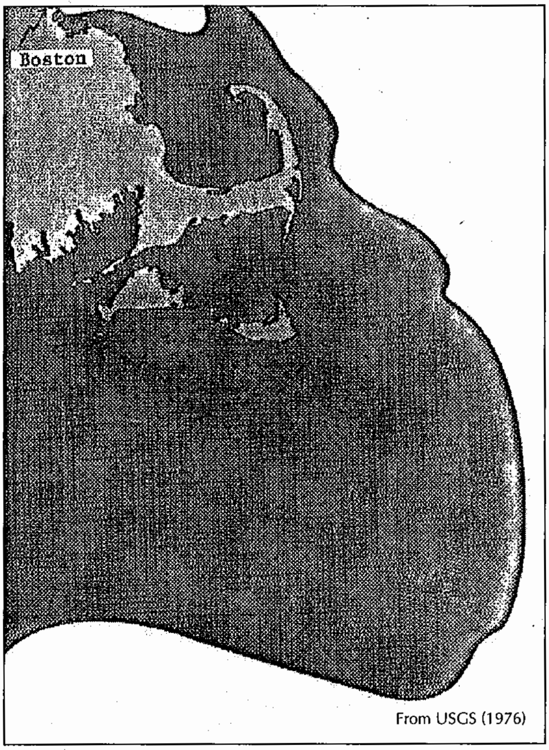


FIGURE 2-38. Map of southeastern Massachusetts showing positions of the shoreline at the end of the Pleistocene and at the present.

sea level and post-glacial isostatic rebound (see Figure 2-41). The rise in sea level has long been noted from its effects on the shoreline and early man-made structures (Sears, 1894 & 1895). Tree stumps are exposed at low tide along the New Hampshire coast and barrier beaches at Duxbury and Castle Neck, south and north of Boston, respectively, where the sea has moved inland, crossing over estuary deposits. Calculating the rate of the general sea-level rise is compromised where data are obtained from deposits that may have been compressed and give too high an estimate or when neotectonic movement is ignored. The world-wide rise in sea level as measured by satellite since 1993 is 3 millimters (0.1 inch) per year, or 30 centimeters (1 foot) per century (Carpenter, 2008). Deviations from this rate are due to the other factors listed above. Recent predictions of an increased 1 to 1.5 meter (3 to 5 foot) rise over the next century have yet to show up in any measurements.

Crustal rebound from the melting of the glacial ice mass and the springing back of the compressed rock has caused uplift and a tilting to the south across New England and adjacent Canada. The tilt, which results from more ice having been to the north and a greater compression there, forms a slope of roughly 1 meter rise for every kilometer northwards (4 feet per mile) as measured from glacial lake shorelines. The uplift caused the relative sea level to fall 83 meters (272 feet) in 2,500 years, from a high stand of nearly 33 meters (108 feet) above present mean sea level about 14,500 years ago to a low of –50 meters (–164 feet) at 12,000 years in northeastern Massachusetts (Oldale *et al.*, 1993). The rising ocean from glacial melting and the southward tilt of the land are in equilibrium just south of Boston, where the Late Pleistocene and the present sea level match (see Figure 2-38). The old shore is deeply submerged to the south and fishermen occasionally snag tree stumps on the bottom. Just recently, cypress tree fragments were recovered from borings for proposed wind turbines south of Cape Cod. The Pleistocene shoreline steadily rises north of Boston to about 250 meters (820 feet) near the St. Lawrence River. This rebound appears to have ended long ago near Boston and is estimated to have terminated about 11,500 years ago along the Maine coast (Stuiver & Borns, 1975; Stuiver *et al.*, 1978), although it may still be occurring farther north in Canada. Since then, the rise in ocean level has dominated the shift in the shoreline.

A seaward tilt of the edge of the continent began by about the Middle Jurassic (176 million years ago) as it sagged into the opening North Atlantic Basin and the subsequent weight of the resulting Coastal Plain deposits (which had been eroded from the land to the west) and advancing ocean water exacerbated the movement. The Coastal Plain deposits tilted seaward with the movement and the New England Seamounts were deeply depressed. These seamounts were volcanoes at the surface near the continental border southeast of New England during the Eocene, and now lie as much as 1,830 meters (6,000 feet) beneath sea level (O'Leary, 1984), which demonstrates the subsidence since the early Tertiary. The

Atlantic is still indicated to be widening and sediment continues to be carried offshore, so some degree of oceanward tilt should still be occurring.

An additional regional northerly tilt also has affected the Coastal Plain deposits along the entire East Coast. This tilt results in their uplift in the southeast United States and their plunging northward beneath the sea in New York. The tilt began in the Cretaceous and the increase in elevation with the age of the deposits at the southern end of the Appalachian Mountains records its progress. The tilt raises the coral and shell platform of Florida and then lowers New England to provide its famed rocky shores. The amount of subsidence is difficult to measure in New England due to the disturbance of the submerged Coastal Plain by glaciers, but it appears reflected in the greater rate of present sea-level rise recorded in the Canadian Maritimes than in southern New England.

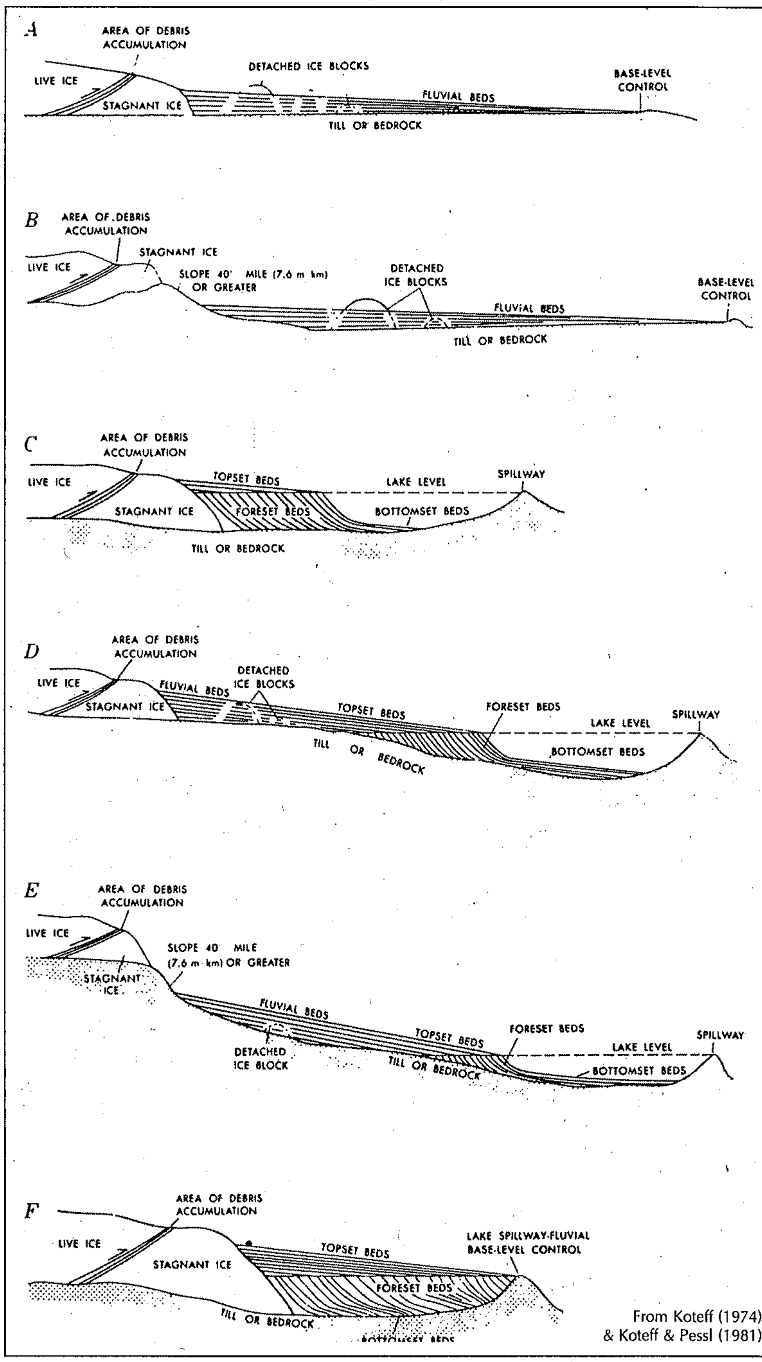


FIGURE 2-39. Diagrammatic profiles of typical sequences of glacial lakes and their deposits present in the valleys of southeastern New England that were deposited near the ice front.

The previously mentioned transverse embayments along the inner Atlantic coastline mark areas where subsidence has been more active. By Late Cretaceous time, the axes of these basins became oriented to the northwest and their positions appeared to be controlled by underlying northwest-trending fracture zones aligned with the major oceanic fracture zones (Barosh, 198la, 1981b, 1986d & 1990a). The embayments are continuing to subside and have seismicity associated with them. This activity is less obvious in the embayed coast of New Hampshire and south-

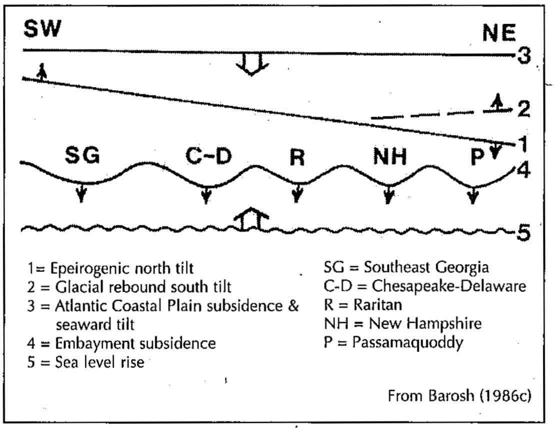


FIGURE 2-40. Schematic diagram showing present-day relative crustal movements and sea-level change along the East Coast of the United States. Arrows represent the relative direction of movement.

ern Maine, north of Cape Ann, than to the south, but it was subsiding 3,400 to 3,250 years ago (Harrison & Lyon, 1963) and the present subsidence is indicated to be perhaps one-third to two-thirds of a meter (1 to 2 feet) per century (Tyler & Ladd, 1981; Smith, 1982). This broad embayment, which contains thin remnants of Cretaceous and Tertiary sediments just offshore (Weed *et al.*, 1974), encompasses the Cape Ann seismic area and the sites of the 1727 and 1755 earthquakes.

The glacial rebound is finished and the general northerly and seaward tilts along the East Coast apparently are too slow to cause noticeable seismic activity and too broad to cause concentrations of activity. Thus, it is the subsidence in the northwest-trending embayments and in a few lesser associated north-trending grabens, such as Narragansett Bay and Lake Champlain, that correlate with the seismicity. This finding matches the one that post-Early Jurassic northwest- and north-trending faults form the youngest fault sets across New England.

Seismicity. New England is a region of moderate seismicity, experiencing an earthquake every few days, although most are very small (see Figure 2-42). This rate of activity is at least an order of magnitude less than that for Southern California (Devane & Holt, 1967). The distribution of activity, however, is highly variable within the region. Some areas are quite active, whereas others are nearly aseismic. Northeastern Massachusetts is one of the relatively more active areas and the Boston area has been damaged by earthquakes in 1638, 1669, 1727 and 1755. The greatest earthquake recorded for New England occurred northeast of Boston, offshore of Cape Ann, in 1755. This event had a probable epicentral intensity of VIII on the Modified Mercalli (MM) scale. Its description by Winthrop in 1757 was the first earthquake depicted in a modern straightforward manner without a strong religious bias of "God's just punishment of we all-too-mortal sinners."

The recording of earthquakes began early and these records provide the basis in revealing their cause. Roger Williams's mention of three strong earthquakes felt by the Indians in the ninety years prior to 1643 in southern New England may rank as the first short catalog that was followed by more extensive ones before 1900 (Brigham, 1871; Lancaster, 1873), along with short

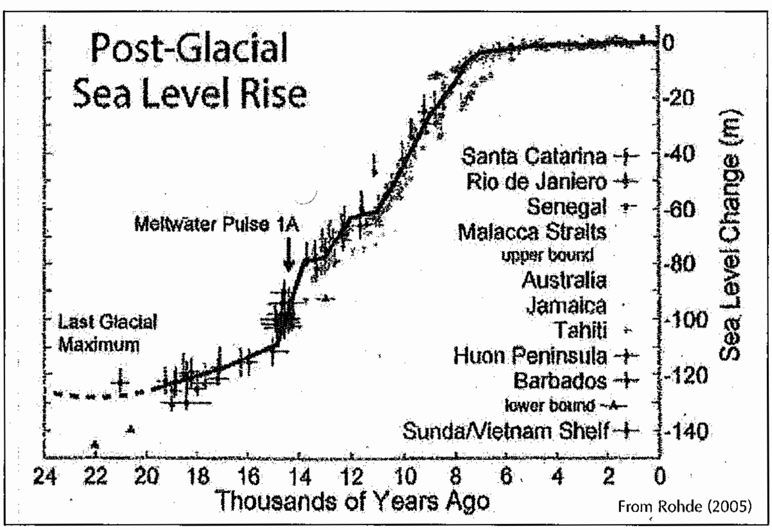


FIGURE 2-41. Global sea-level rise associated with the melting of ice after the last glacial advance.

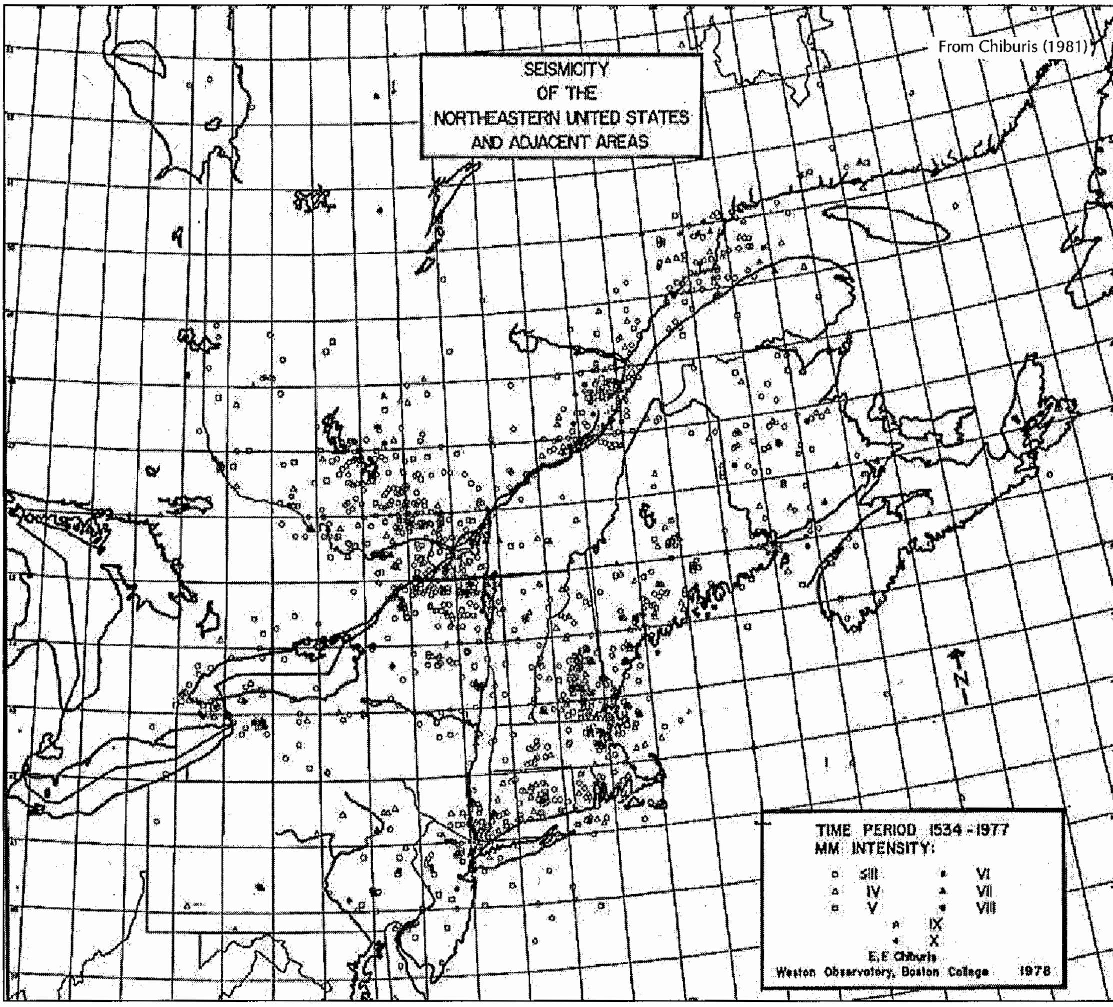


FIGURE 2-42. Map showing the seismicity of the northeastern United States and adjacent Canada from 1534 to 1977.

studies of a few individual earthquakes. De Montessus de Ballore (1898, 1906) assembled epicentral maps of the United States that Hobbs (1907) used to demonstrate the structural relations of earthquakes in the northeastern United States. This study was followed by the start of routine reporting of earthquakes of the region by the U.S. Coast and Geodetic Survey, the initiation of a seismograph network, more detailed descriptions of earthquakes and their effects, and a much better description of the distribution of earthquakes in the New England regions and adjacent Canada (Heck & Epply, 1958; Brooks, 1959; Smith 1962, 1966a & 1966b). Boston was placed in an unwarranted high hazard category (Heck, 1938) due to an error that placed the 1755 earthquake within metropolitan Boston (Devane & Holt, 1967). A study of many of the historic earthquakes of southern New England to improve intensity assignments and epicentral locations, as well as to assemble isoseismal maps, was a major contribution in the investigations for the Pilgrim Nuclear Power Plant site at Plymouth, Massachusetts, and the nuclear plant site at Seabrook, New Hampshire (Boston Edison Company, 1976a, 1976b & 1976c; PSNH, 1980). The Northeastern U.S. Seismic Network of the Weston Observatory, the Masscuhsetts Institute of Technology and the Lamont-Doherty Laboratory began a much needed expansion in the

1970s to improve the accuracy of epicentral locations for the detection of nuclear blasts and nuclear power plant safety. A vastly improved epicentral map and earthquake catalog up to 1980 was then produced for the Nuclear Regulatory Commission for the Northeast (Nottis, 1983). A new epicentral map added locations to 1998 (Wheeler *et al.*, 2000), but in magnitude values rather than in the more useful intensity values and at too small a map scale to be helpful. Recent epicenters are posted now on the Internet by the Weston Observatory and the USGS.

All of these records show well the locations of the larger earthquakes and point out the seismic source zones in the region, but the distribution of the small earthquakes can be misleading. Funding cuts have reduced the number of seismic stations in the Northeast and the unequal distribution of stations is reflected in the unequal distribution of the numbers of small earthquakes recorded. Many such events are recorded in the environs of New York City by a cluster of stations, whereas the single station in the region around Rhode Island misses many and makes determining accurate locations difficult. For example, a recent Rhode Island earthquake was mislocated (Barosh, 2006b) by 16 kilometers (10 miles).

Regional Distribution of Seismicity. The earthquake record for New England is the longest and most complete in the United States and displays several features. During the past four hundred years, earthquakes have been concentrated in certain areas, whereas other areas have remained very quiet. The instrumental record from the expanded seismic network shows the same pattern as the earlier felt events (Barosh, 1979b). The rate of activity within the more active areas may change from time to time (Shakal & Toksoz, 1977), but the areas have not. Thus, the record indicates that significant earthquakes occur in just certain areas and not just anywhere. Many of the scattered earthquakes outside these areas are shown to be spurious (Nottis, 1983) or frostquakes (Barosh & Smith, 1979 & 1982; Barosh, 1999b). The general active zones of the eastern United States were broadly outlined by Hadley and Devine (1974) by contouring the numbers of earthquakes per unit area (see Figure 2-43). The areas of relatively higher seismicity were next delineated in more detail (see Figure 2-43) by arbitrarily defining areas of MM intensity V and above (Barosh 1979b, 1981b, 1982c & 1982d). These areas were confirmed by Chiburis (1981) in a more statistical manner (see Figure 2-44) and reconfirmed by Ebel (1984) using only the post-1978 earthquakes. The general areas of relatively high activity appear well defined on detailed maps and as earthquakes become better located, the size of these source zones tends to diminish, but not always. These clusters of epicenters identify the major source areas in the region.

The seismically active area of greatest concern to Boston and the surrounding urban area is that centered near Cape Ann, to the north and northeast of the city. Other nearby active areas are located in Narragansett Bay and adjacent southeastern Massachusetts, around Moodus in south-central Connecticut and along the Merrimack River valley and central part of New Hampshire. The more distant La Malbaie area on the St. Lawrence River, northeast of the city of Québec, is by far the most active area in the broader region and the site of the largest earthquakes (Smith, 1962; Chiburis, 1981; Nottis, 1983), which have caused damage in the Boston area (see Figure 2-44).

The earthquakes tend to be very shallow and, as a consequence, produce noises. Most of those whose depths have been determined are less than 10 kilometers (6 miles) and many are of only a few kilometers. A suggestion that the larger, more destructive earthquakes were much deeper (Acharya, 1980a & 1980b) has not proven to be so (Stevens, 1981). The shallow nature of the seismicity and the generally moderately to steeply dipping geologic structure indicates that the seismicity should be closely related to the surface geology, which is indicated by its relation to geomorphic features, which are structurally controlled. Most of the earthquakes in the northeastern United States and adjacent Canada are concentrated (see Figures 2-43 & 2-44) in bays, river estuaries and along a few north- and northwest-trending river valleys. The great majority occur in lowlands, below 300 meters (984 feet) altitude, with some upland activity taking

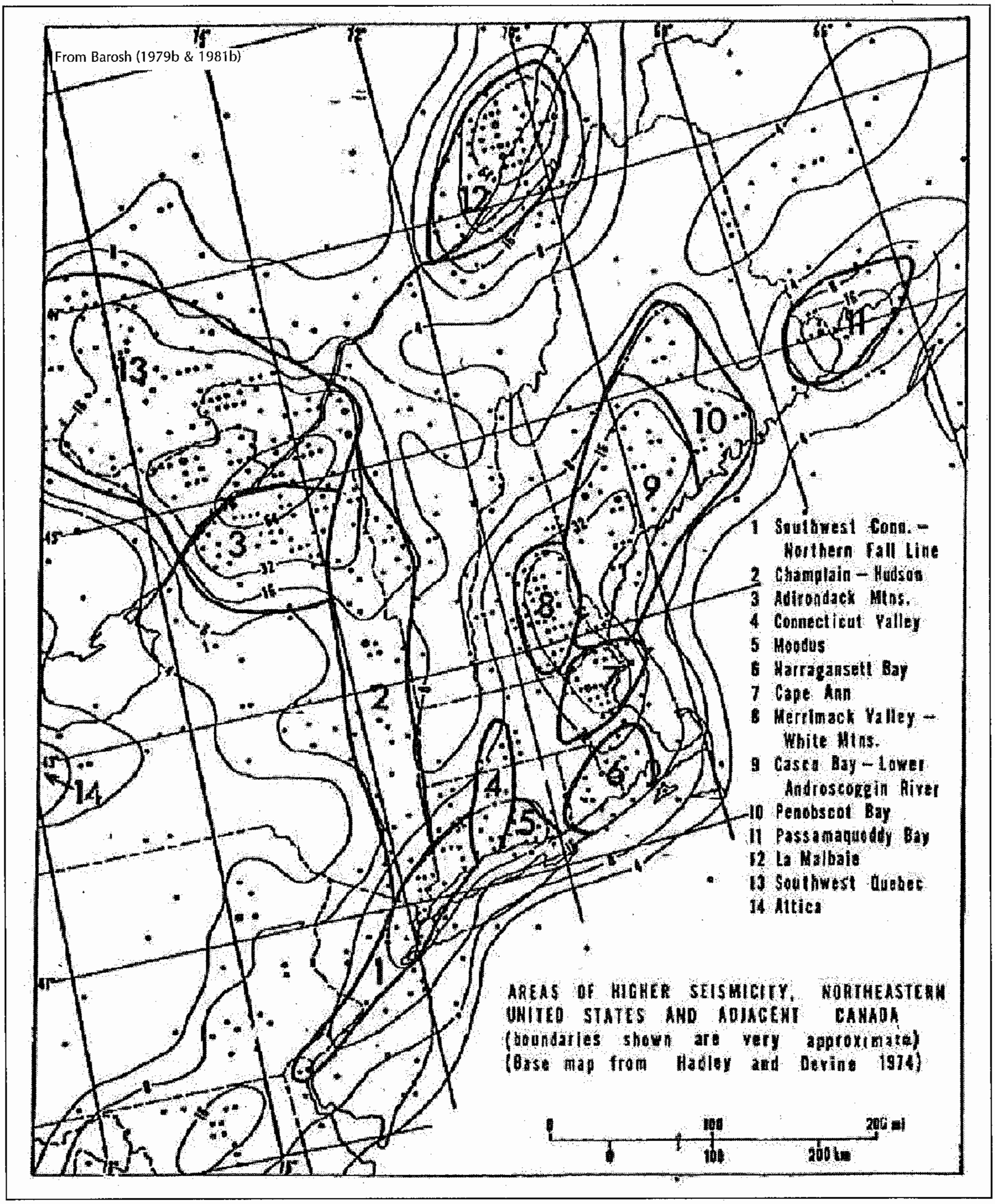
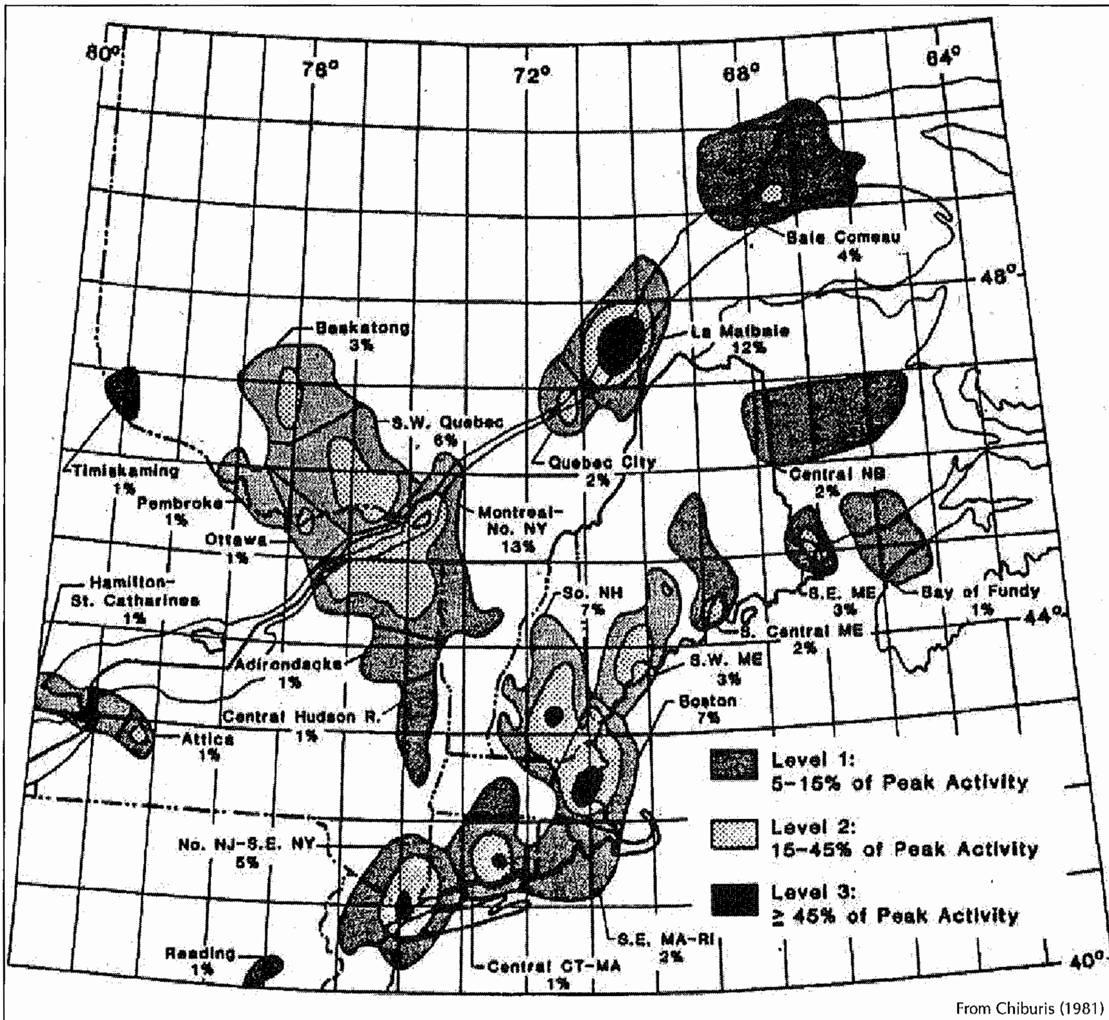


FIGURE 2-43. Map of the northeastern United States and adjacent Canada showing areas of relatively higher seismicity.

place in the Adirondack Mountains, the southern edge of the White Mountains and central New Brunswick (Barosh, 1979b).

Cause of Seismicity. "Earthquakes, the effects of God's wrath" (Burt, 1755) was preached widely across New England following the earthquakes of 1727 and 1755, but the later event also spawned a more rational evaluation (Winthrop, 1755) and other specific causes have been argued since. Several dif-



From Chiburis (1981)

FIGURE 2-44. Map of the northeastern United States and adjacent Canada showing sub-regions of seismicity between 1534 and 1977 contoured at three levels of relative activity and their percentage of the overall activity.

ferent causes have been proposed for earthquakes in New England and elsewhere in the eastern United States. Earthquakes have been ascribed to volcanism, glacial rebound (Leet & Linehan, 1942), rebound from a meteorite impact, granitic plutons (Collins, 1927; Billings, 1956), basic plutons (Kane, 1977; Long & Champion, 1977; Simmons, 1977; Leblanc *et al.*, 1982), reactivation of ancient deep thrust faults (Behrendt *et al.*, 1981; Seeber & Armbruster, 1981), reactivation of Triassic rifts (Page *et al.*, 1968; Ratcliffe, 1971 & 1980; Sykes *et al.*, 2008), Post-Cretaceous reverse faulting (Wentworth & Mergner-Keefer, 1980), northeast-southwest oriented compression (Zoback & Zoback, 1980), pure random occurrences with present earthquake clusters being aftershocks (presentation by Devine, 1982; Ebel, 2008), a hypothetical Boston-Ottawa seismic zone (Hobbs, 1907; Sbar & Sykes, 1973) and intersections of major structural zones (Hobbs, 1907; Barosh, 1986d & 1990a). All of these studies fail the test of adequately matching the distribution of seismicity, except for the last. Several of these proposed causes were an attempt to provide a non-fault explanation (the folding theory as discussed above in the section on the Sturbridge Terrane) prior to the knowledge of the extensive faulting in the region (Bell, 1967; Barosh, 1976d & 2005; Barosh *et al.*, 1977a). Others attribute all seismicity to one simple type of structure without adequate consideration for the complex interrelations of geologic structure and tectonic movements. The pattern of seismicity shows no relation to post-glacial rebound, which is long over; the activity extends across the area of rebound into the southern states and there is no evidence that such movement is continuing. The Boston-Ottawa seismic zone was proposed as a broad northwest-trending zone with seismic activity passing through Boston and Ottawa, Ontario. This proposed zone provides only a partial explanation since the proposed zone crosses both seismically quiet and active areas and its relation with seismicity is complex. However, in almost all these causes, the critical geologic structures have not been shown on published geologic maps and seismologists have, therefore, had to theorize at possibilities.

The major earthquakes of southeastern New England were located offshore and none of the smaller onshore ones have had any known surface faulting associated with them. The region is known to be intensely faulted, but most of these faults are quite ancient and active faults are difficult to prove. The suggested relation with northeast-trending Triassic faults, such as the Ramapo Fault of New Jersey and New York, arose from their being considered the youngest in the region. The Ramapo is still considered active in a recent evaluation of the seismicity of the New York City area (Sykes *et al.*, 2008), but it is offset by younger faults, and studies for the nearby Indian Point Nuclear Power Plant nearly thirty years ago demonstrated that this fault was inactive (Dames & Moore, 1977). Post-Early Jurassic faults are found to be very common where looked for in and near southern Rhode Island (Frohlich, 1981; Barosh, 1999a). However, these and the earlier fault evaluations were not included in a recent summary by Wheeler (2006).

Very small post-Pleistocene offsets of bedrock surfaces have been found across the region (Woodworth, 1907; Adams, 1981). However, a number of factors make it difficult to show that most small offsets are tectonic in origin: the documentation of ground cracking accompanied by shaking, which may reach MM intensity V, due to deep freezing of the ground in the region (Barosh & Smith, 1979 & 1982; Barosh, 1999c); offsets from residual-strain release from unloading; and, possible freeze-thaw fissures and collapse in glacial deposits. Confusion also can result if unreliable focal-plane solutions are used in the region.

The high residual strain in the pre-Silurian rock of the region from the plate collision may cause rocks to move when they are uncovered and surface rocks to buckle into "pop ups." This phenomenon has been directly observed or measured in quarries and road cuts. The movement takes place along old fractures and is commonly mistaken for, and reported as, recent fault offset. Studies on regional stress for earthquake hazard evaluation using borehole measurements (Zoback & Zoback, 1980) made this mistake and report ancient strain release as the present-day tectonic stress (Barosh, 1986c). However, the fact that the rock in the region holds this high residual strain probably affects its response to present tectonic stress and is a factor why eastern earthquakes are different from western ones.

The neotectonic movements causing most earthquakes in the eastern United States are related mainly to subsidence and this appears to be the case in southern New England. Here, the events are related to northwest- and north-trending faults; the youngest sets found in the region (see Figure 2-45). In a broad sense, this movement is most closely related to the transverse arches and embayments of the coast. Within these areas in the region, most earthquakes happen at fault intersections along the northwest-trending faults as indicated in 1907 by Hobbs (Barosh, 1990a). A zone of northwest-trending faults across New Hampshire, which is part of the Ottawa-Boston zone, extends offshore east of Boston through the New Hampshire embayment and epicentral area of the 1755 Cape Ann Earthquake, which had a probable MM intensity of VIII and an estimated body wave (m_b) magnitude of 5.8; the largest one recorded for the northeastern United States.

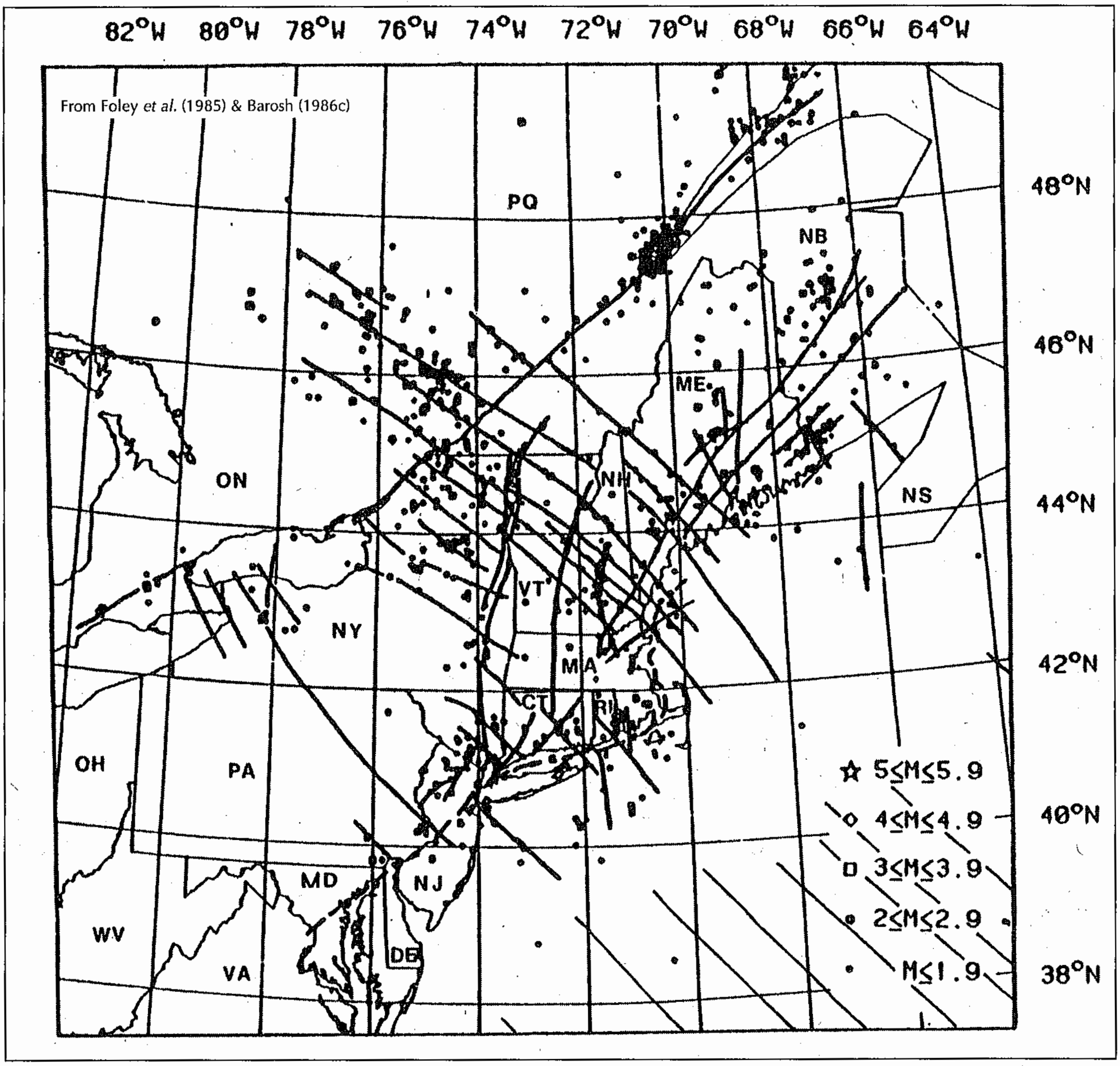


FIGURE 2-45. Map of New England and adjacent areas showing earthquake epicenters for the period October 1975 to March 1984, generalized fault and probable fault zones spatially related to earthquakes (solid lines), and border of the coastal plain deposits (dashed line).

This coastal embayment appears controlled by a system of northwest-trending fault zones. A broad largely unmapped northwest-trending system forms a broad zone, the Winnipesaukee-Winooski Lineament zone, that extends from the northeast side of the Adirondack Mountains, along the Winooski and other rivers of central Vermont, across the Winnipesaukee Lake area of New Hampshire and continues out to sea northeast of Cape Ann (Barosh, 1976a, 1982b, 1986b & 1986c). Hobbs (1904) apparently recognized some of the topographic lineaments along this zone. It consists of some mapped faults and topographic, bathymetric, LANDSAT and geophysical lineaments, that indicate many more (see Figures 2-33 & 2-45). Several individual fractures within the zone are shown to have post-Cretaceous movement (Freedman, 1950; Barosh, 1992) and some have alignments of epicenters along them (Barosh, 1986b, 1986c & 1986e). The zone passes through the most active seismic area in New Hampshire, the site of the 1940 Ossipee earthquakes, and the active area off Cape Ann. However, the zone does not appear active along its entire length and does not constitute a simple "Boston-Ottawa seismic zone" as described by Sbar and Sykes (1973). The seismic activity in New Hampshire may be due to intersections with north-trending faults along the Merrimack River valley and there also may be a controlling intersection off Cape Ann. Cape Ann itself is cut by many post-Ordovician northeast-trending faults (Dennen, 1981) and the Nashoba Thrust Belt, the largest Paleozoic structural zone known in New England, passes out to sea north of this cape (see Figure 2-12). These structures are very old, and although parts of the thrust belt were reactivated during the Mesozoic, the major fault in the belt, the Clinton-Newbury, is cut by both north- and northwest-trending faults. The Nashoba Thrust Belt itself shows no indication that it is an active structure, but it might aid strain buildup where crossed by the younger faults. The only other known seismicity close to it is near Moodus, Connecticut, where it also is crossed by a zone of northwest-trending faults.

A zone of northwest-trending lineaments, defined by both bathymetry and sediment distribution, is present off Cape Ann along the projection of the Winnipesaukee-Winooski Lineament Zone. The most prominent of these lineaments passes between the east end of Cape Ann and the southwest end of Jeffrey's Ledge, a submerged ledge that lies to the northeast; it may well represent the fault zone that caused the 1755 earthquake. The peripheral earthquakes may be caused by local adjustments on various faults due to the subsidence. These relations are similar to those found elsewhere along the Atlantic Coast (Barosh, 1986d & 1990a).

The apparent structural and tectonic controls of earthquakes in New England can explain the irregular distribution of activity as shown by the history of seismicity in the region. These relations do not suggest any new areas of potential activity. The concept of "seismic gaps," quiet areas that may be building up strain between seismically active ones and therefore constitute sites for future large earthquakes, does not apply to New England. This concept applies only to gaps within a single active zone, not to gaps between separate active zones or ones controlled by structural intersections. Nor can fault length be used to indicate the size of a potential earthquake, where only some segments of a fault are active.

The great majority of earthquakes are too small to cause post-Pleistocene fault offset and the epicenters of the larger ones usually are along submerged faults (Barosh, 1986c). These occurrences make the recognition of specific active faults in the region difficult, especially since relatively few faults are mapped. The greatest problem in recognizing such faults remains the lack of fault investigations and tight epicentral control. A great number of post-Early Jurassic faults are present and topographic expression across some of them suggest offset, as in seismic surveys of normal faults in Lake Champlain and Lake George. A few faults are now sufficiently related to earthquakes and their effects to be considered active. These faults include a northwest-trending one in southwestern Pennsylvania (Alexandrowicz & Cole, 1991) and one in the Sakonnet River channel in Narragansett Bay (Barosh, 2006c). The latter occurred near a submerged fault intersection along a northwest-trending fault (see Figure 2-32), which is expressed on the bedrock surface and bottom bathymetry and aligned with an isoseismal pattern (Barosh, 2006b). The seismicity in New England is found related to movement along post-Early Jurassic north-trending extensional faults and northwest-trending ones, most notably at fault intersections, with the driving force being the continuing opening of the North Atlantic Basin.

Geology of the Boston Basin

The enormous amount of new data has helped to unravel the complex and often intriguing geology of this unique area.

PATRICK J. BAROSH & DAVID WOODHOUSE

Boston Basin is an ancient fault-bounded structural and topographic basin in a region with a long involved geologic history (see Figure 3-1). Boston lies in the midst of this lowland facing both inland over

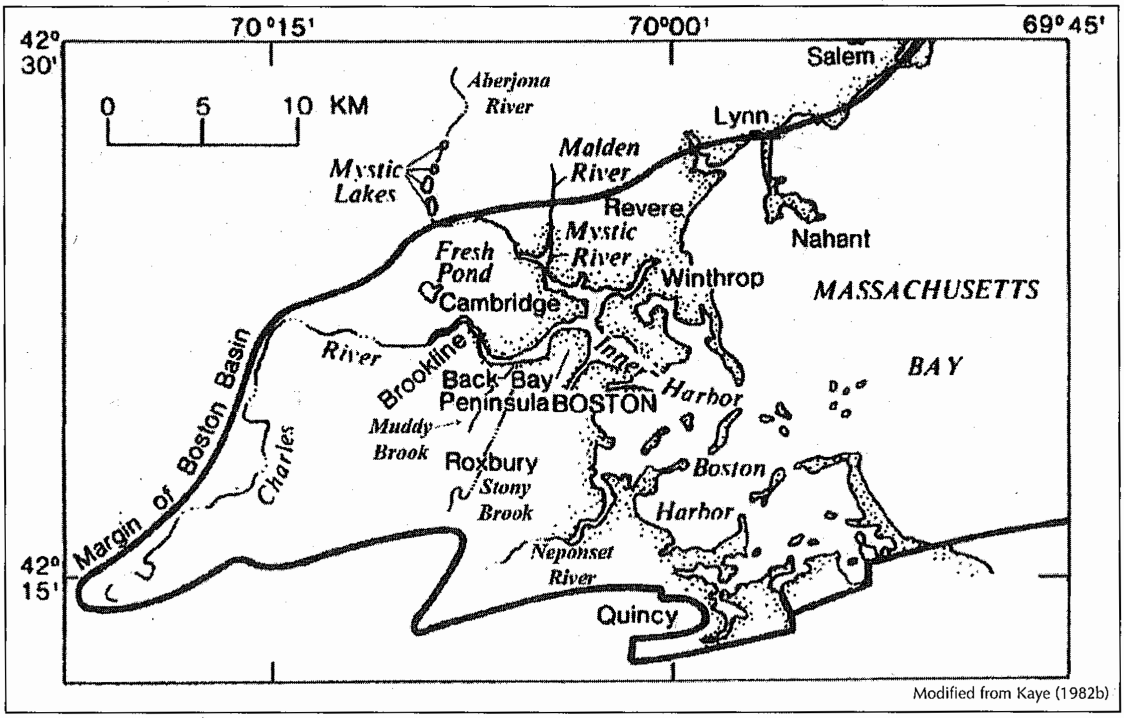


FIGURE 3-1. Outline of the Boston Basin and its major rivers and streams.

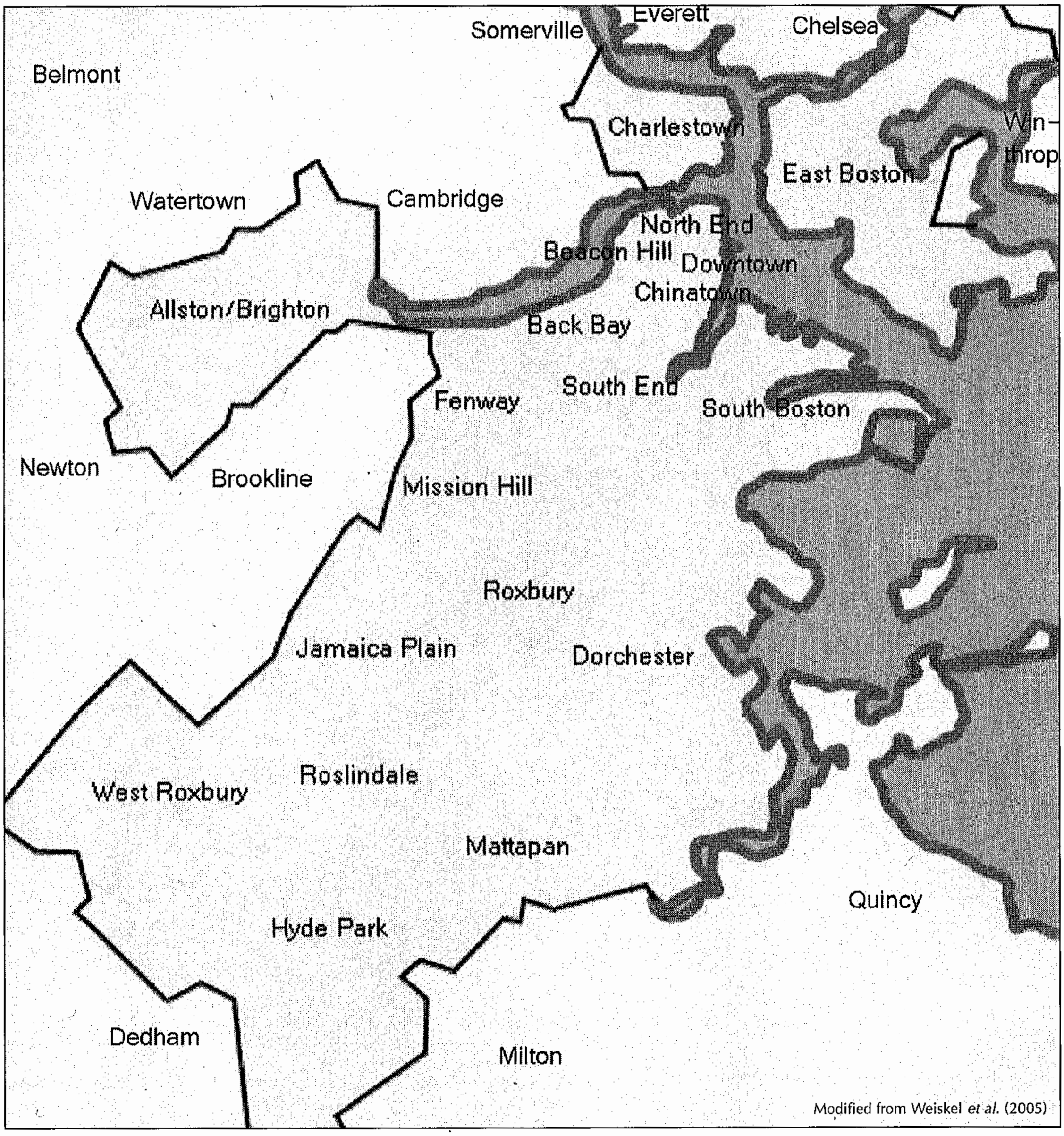


FIGURE 3-2. Boston and adjacent towns in the Boston Basin.

the Charles River and seaward across the islands of the harbor that stretch out eastward (see Figures 3-2 & 3-3) — a prospect that greatly pleased the Puritans. The Charles River is joined by the Mystic River from the north, along with other rivers, to form the inner Boston Harbor, but few rivers enter the basin from the south. Many small streams drain the area near the city, although they are easily overlooked in their concrete conduits and are rarely noticed, except in parklands, where glimpses of the natural beauty of the setting may still be found (see Figure 3-4). Today, it is the man-made beauty of the mix of mellow nineteenth-century townhouses, civic buildings and new skyscrapers, joined by historic homes and spreading campuses that are admired. All of these buildings rest on what is perhaps the most complex geology of any North American city.

Boston is located near the center of the Boston Basin — a wedge-shaped, down-fault-

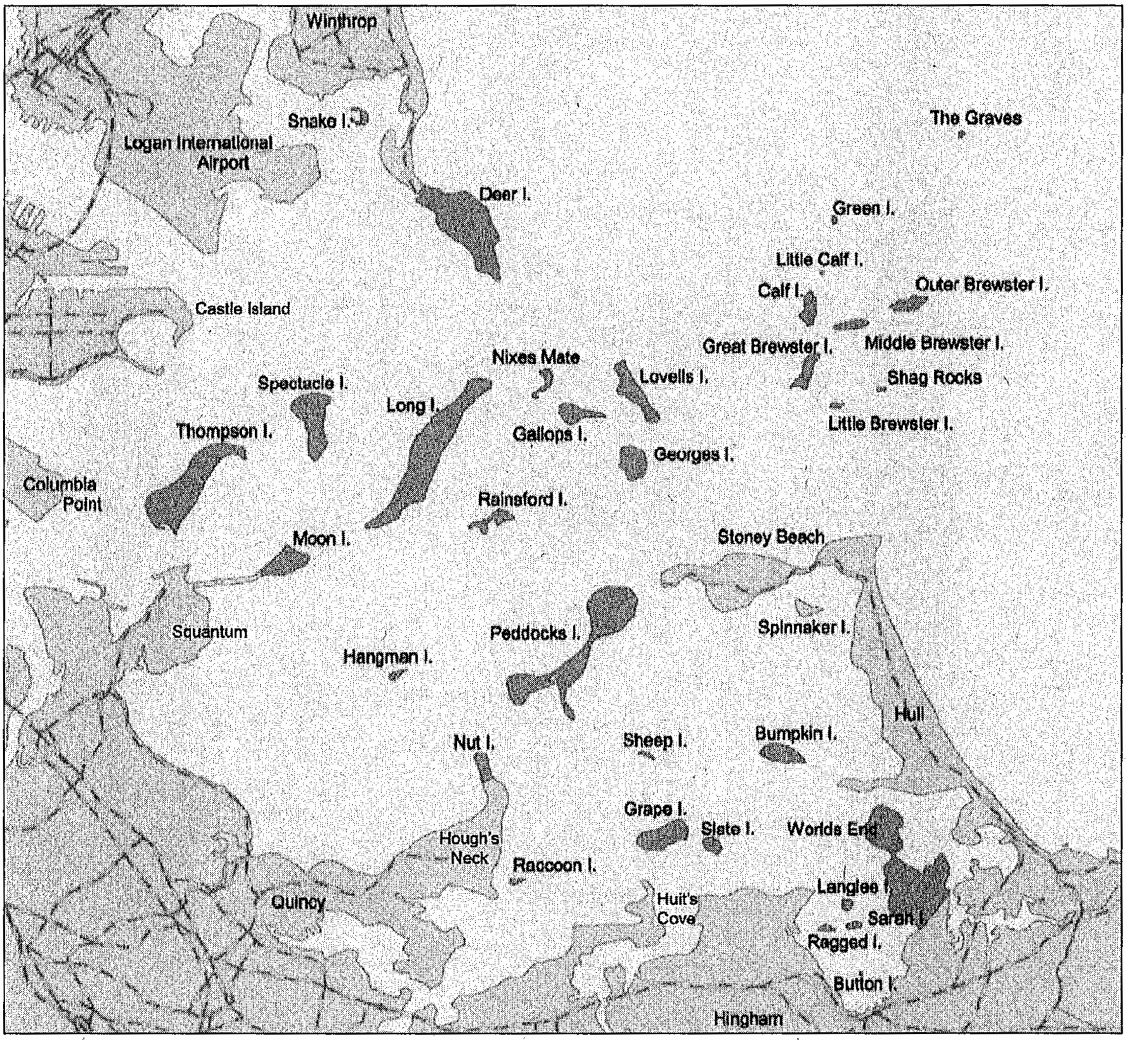


FIGURE 3-3. Map of Boston Harbor and islands. (Courtesy of the National Park Service.)

ed body of slightly metamorphosed sedimentary and volcanic rock that is flanked on the north, south and west by various granitic rocks and invaded metamorphosed strata (see Figure 3-5). Two hundred years of geologic mapping now provide abundant data on the bedrock and surficial geology of the Boston Basin and its borders. This mapping has made steady progress in the understanding of the basin, despite conflicting theoretical concepts. In this description, the elevations given refer to mean sea level (MSL for the National Geodetic Vertical Datum, NGVD). This reference point is different from the commonly used Boston City Base (BCB) which sets 0.0 feet elevation at –1.72 meters (–5.65 feet) below MSL, which was at about mean low water, to keep most measurements in positive numbers in city construction. (Elevations given in MSL are therefore 1.72 meters [5.65 feet] below the BCB elevation.)

The basin is larger than first appears because less than half is above water. The Boston Basin measures about 24 kilometers (14.5 miles) north to south at the coast and widens offshore to the east under Boston Harbor (see Figure 3-1). Farther eastward beyond the harbor, irregularities in the seafloor topography suggest that basin structures continue across Massachusetts Bay to their burial beneath the thick Pleistocene deposits of Stellwegan Bank (Ballard &

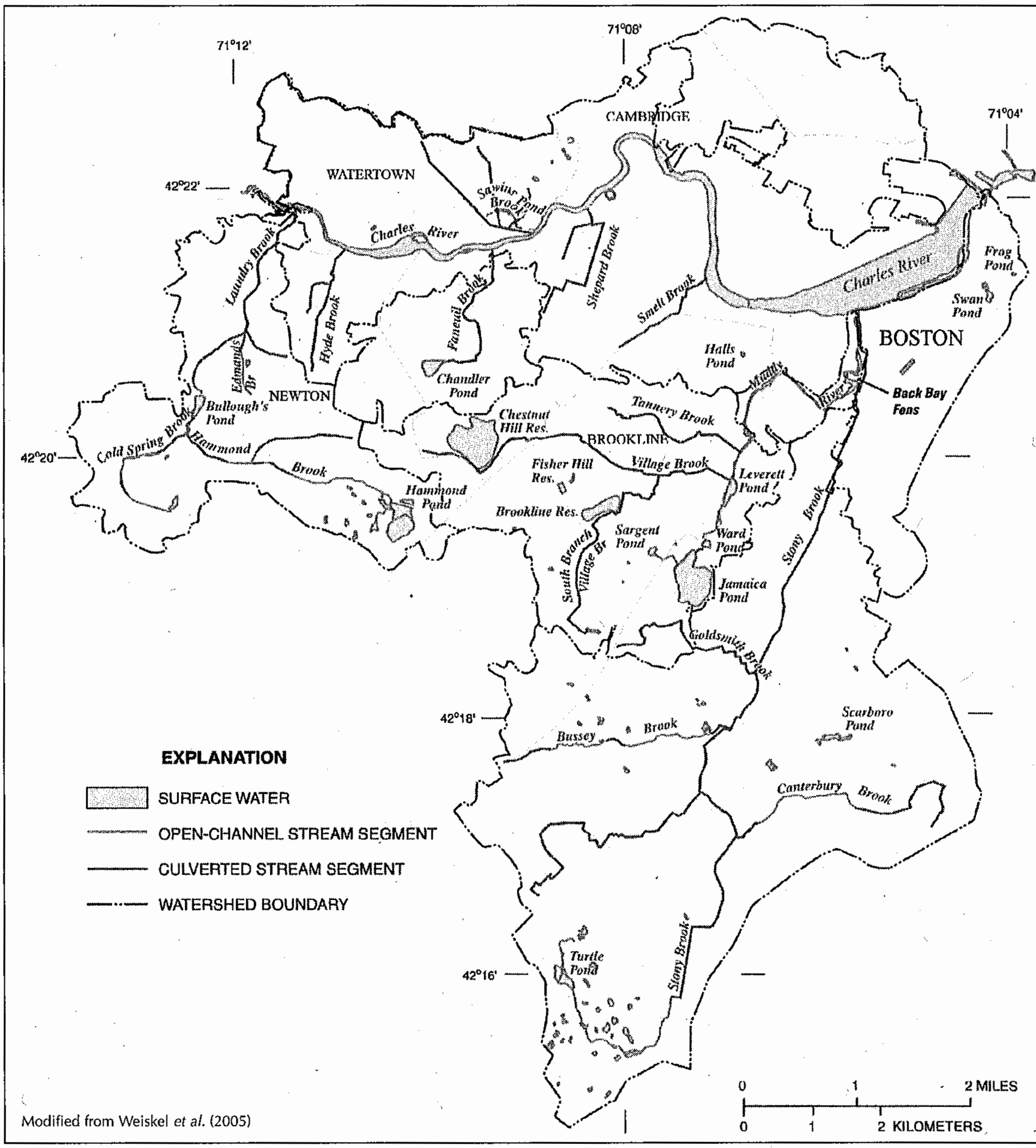


FIGURE 3-4. Map showing rivers and streams in the lower Charles River watershed.

Uchupi, 1975; Schlee *et al.*, 1973; Oldale & Bick, 1987). The basin fill tapers to a point about 29 kilometers (18 miles) west-southwest of Boston. However, longitudinal faults, which are the principal structural control of the basin, continue another 25 kilometers (15 miles) west to the Bloody Bluff Fault Zone (Nelson, 1975a & 1975b; Barosh, 1977a & 1977b). The surface of the central Boston area is mostly low lying, rarely exceeding an elevation of 15 meters (49 feet) MSL, except for several drumlins that reach elevations of almost 61 meters (200 feet) MSL and a high standing bedrock area in the southwest that rises to an elevation of about 30 meters (100 feet) MSL. The lower portions of the rivers originally meandered through low-lying tidal land that consisted of extensive salt marshes and mudflats (Kreiger & Cobb, 1999). The mudflats that were filled in during the late nineteenth cen-

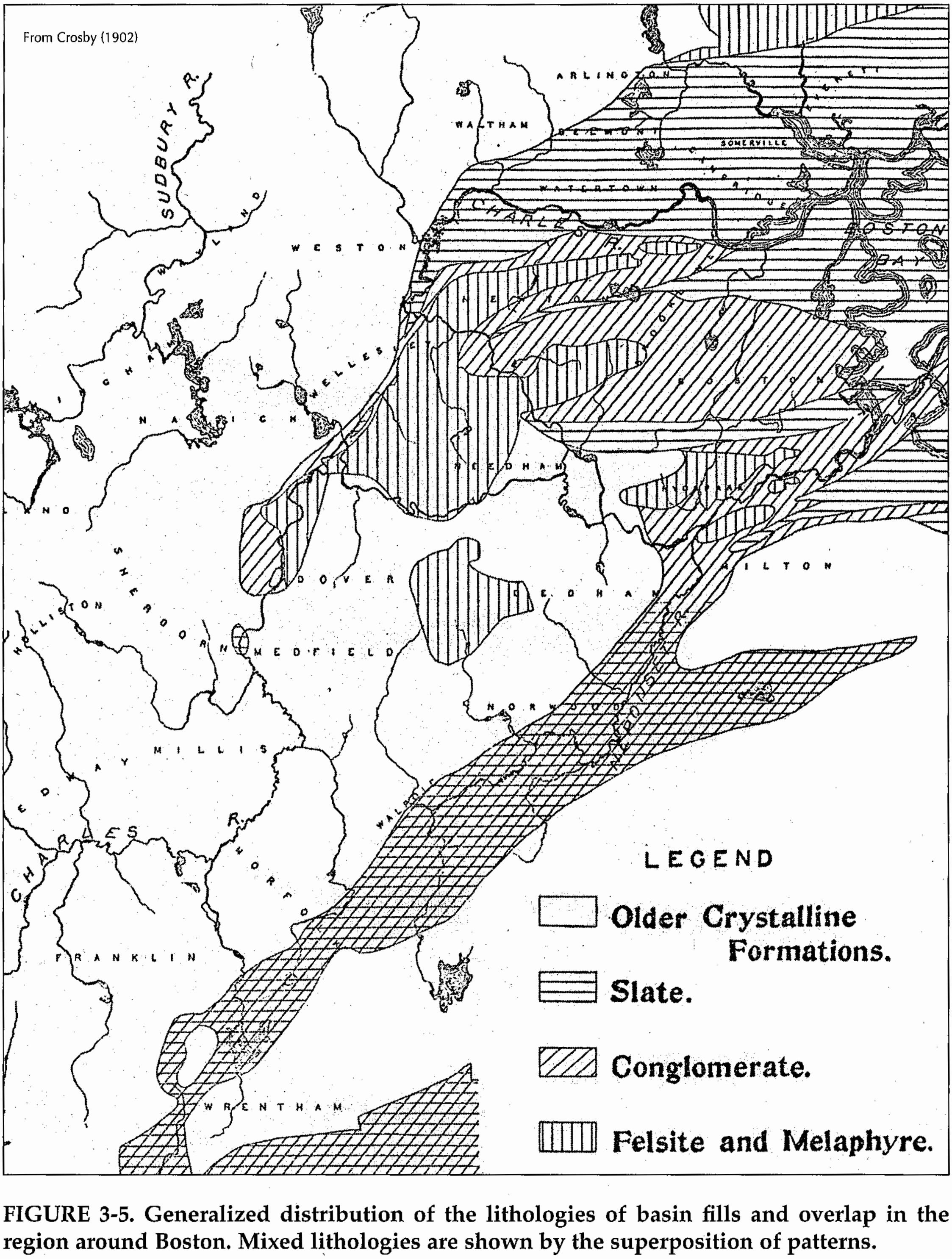


FIGURE 3-5. Generalized distribution of the lithologies of basin fills and overlap in the region around Boston. Mixed lithologies are shown by the superposition of patterns.

tury on the south side of the Charles River have a present ground elevation of about 3.15 to 3.76 meters (10.35 to 12.35 feet) MSL in Back Bay (Lambrechts, 2012) and those filled on the northern side in Cambridge support the Massachusetts Institute of Technology (MIT) at a similar altitude (Whitehill, 1968; Aldrich, 1970; Kaye, 1976a).

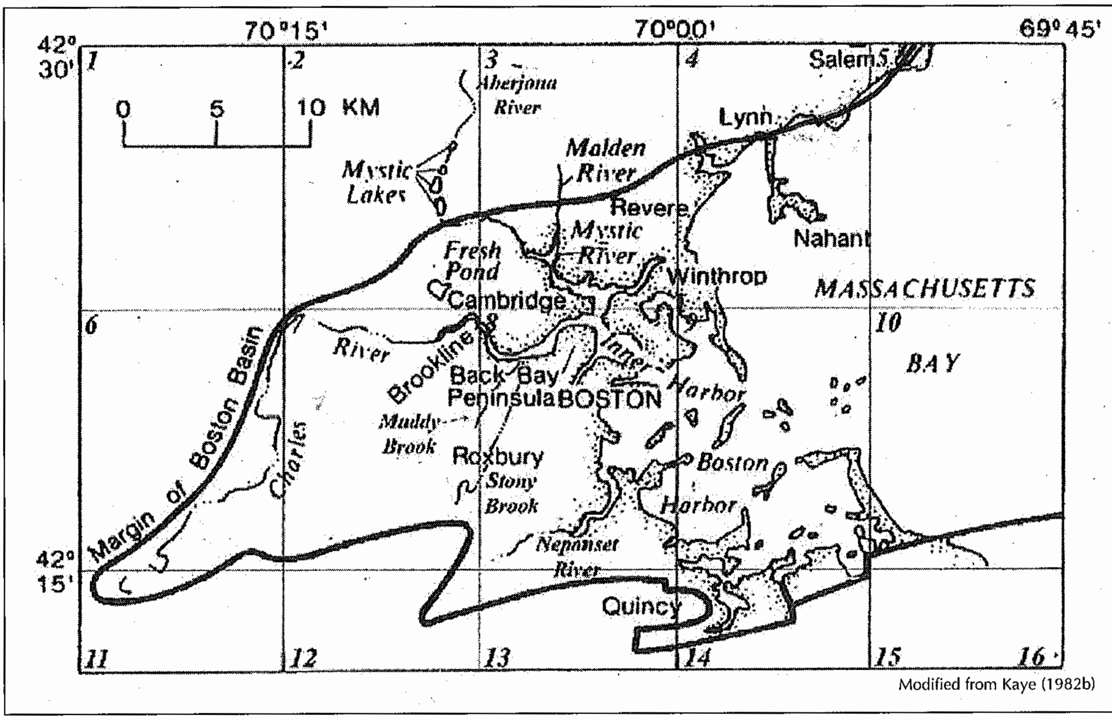


FIGURE 3-6. Map showing the border of Boston Basin with included towns and rivers, plus an index of 1:24,000 scale quadrangle maps. The numbers indicate the quadrangle maps listed in Table 3-1.

The basin contains a wide variety of only slightly metamorphosed rock, which has highly intricate stratigraphic and structural relations, overlain by glacial materials of such complexity that their study ultimately led to the development of soil mechanics as a science in this country. Many outstanding geologists have contributed to the understanding of the basin, but the work of Crosby at the turn of the nineteenth century, LaForge in the first part of the twentieth century, and Kaye and Bell in the latter part of the twentieth century stand out. Kaye (1980b) prepared a preliminary detailed geologic map at a scale of 1:24,000 and several reports summarizing much of this complex geology (Kaye, 1976a, 1976b, 1976c, 1978 & 1982b). These reports are further summarized below, along with findings from the work in the surrounding quadrangles (see Figure 3-6 & Table 3-1) and the immense amount of new data from construction projects in and around the city. The quadrangle geologic maps are a proud accomplishment of the old United States Geological Survey (USGS) and the fact

TABLE 3-1.
Boston Area Bedrock Geologic Quadrangle Maps

No.	Name	Reference
1	Concord	not compiled
2	Lexington	not compiled
3	Boston North	Kaye (1980a)
4	Lynn	Bell (1977)
5	Marblehead South	Bell (1977)
6	Natick	Nelson (1975a)
7	Newton	Kaye (1980a)
8	Boston South	Kaye (1980a)
9	Hull	Bell (1975b)
10	Nantasket	Bell (1975a)
11	Medfield	Volckmann (1977)
12	Norwood	Chute (1966)
13	Blue Hills	Chute (1969)
14	Weymouth	not completed
15	Cohasset	not completed
16	Scituate	Chute (1965)

Note: Locations shown in Figure 3-6 by the number listed here.

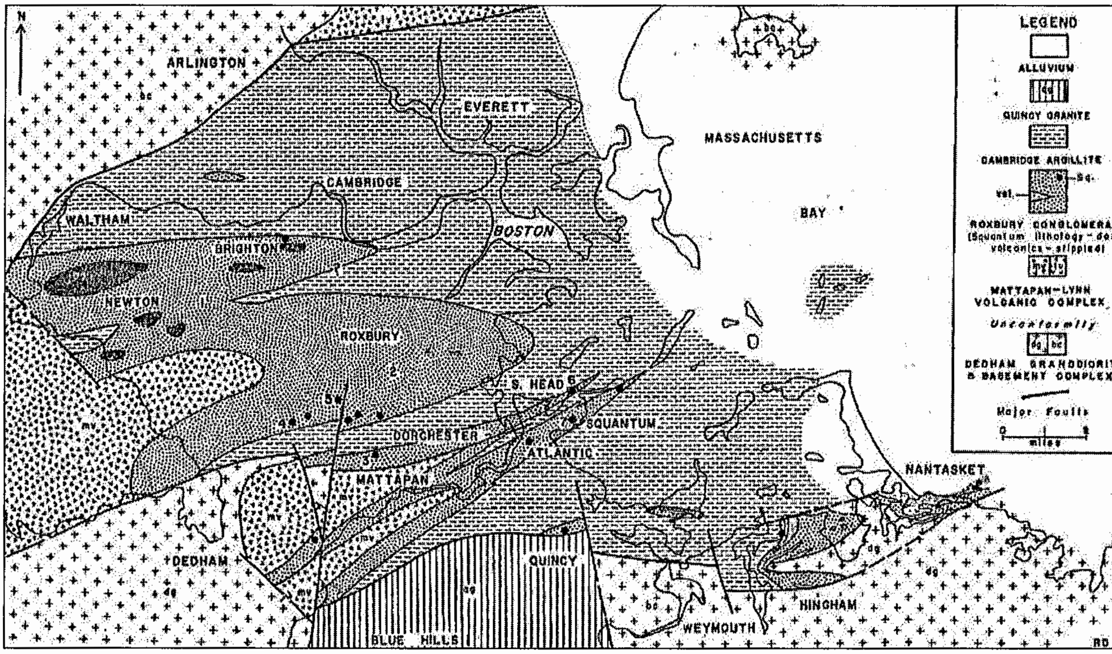


FIGURE 3-7. Simplified geologic map of the Boston Basin by Dott (1961), after LaForge (1932), showing the generalized distribution of lithologies and locations of stratigraphic studies.

that most have not been completed in final form and published is a task yet to be accomplished by the current USGS.

Unraveling Bedrock Geology

The elongate east-plunging Boston Basin is strikingly asymmetrical in its topography, stratigraphy and structure in a north-south profile. The north side of the sedimentary trough forming the basin is cut off sharply against the Northern Boundary Fault, but the southern side is very ragged and some of the bounding faults extend into the Norfolk Basin to the south (see Figure 3-7). The sedimentary framework reveals that the basin was one-sided with active faulting on the south side, which provided the source material and, thus, controlled almost all of the deposition along with controlling the position of volcanic activity. In general, the deposits begin with the Mattapan Volcanic Complex, which is overlain by an intertonguing mixture of the Boston Bay Group comprised of the Roxbury Conglomerate and Cambridge Argillite along with the Brighton Basalt (Melaphyre) that both intrudes and lies as beds within the conglomerate (see Figure 3-8). An easterly slope of the basin causes the older strata to be widespread in the west and the younger to dominate in the east. This tilt also may have played a part in the sedimentation. Remnants of Cambrian strata lie at the edges of the basin and are invaded on both sides by Late Ordovician volcanic complexes that are overlapped on the south by the Lower Pennsylvanian strata of the Norfolk Basin. The Boston Basin fill is very complex with facies changes over short distances that can only be understood in three dimensions (see Figure 3-9). The strata change northward away from the source, as well as laterally along the south side and vertically as the bordering faults are buried (see Figure 3-10). Similar features are present in the basin of almost the same age near Saint John, New Brunswick (see Figure 3-11). In addition, volcanic material is locally interbedded at different horizons. Understanding and placing this highly variable lithology into formal stratigraphic nomenclature has been a challenge. Nomenclature problems arose early from both an incomplete understanding of the units and in oversimplifying relations before these relations were solved, in the most part, by more detailed studies of the stratigraphy and sedi-

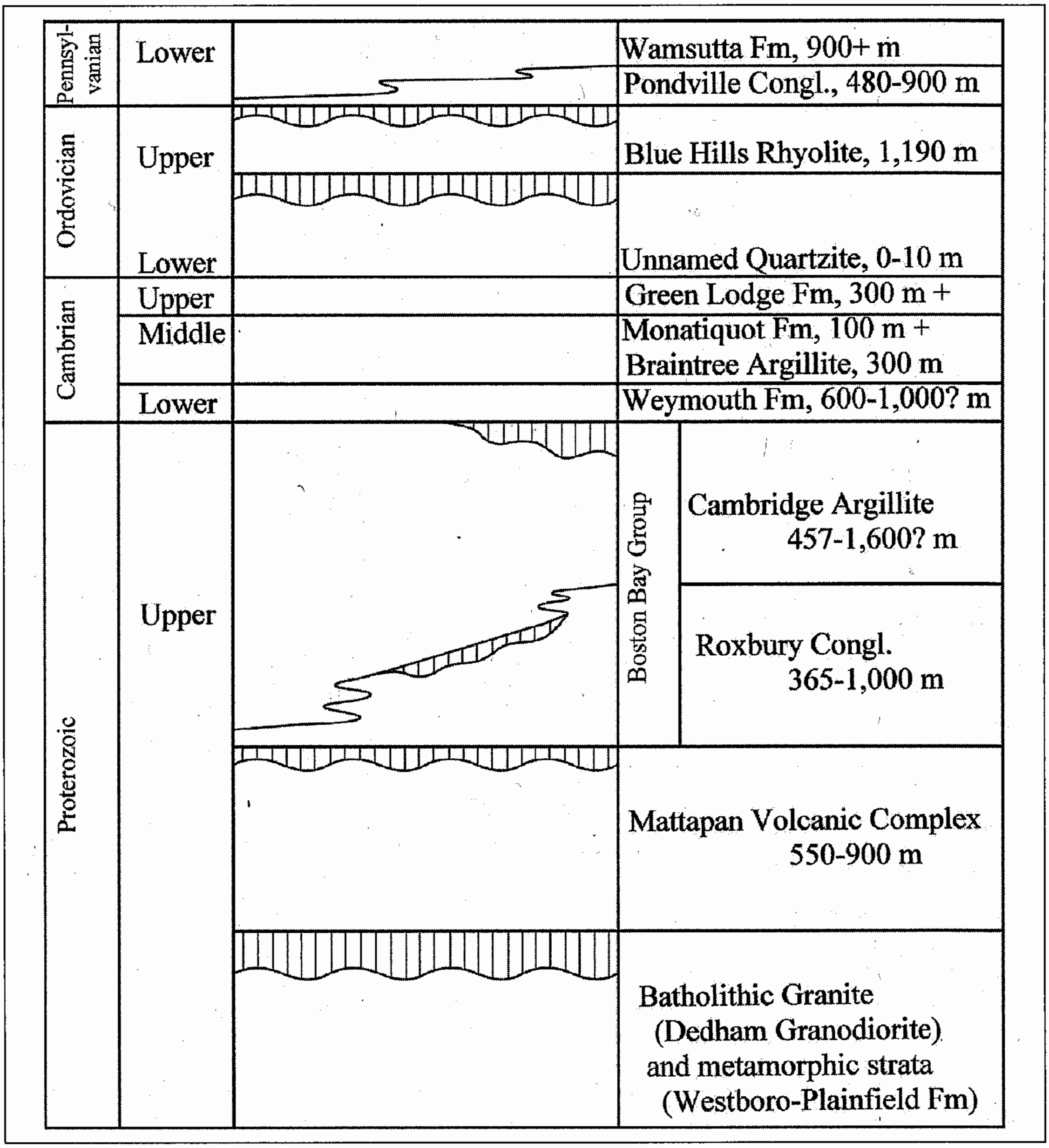


FIGURE 3-8. Stratigraphic column for the Boston Basin.

mentary structures. Confusion now is caused by continuing the old concepts, as well as the recent application of radiometric ages since they lack the accuracy needed.

There have been several stratigraphic problems relating to the Boston Basin fill: the age of the strata, the Squantum "tillite," the relation of the Cambridge Argillite with the Roxbury Conglomerate and the relation of these strata with the Cambrian strata. These problems are all important in the unraveling of the basin structure and its tectonic history. The age of the volcanic and sedimentary fill of the Boston Basin was long a matter of debate. Fossils are scarce and outcrops of the argillite are limited and widely scattered, although the conglomerate outcrops are common in the central, western and eastern parts of the basin. By the second half of the nineteenth century, Early Cambrian and Middle Cambrian fossils were

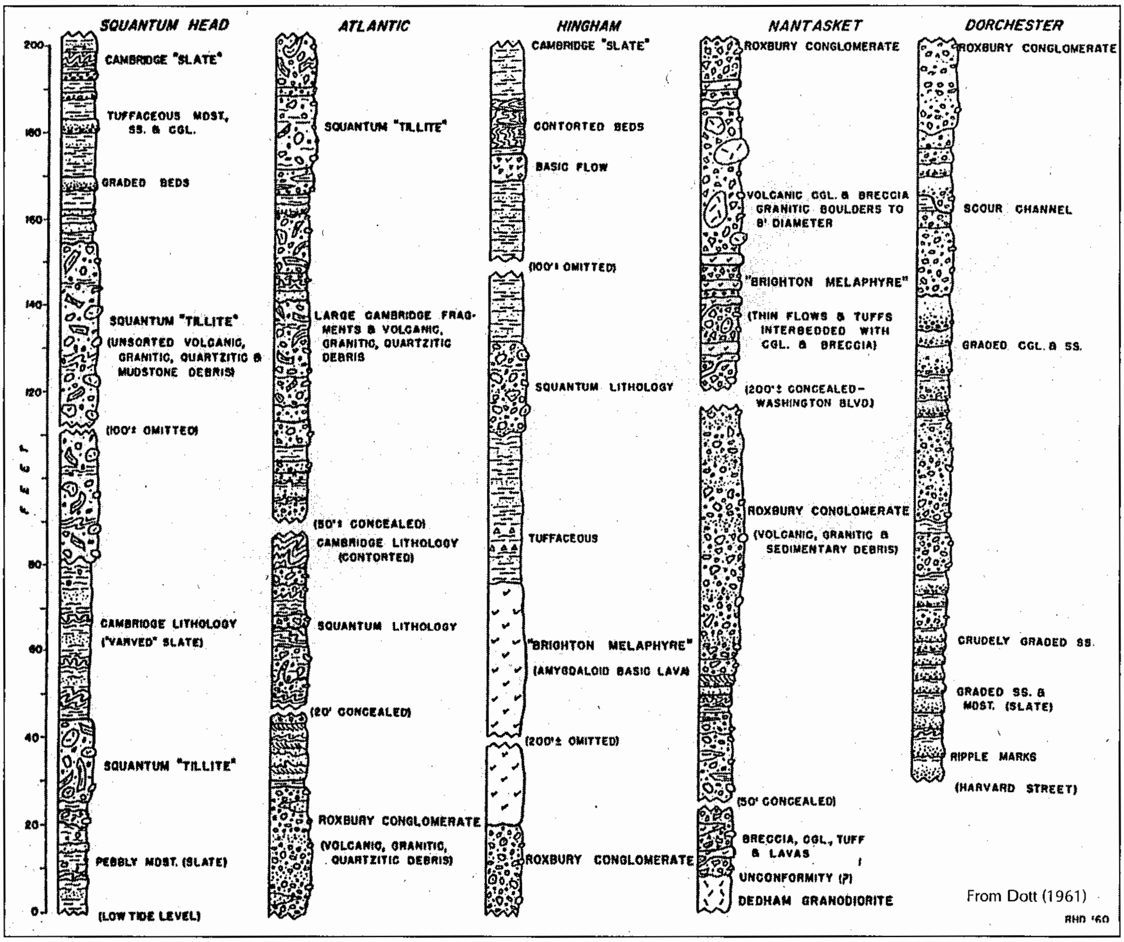


FIGURE 3-9. Stratigraphic sections along the southern side of the Boston Basin demonstrating large local variations.

known from the margins of the basin, especially in the Weymouth-Braintree and Nahant areas (Bailey, 1984), and fossiliferous Early Cambrian debris was found on Georges Island within the basin (see Figure 3-3). The rest of the basin appeared barren of fossils, but some strata in both the Blue Hills in the south and Malden in the north are identical to the fossiliferous rock (Crosby, 1880). At first, the entire basin was thought to be Cambrian and lie under the fossiliferous strata on the basis of sedimentary features, but later the prevailing view was that the basin was perhaps Devonian-Carboniferous or Carboniferous-Permian by making a match between the Roxbury Conglomerate and Pennsylvanian Conglomerate in the Norfolk and Narragansett basins south of the city. This view was reinforced by supposed fossil tree trunks, suggestive of the Devonian-Permian fossil remains of *Cordaites* or *Collixlon* found in the argillite (Burr & Burke, 1900). However, further investigations by Bailey *et al.* (1976) and Barghoorn (in Lenk *et al.*, 1982) reached the conclusion that these structures were inorganic and that the strata in these basins did not match (Dott, 1961). This younger date supposed that the Cambrian strata represented fault blocks of older terrain. Others felt that a similarity of some Mattapan Volcanic Complex in the basin with the Lynn Volcanic Complex (which is associated with granite dated as Late Ordovician granite) suggested that the basin strata were Ordovician. This problem was compounded when tuff related to the Late Ordovician Quincy Granite was included with the Mattapan along with the Brighton in places. Now the basin fill is proven to have been deposited at the very end of the Proterozoic and to lie beneath the Lower Cambrian strata, as it was considered earlier.

The age is established by the relative age of the strata as determined in the field, and both fossil and radiometric ages (Kaye & Zartman, 1980; Lenk *et al.*, 1982; Bailey, 2005). The sequence of the volcanic rock, conglomerate and argillite overlies the Late Proterozoic granitic rock on the west and apparently plunges beneath the Cambrian strata to the east to establish the probable sequence. All these rocks are cut by greenstone (altered basic) dikes, which invade the Cambrian (542 to 548 million years ago), but are not known to cut either the Quincy or Cape Ann granites, both of which are well dated (LaForge, 1932; Zartman & Marvin, 1971; Dennen, 1991a) as Late Ordovician (461 to 444 million years ago). The Quincy invades Middle Cambrian strata (Crosby, 1880; LaForge, 1932) and the Cambridge Argillite (Hager, 1995). The Cape Ann Granite lies beneath redbeds related to a sequence of unmetamorphosed fossiliferous Siluro-Devonian strata (Bell *et al.*, 1977). Furthermore, no pebbles of these Ordovician granites are found in the Roxbury Conglomerate (LaForge, 1932; Chute, 1966). The basin strata are not known to be younger than Middle Cambrian in age. However, Late Cambrian rock is present at the south edge of the basin (Rhodes & Graves, 1931; Chute, 1966) and appears to be a continuation of the same sedimentary sequence.

Crosby (1880) found rock in the upper Cambridge Argillite indistinguishable from the

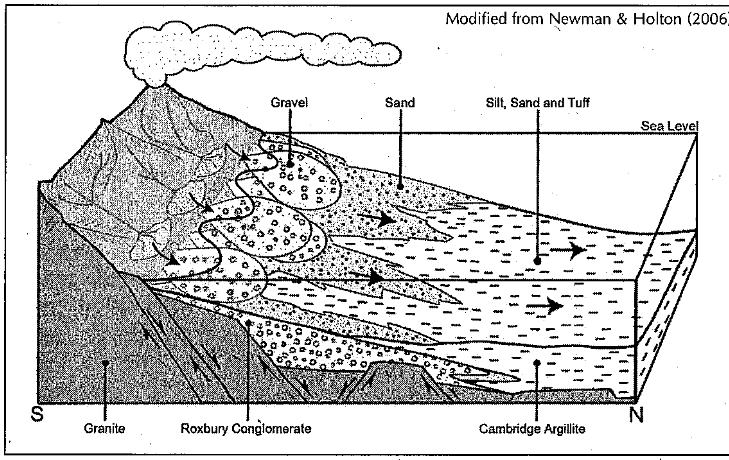


FIGURE 3-10. Diagram illustrating the depositional environment of the Boston Basin.

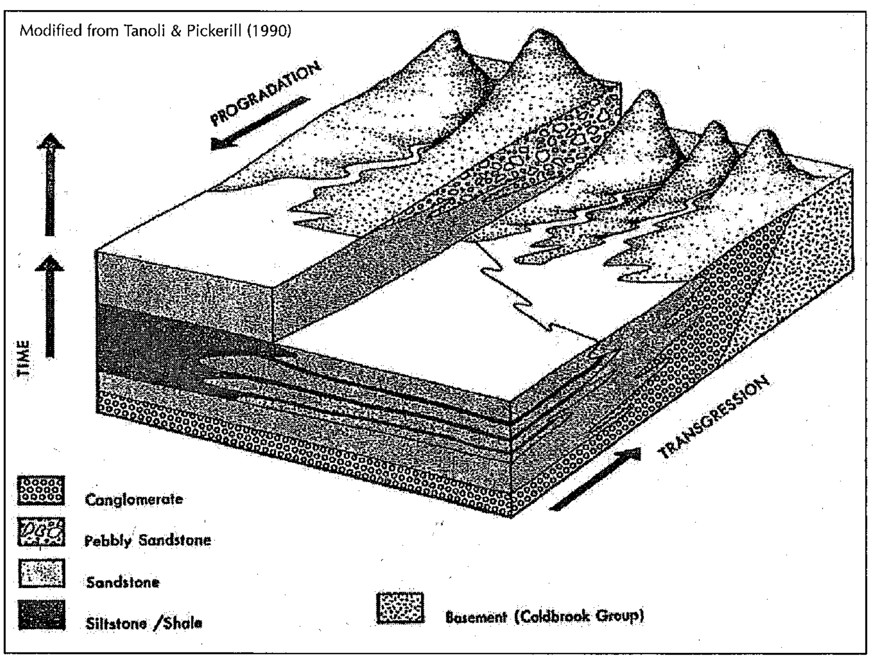


FIGURE 3-11. Diagram showing the interpretation of facies changes in the Ratcliff Brook Formation during the deposition of Early Cambrian marine transgressive strata near Saint John, New Brunswick.

Cambrian, as did Kaye and Zartman (1980) and others who found the two in structural conformity near the Quincy Granite, with an exposed depositional contact marked by a thin conglomerate. Crosby (1900) thought this conglomerate might represent an unconformity, but Kaye (1984a) pointed out that it is just another interbed of no particular significance. The Cambridge Argillite on Slate Island and Grape Island is less than a kilometer north from exposures of the Weymouth Formation (argillite) and the Braintree Argillite of Cambrian Age, and is so similar to these formations that when samples are laid side by side, they appear to be the same rock (also confirmed by Woodhouse). The argillites could be one and the same rock and the Cambridge grades up into the Braintree and Weymouth. This conclusion is based on logging thousands of feet of argillite core from the Boston area, examining the argillite *in situ* in underground excavations and tunnels, and measuring the argillite in outcrops. The general gray-to-black color indicates that chemical reducing conditions were present in most of the Cambridge section, whereas the red and green argillite in the upper part of the section appears to represent the Weymouth and Braintree that were deposited in a more oxidizing environment. No mega fossils are found in the Cambridge Argillite, but fossil acritarchs discovered in the Massachusetts Bay Transit Authority (MBTA) Red Line Extension Northwest tunnel in Cambridge and Ediacaran taxon *Aspidella* present on Grape Island, Slate Island and at Hewitt's Cove in Hingham indicate a Late Proterozoic age (Lenk *et al.*, 1982; McMenamin, 2004; Bailey, 2005).

The apparent continuity across the Proterozoic-Cambrian boundary found in the basin is widespread in other places where strata of these ages are present and are not unusual. A gradual transition from the Late Proterozoic to Early Cambrian strata occurs in southeastern Cape Breton and southeastern Newfoundland in the same tectonic belt as Boston (Landing, 1991). A similar transition occurs on the western side of the continent where the very thick continuous sandstone-shale sequence in southern Nevada and adjacent states has Early Cambrian fossils in only its upper part, which has sparked endless debate on where to draw the pre-Cambrian/Cambrian boundary (Mount *et al.*, 1983; Corsetti & Hagadorn, 2000). These fossils belong with the Laurentian faunas that occur in a concentric belt around North America (Lieberman, 2003). The transition to the Cambrian in the Boston Basin is not completely clear, but the similarity in lithology does not suggest any break. A break at the base of the Cambrian strata is only seen to the south and is the result of continued subsidence and transgression by the Rheic Ocean onto the older rock outside of the basin. The reddish zone at the base of the Cambrian might suggest shallower conditions or better circulation, although the zone grades laterally into normal gray strata.

The pre-Cambrian age of the argillite appeared contradicted by the presumed age of the Mattapan Volcanic Complex that is at the base of the sequence. The Mattapan volcanic rock in the basin, rhyolite in the Blue Hills and some rhyolite in the Lynn Volcanic Complex to the north were considered correlative (Kaye, 1984a). The rhyolite ash flows (welded tuffs), breccia and flows in the Blue Hills that were included in the Mattapan by Chute (1966 & 1969) are involved with the Quincy, which intrudes Cambrian strata. However, these volcanic rocks were separated by Kaktins (1976), who found them to be a much younger unit (described below as the Blue Hills Rhyolite). This rhyolite and the Lynn volcanic rock are associated with the Quincy and Cape Ann granites, respectively, which have the same Late Ordovician age (Zartman & Marvin, 1971; Dennen, 1991a), which is about 100 million years younger than the Cambridge Argillite.

Radiometric dating has produced mixed results and is not always consistent with the field relations. The chronological data have become more confused and contradictory as the process of rock dating becomes easier and practitioners multiply. Thompson and Grunow (2004), Hatch (1991), and Kaye and Zartman (1980) describe the controversy and chronological challenges of the Boston Bay Group and Naylor (1976), who was an expert in the field, emphasized that fossil dating is better in the region. Dating is a difficult task when samples are disturbed by metamorphism or when using detrital zircons. Zircons, and other minerals commonly used for dating, formed with the inclosing igneous rock and the radioactive decay date determines the rock's age. Ratios of various elements are used, such as rubidium/strontium (Rb/Sr) and lead and argon ratios. However, these ratios can be reset or partially reset by later heating and, therefore, would not give the original age of the rock. There have been numerous times of heating in the region that have affected the rock. Also the different elements used in dating give somewhat different results. Unlike zircons formed in an igneous rock, detrital zircons are ones carried in with the sediment that later formed sedimentary rock and their age gives a maximum age for the rock. A major problem is the sampling of the wrong rock by someone unfamiliar with the geology (usually, an error that tends to favor a younger, fresher looking rock). Invalid interpretations of the laboratory data may thus stem from various problems, including insufficient sample control, misunderstanding the local geologic relations, laboratory error and the general limitations of the methods. Radiometric ages are far from precise in southern New England and experience demonstrates that they are commonly only suggestions — but are still useful ones within their limits.

The underlying Dedham Granodiorite produced dates of 606 to 622 million years ago and a maximum age of 630 (±15) million years ago (Zartman & Marvin, in Hatch, 1991). Dates from this Late Proterozoic batholith, which includes the Dedham, are generally in the 620 to 630 million years range (Zartman & Naylor, 1984). The Dedham was given as 630 (±15) million years by Zartman and Naylor (1980) and detrital zircons from the intruded Westboro Formation yield a date of 1,500 million years ago (Olszewski, 1980). Kaye and Zartman (1980) have shown that rhyolite in the Mattapan at the base of the Boston Basin section dates from the very end of the Late Proterozoic. They used Rb/Sr to produce a date of 459 (±92) million years ago for the rhyolite; whereas zircons from the same rock produced ages of 498 (±5) million years ago to 605 million years ago. Their most reasonable interpretation led to a Concordia-intercept age of 602 (±3) million years ago. This date is reasonable, but their work demonstrates the difficulty in dating and the wide range of a possible age. Thompson and Grunow (2001 & 2004) interpreted the pebbly layer in the Cambridge Argillite at Squantum as younger than 595 million years ago, but also dated single zircons in volcanic ash in the Cambridge Argillite at Nantasket as Devonian. Johnston *et al.* (1995) dated a tuff bed in the argillite at 643 (± 6) million years ago. This dating has led some to suggest that the argillite is older than the underlying Roxbury and, therefore, has been thrust over it. Such thrusting of the argillite is unnecessary since the age range of Ediacaran fossils, which are found in the middle or upper argillite, is at least 572 to 543 million years ago and the following Cambrian explosion of fossils happened over a 10-million-year interval between 530 and 520 million years ago (Bowring *et al.*, 1999).

A compilation of the recent dates by Thompson and Grunow (2004) demonstrates how confusing and contradictory ages can be. A recent dating of several granites at the southwest edge of the basin to determine the intrusive sequence (Thompson *et al.*, 1996) produced results that are in almost the reverse order of the known field relations. The radiometric dates do, for the most part, indicate a Late Proterozoic age for the Boston Bay Group, and demonstrate that most radiometric ages, although only very approximate, agree in a very general way with the known sequence, but many are wide of the mark. The radiometric dates obtained in the past twenty years have not improved our knowledge of the Boston Basin, but rather show the need for more paleontology coupled with measured and described sections. The age for the Boston Basin is near that of the very similar basin at Saint John, New Brunswick, which is also similar in both setting and stratigraphy (Tanoli & Pickerill, 1990; Barosh, 1995). The same tectonic conditions were probably widespread and other contemporary basins may lie submerged beneath the intervening marine waters. Similar such basins of the same age also are present in Morocco (Thomas *et al.*, 2002).

The Boston Basin strata appear to have been deposited in a trough that was undergoing active block faulting (see Figures 3-7, 3-9, 3-10 & 3-12). The initial rifting triggered extensive

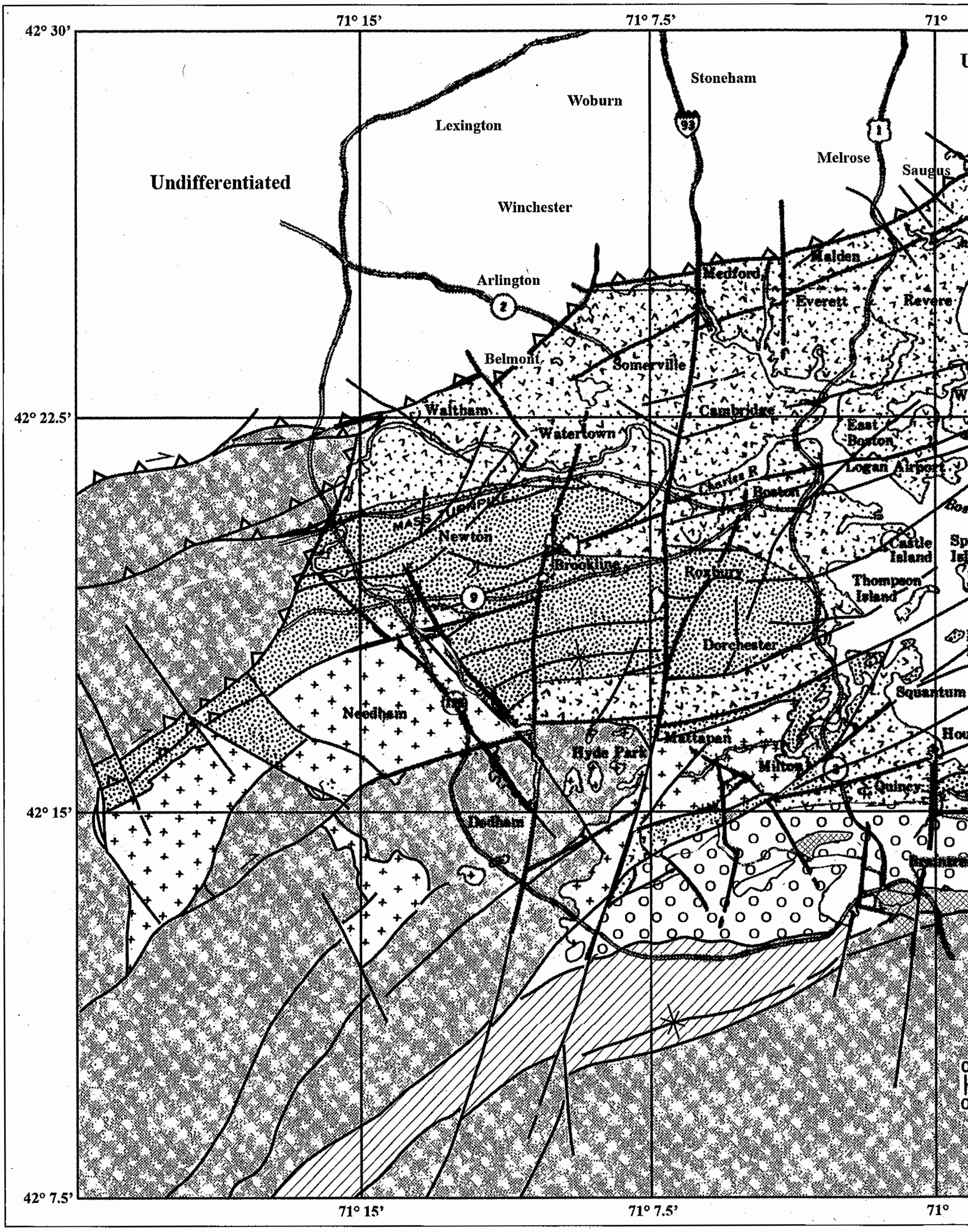
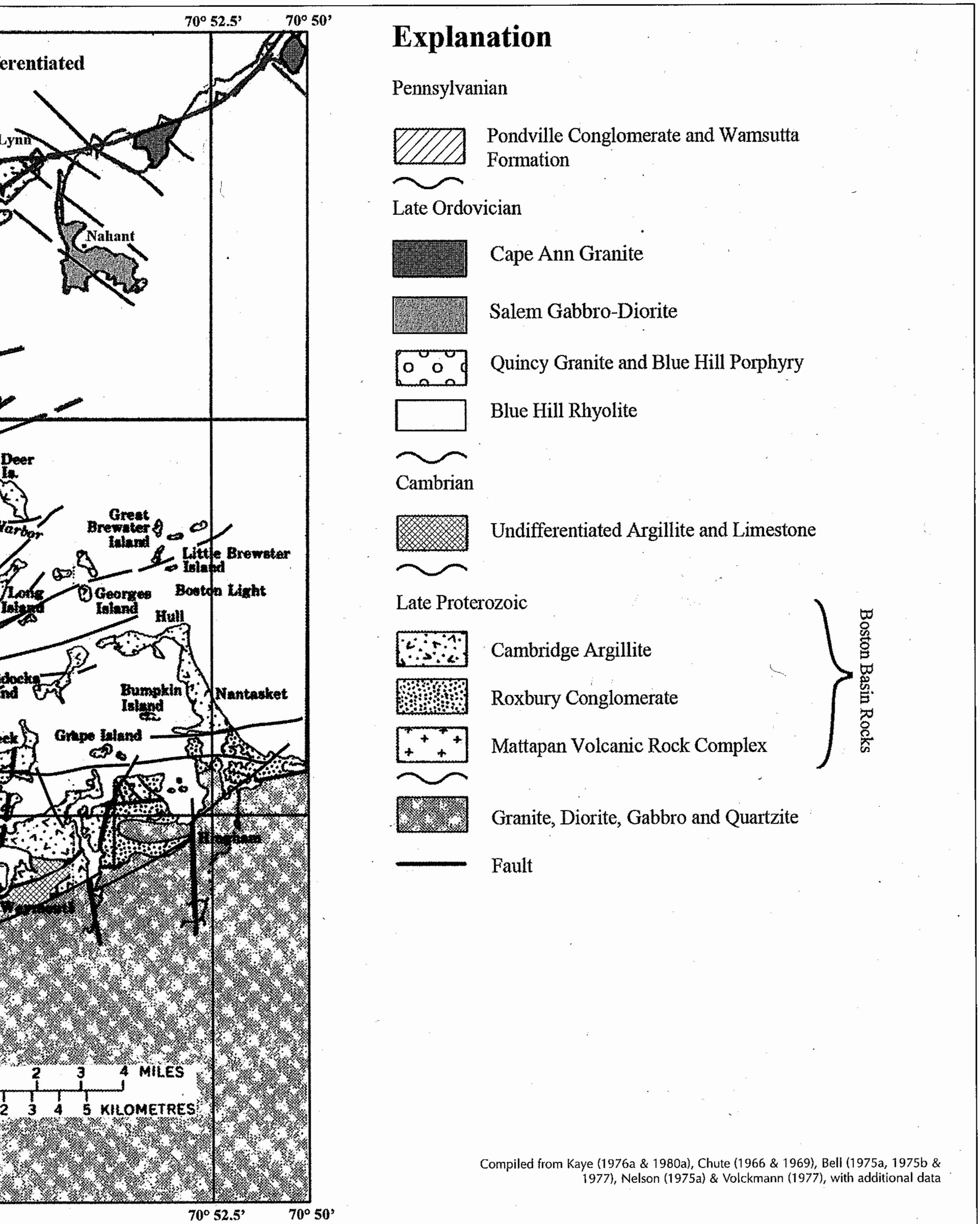
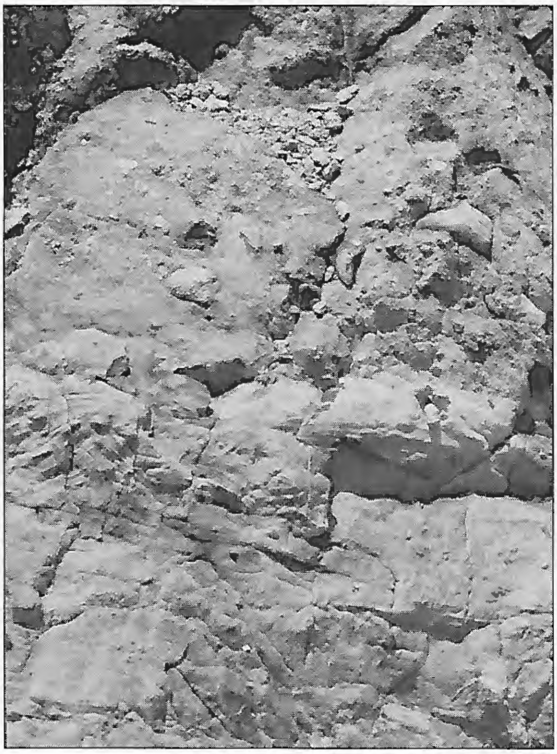


FIGURE 3-12. Bedrock geologic map of the Boston area.



Compiled from Kaye (1976a & 1980a), Chute (1966 & 1969), Bell (1975a, 1975b & 1977), Nelson (1975a) & Volckmann (1977), with additional data



(see color version on page 450)

FIGURE 3-13. Pebbly mudstone slump deposit, which has been called the "Squantum Tillite," in the Cambridge Argillite at Squaw Head, Squantum, Quincy.

and varied volcanism that was guided by the early faults. The volcanic activity was widespread and occurred in at least six intervals of shallow intrusive and extrusive rock (Kaye, 1980a). Some conglomerate was deposited between flows, but the principal deposition of conglomerate occurred as the volcanic activity died down and the bordering ranges eroded. When the sea began to creep into the deepening basin, progressively more silt and mud accumulated offshore. Detritus eroded from surrounding highlands and fault scarps and was rapidly deposited as talus to the water's edge. Coarse gravels, sand, mud and volcaniclastic sediment interfingered over short distances. The relative minor occurrence of sandstone suggests that the rapid dumping of debris eroded off rising escarpments, with stream transport too short to break down and sort much material. The stratification and composition of the conglomerate indicates that it formed as a terrestrial talus, but many beds extended northward into the water, which formed ripple marks and cross-bedding in the overlying thin sandstone, and intertongued with the mud that formed the argillite (Crosby, 1880). The thinly layered argillite varies greatly in detail and contains thin limestone interbeds as well as locally abundant sandstone and tuffaceous beds. Bottom conditions were unstable in the deepening depositional basins because at many higher stratigraphic levels the telltale evidence of submarine sliding and turbidity currents (including convoluted bedding, intraformational breccia, graded-bedding and large lenticular slumped masses of pebbly to bouldery mudstone) are present (Dott, 1961; Bailey *et al.*, 1989). Bottom slumps and slides were probably triggered by earthquakes that originated from volcanic eruptions and faulting at the borders. The preserved record of rock distribution and interfingering clearly shows that the south side of the basin border was the active one. In time, subsidence became more general as the faulting diminished and the silt, quartz sand and some mud spread into shallow water beyond the basin in a general transgression during the Cambrian and Ordovician.

Describing these strata and developing a stratigraphic nomenclature that reflects the units has been a slow process. That this process is a slow one is largely due to the lack of applying the principles of modern stratigraphy and sedimentation and resistance to change. Traditionally, the early volcanic rock has been called the Mattapan Volcanic Complex overlain by the Boston Bay Group made up of a lower Roxbury Conglomerate and upper Cambridge Slate now described as argillite (LaForge, in Emerson, 1917). However, this nomenclature was confused by making the break between the Roxbury and Cambridge at an assumed thin pebble-bearing Squantum unit within the fine-grained strata and not at the principal lithologic break below. The Roxbury Conglomerate was thus described as composed of three members, in ascending order (see Figure 1-29): the Brookline Conglomerate, the Dorchester Shale and the Squantum Tillite (LaForge, in Emerson, 1917).

The Squantum consists of lenses of mudstone with "floating" clasts of the same rock types as found in the Roxbury, plus fragments of argillite interbedded in the argillite sequence (see Figure 3-13) and more regular conglomerate beds. It was interpreted as a tillite by Dodge (1875) and Sayles (1914), who were influenced by the discovery of late Paleozoic glacial deposits in Africa (Dott, 1961). Typical examples of the rock are found at Squaw Head, Squantum, in Quincy; similar beds also occur in Brighton, Jamaica Plain (at the Arnold Arboretum) and in Hingham along the southern side of the basin (see Figures 3-2 & 3-3). The Squatum Tillite has been described numerous times (Sayles, 1914, 1916, 1919, 1924 & 1929; Sales & LaForge, 1910; Schwarzbach, 1960).

Most subsequent authors have followed this arrangement and employ the Squantum to maintain a three-member Roxbury Conglomerate. However, LaForge (1932), with further mapping, did not find the Squantum to be a mappable unit and useful in separating a Dorchester Member from the overlying Cambridge Argillite, which is a term more suitable than Slate. Neither did Dott (1961) and Kaye (1980a). Tierney (1951) did not find the pebbly argillite below the Cambridge in the west to be a tillite, nor did Nelson (1975a) later on. Tierney noted that the clasts were surrounded by the matrix and that there was abundant evidence for sliding within the unit in the City Tunnel. However, to reinforce the disagreement among geologists, when a summary was prepared later with Billings (Tierney *et al.*, 1968) it was changed to a tillite. Several stratigraphers, including Pettijohn (1957), cast doubt on the tillite interpretation between 1947 and 1959, and Dott (1961) carried out an exhaustive investigation on the rock type. He demonstrated that the "Squantum" was a pebbly mudstone subaqueous mass-movement or slump deposit that occurs at various indefinable horizons within Cambridge Argillite. The Squantum at Squantum Head is typical of the pebbly mudstone slump deposits present in Tertiary deposits along the California coast. Caldwell, a glacial geologist, first agreed with the tillite designation and later realized that the basin rock shares no similarity with glacial deposits (Caldwell, 1981; Bailey, 2005) nor does the "tillite" resemble any of the overlying glacial material in the basin. The huge thickness of the Cambridge Argillite, along with its sedimentary features, rules out any glaciolacustrine origin. Such slumps, with or without pebbles, and slump folds are common in the argillite and show that it was deposited under active conditions. Without the Squantum Tillite Member it is difficult to maintain a separate Dorchester Shale Member. The Roxbury Conglomerate, thus, at this time, is better described as a single unit, which consists of conglomerate, sandstone, argillite and shale, along with some interbedded altered basalt and andesite in its upper part and it rests below a predominantly argillite section. However, some subsequent authors continue to cite a glacial origin (Socci & Smith, 1990; Rehmer, 1981; Rehmer & Hepburn, 1974). Socci and Smith (1990) tried to combine both a slump and glacial origin for the basin deposits. A tillite origin for the Squantum also has been used to bolster glacial theories for various ages, such as a worldwide Permian glaciation (Billings, 1929) and a "Snowball Earth" in the Cambrian (Kirschvink, 1992; Kirschvink *et al.*, 2000; Hoffman *et al.*, 1998).

To better understand this stratigraphy and place the terminology on a firmer basis, the quadrangle mapping by Kaye (1980a) and Bell (1975a, 1975b & 1977) of the USGS's Boston office described the lithologies in detail and did not use the formal terminology of either LaForge (in Emerson [1917] or LaForge [1932]). The lithologies were to be grouped systematically for a consistent, revised stratigraphic terminology based on the final published maps; unfortunately, those efforts were curtailed. Kaye (1979) recognized that the extensive facies changes in the basin make the application of any formal stratigraphic terminology difficult. Kaye's geologic maps of the three quadrangles covering the central Boston Basin and Bell's adjacent maps incorporate tunnel and boring data and show considerably more detail than the earlier maps. The bedrock in central Boston is deeply buried and most of the new information was obtained from rock cores taken in foundation borings and from bedrock tunnels. The sedimentary rock of the Boston Bay Group is made up of three main facies: coarse-grained conglomerate and sandstone, fine-grained argillite and a mixed facies consisting of maroon and green tuffaceous siltstone and sandstone, along with some interbedded volcanic rock. These lithologic descriptions were followed in the previous *Geology of Boston* (Woodhouse & Barosh, 1991). (Now, with corrections, additional age relations, recognition of the importance of unconformities and new work in adjacent areas, an attempt is made to revise the stratigraphic terminology [see below].)

Another problem to be resolved is that of determining the exact stratigraphic relations between the Cambridge Argillite and the Roxbury Conglomerate. The Cambridge had been shown to rest on the Roxbury in a simple layered sequence (LaForge, in Emerson, 1917; LaForge, 1932). However, the interbedded argillite and conglomerate shown on the south shore by Crosby (1880) and in the tunnels suggests that at least a partial intertonguing relation in a facies change between the two formations. Billings and Tierney (1964) call upon such a facies change in trying to match limbs of different rock types in a proposed Charles River Syncline. However, their illustration of the correlation between the Cambridge Argillite and Roxbury Conglomerate presents such an extremely abrupt facies change that it demonstrates a lack of correlation and instead demonstrates the presence of a fault. Kaye (1979) implied such facies changes when he (Kaye, 1980a) tried to unravel the relation of various mapped fault blocks of argillite and conglomerate around Boston. A broad view of his map, however, indicates an additional relation. The base of the argillite in the different fault blocks rests on progressively older rock to the south. The base lies on upper Roxbury at Newton, lower Roxbury at Brookline and Mattapan at Mattapan. This relation indicates a slight angular unconformity at the base of the Cambridge Argillite and explains some of the confusion in local correlations. This relation also explains why the Brighton Basalt (Melaphyre) intrudes the Roxbury, but not the Cambridge if it were the same age. The unconformity would not preclude the Roxbury from grading into a more argillaceous section basinward to the north, but this unit would be older than the general Cambridge Argillite. The younger argillite may also interfinger with the conglomerate close to the southern edge of the basin. The present evidence thus indicates that the Cambridge Argillite rests over much of the lower Roxbury Conglomerate with a slight angular unconformity that is perhaps the result of active faulting followed by subsidence of the Boston Basin and the spreading of the fine material to the south. The upper section of the conglomerate, which intertongues with the argillite, appears more restricted to areas close to the southern border of the basin. Thus, it appears that the gravel fans extended some distance into the basin to grade to sands and mud, then with subsidence the fine material spread southward over the gravel to grade into more restricted gravel fans near the border.

The present understanding is that of basal volcanic rocks of the Mattapan being poured out along a north-facing bluff to intertongue laterally and basinward with coarse gravel and sand, which eventually overwhelmed and covered the Mattapan as the volcanic activity died down. The higher clastic strata were intruded later by younger volcanic rock (Brighton), which also forms local interlayers. These strata grade basinward to the north into mud, silt and some sand, the Cambridge, which then transgress southward across the earlier units to apparently still intertongue farther south with gravel and sand continuing to accumulate at the edge of the basin. Subsequently, mud, silt and sand filled the basin in the Early Cambrian and spilled out of it. The basement unconformity over the granite may be locally overlain by any of the lithologies and is of a different age from place to place. This interfingering and time transgression of the lithologies deposited in a dynamic environment is what poses difficulties for a formal stratigraphic nomenclature.

Pre-Cambrian Stratigraphic Units

The stratigraphy adopted here for the Boston Basin consists of a basal Mattapan Volcanic Complex that is overlain by the Boston Bay Group, which consists of the Roxbury Conglomerate and Cambridge Argillite. The units may interfinger, be conformable or have local unconformities separating them (see Figure 3-8). LaForge's member division of the Roxbury

Conglomerate into the Brookline Conglomerate, Dorchester Shale and Squantum Tillite members is abandoned along with these terms since the Squantum is not a mappable unit. The Roxbury Conglomerate is restricted to the former Brookline Conglomerate Member, making it consist predominantly of conglomerate without any member divisions. The Brighton volcanic rock is used as an intrusive unit rather than a stratigraphic one, while recognizing connected surface flows within the Roxbury. For clarity, the Brighton is also renamed a basalt rather than the archaic melaphyre. The division between the Roxbury and the Cambridge is determined by the local break between predominantly conglomerate below and finer material above, with the understanding that the division does not represent a single horizon from place to place. The Cambridge Argillite consists of the former Dorchester Shale and Cambridge Slate. The pebbly mudstone and conglomerate of the former Squantum are treated as local mappable beds or units, as is the Tufts Quartzite because of its limited extent in Medford, near the north side of the basin. The Milford Quartzite Member of the Cambridge in the south is abandoned because it lacks a firm basis. Any other formal member divisions must wait for considerably more detailed measured and described sections. All of these stratigraphic units are of latest Late Proterozoic in age and lie above the batholithic granite and beneath the Cambrian Braintree Argillite and Weymouth Formation. In addition, the volcanic rock, described by Kaktins (1976), as associated with the Quincy Granite and Blue Hills Granite Porphyry, is separated from the older Mattapan Volcanic Complex as the Blue Hills Rhyolite, a new formational term. This stratigraphy is presented below with the lithologic descriptions drawn chiefly from LaForge (1932), Kaye (1976a, 1978, 1980a & 1982b) and others.

Basement Rock. The Late Proterozoic basement rock beneath the Boston Basin, although deeply buried, is reasonably known. Batholithic granite, which includes the Dedham Granodiorite, Westwood Granite and small quartz diorite and gabbro bodies, underlies the basin fill. This arangement is demonstrated by both the volcanic rock and conglomerate resting unconformably on it to the west and south, respectively, and granite fragments carried upwards within dikes cutting the argillite of the north-central part of the basin. The basin is dropped into a broad gently north-dipping contact zone of the Dedham Granodiorite. The Dedham is 590 to 640 million years old, based on USGS radiometric dating, and is generally a medium-grained rock that is medium-gray to the south and altered to reddish gray or red to the west and north. Weak to moderate foliation in the granite dips north to northwest beneath the basin as does the stronger foliation around the west end of the basin. Just south of the basin, the Dedham contains much of its fine-grained border facies, which has been mapped separately in part as the Westwood Granite (Chute, 1966). The Dedham contains some xenoliths, pendants and small bodies of earlier quartz diorite and gabbro that are the oldest known intrusive rocks in the area (Volckmann, 1977). These rocks were mislabeled as the Salem Gabbro-Diorite by Chute (1966). Scattered remnants of the intruded quartzite of the Westboro Formation (1,500 million years old) occur locally. North of the basin, there is a much higher proportion of Westboro and the overlying units of metamorphosed volcanic strata, which cover most of the Dedham.

Mattapan Volcanic Complex. A large variety of shallow fine-grained intrusive rock and extrusive fine-grained flow and pyroclastic rock representing several volcanic episodes, occurs widely in the southern, western and central parts of the Boston Basin, and spills outside to the west and southwest as patches lying on the granite. A minor amount of andesite porphyry is found west of the basin in Framingham (Nelson, 1975b) and much more lies to the south in Medfield and Norwood (Chute, 1966; Volckmann, 1977). The exposures are concentrated in Needham, Newton, West Roxbury, Hyde Park and Mattapan. Early eruptions were rhyolitic and later ones spilitic and keratophyre basalt and sodic andesite (see Figure 3-14). The volcanic rock grouped under the term Mattapan Volcanic Complex consists of a varied unit of lava flows, flow breccias, explosion breccias, pillow lavas, tuff, mud flows, welded tuff, domes of plug-like bodies,

(see color version on page 450)

FIGURE 3-14. Mattapan rhyolite found at the Tileston School, Mattapan Square, Dorchester.

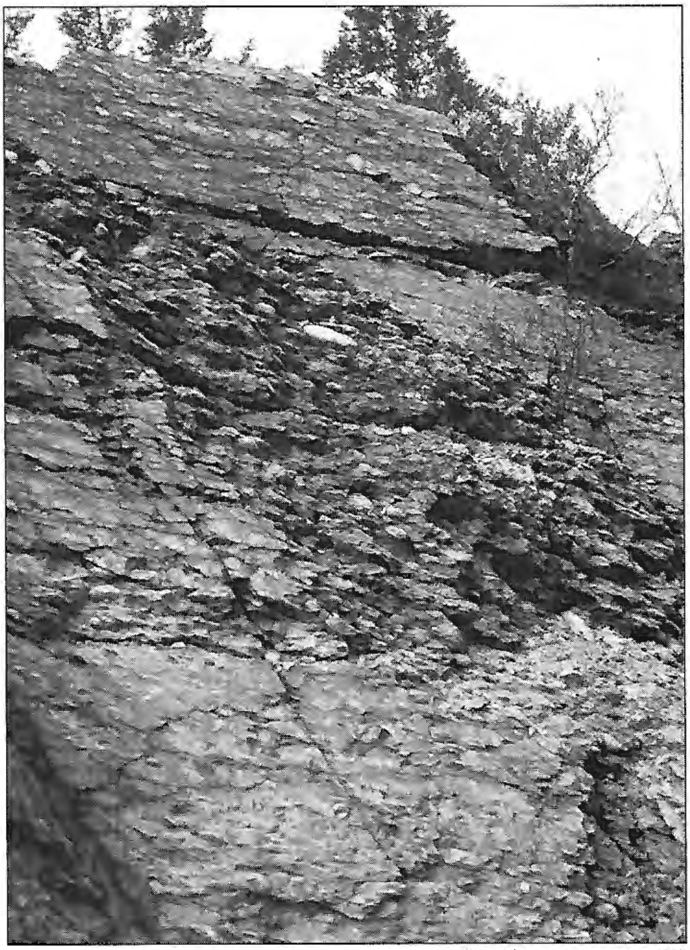
lies within eastern Needham (Kaye, 1980a). It is part of the volcanic complex and may have served as the main vent.

The slightly altered volcanic suite forming the Mattapan lies unconformably on the Dedham Granodiorite, its border phase called the Westwood Granite and the older diorite and associated highly metamorphosed strata. Roxbury Conglomerate overlies the Mattapan with both apparently disconformable and angular unconformable contacts. The thickness of the Mattapan varies from about 900 meters (3,000 feet) in the block referred to as the "Central Anticline," to 670 to 1,945 meters (2,200 to 6,370 feet) in Natick to the west and 550 meters (1,800 feet) near Milton to the south. However, in the Blue Hills, Hingham and Nantasket to the east, it may be missing in places and there the Roxbury lies directly on or adjacent to the granite (Chute, 1966; Nelson, 1975a; Bell, 1975a & 1975b). The Mattapan is Pre-Latest Proterozoic in age as shown by Late Proterozoic fossils in the higher Cambridge Argillite, and Late Proterozoic from approximate radiometric dating of a lower flow within the unit at 602 (±3) million years ago (Kaye & Zartman, 1980).

volcanic necks and agglomerate that apparently spread both on and offshore between roughly 600 and 595 million years ago (Chute, 1966; Nelson, 1975a; Kaye, 1982b; Kaye & Zartman, 1980). The rock ranges from rhyolite through sodic dacite to sodic andesite in composition and exhibits a variety of light to dark-gray colors that may be reddish, bluish, greenish or pinkish. An important widespread spilitic horizon is well marked throughout the areas of volcanic outcrops. Sedimentary strata, which are mainly composed of reworked volcanic material in mud flow deposits, conglomerate, sandstone and laminated argillite, are locally interbedded with the volcanic rock. Chute (1966) separated it in Westwood into three units: porphyritic intrusive rhyolite, eruptive breccia and porphyritic extrusive felsite. It is more varied to the west in Medfield where it is andesitic and basaltic in part (Dowse, 1948). At that location, Volckmann (1977) divided it into four parts: intrusive fine-grained rhyolite, crystal-vitric tuff, rhyolite welded tuff and conglomerate. He called the layered units members, but they appear too patchy for a formal designation and the tiny area of welded tuff could be part of the younger welded tuff of the Blue Hills Rhyolite found to the east. A moderate-sized alkali-feldspar granite pluton, with a fine-grained chilled margin (similar to some of the volcanic rock) and a coarser-grained center,

Boston Bay Group. The Boston Bay Group consists of the Roxbury Conglomerate and overlying Cambridge Argillite, which interfingers with and is equivalent with at least the lower part of the conglomerate. The general rock distribution on the surface and in tunnels has led some to suggest that the thickness of the Boston Bay Group could be on the order of 4,575 meters (15,000 feet). However, much of the thickness is attributable to fault repetition and Crosby (1880) felt that the total was only a fraction of this amount. The more recent discoveries of additional faults tend to support this conclusion. Many of the perceived stratigraphic complexities also appear to be due to fault repetition.

Roxbury Conglomerate. The Roxbury Conglomerate is the second most important sedimentary rock in terms of distribution in the basin. It is largely concentrated in the central part of the Boston Basin, extending west from Roxbury through Brookline and Newton. Isolated outcrops (see Figure 3-15) are known as far west as Framingham, west of the Natick quadrangle (Kaye, 1979; Nelson, 1975a). It also crops out in a narrow belt along the southern margin of the basin and a small patch was described at the northern margin (Crosby, 1880). This distribution, coupled with the structure, shows that the conglomerate is concentrated in the stratigraphically lower, southern parts of the basin, as well as close to the south margin. This distribution supports a southern source for the unit. The Roxbury Conglomerate varies in both lithology and thickness across the basin, reflective of its deposition in an active erosional environment.



(see color version on page 451)

FIGURE 3-15. Roxbury Conglomerate at Route 128 (Interstate 95), south of Route 9, Newton.

The formation chiefly consists of conglomerate with lesser amounts of sandstone and includes lava and tuff associated with the Brighton Basalt (Melaphyre) of LaForge (1932). The present restricted Roxbury Conglomerate is primarily the Brookline Member of Emerson (1917) and forms the chiefly conglomeratic sequence both unconformably beneath, and interfingering with, the Cambridge Argillite and unconformably above the Mattapan Volcanic Complex or older rock. It may be possible with further work to divide the Roxbury into an informal upper member with interbedded Brighton Basalt and argillite over a lower member of more massive conglomerate.

The conglomerate, which was studied in detail by Mansfield (1906), is generally a dark color that varies in shades corresponding to its local composition (LaForge, 1932; Kaye, 1978a & 1979). The clasts generally range from pebble to cobble size, but boulders up to 2.4 meters (8 feet) in diameter occur near the south boundary and are generally rounded to subrounded (see Figure 3-15). The conglomerate is both matrix and clast-supported. The matrix between the clasts is generally arkosic sandstone. The sorting is generally fairly good, except along the contacts with argillite where pebbles are embedded in the argillite. The clasts consist of both dark- and light-colored volcanic rock of the Mattapan, quartzite of the Westboro Formation and foliated Dedham Granodiorite. The relative proportion of these types varies widely from place to place, depending on the source rock then exposed. In some zones, the clasts are almost entirely volcanic, in others, dominantly quartzite, and granitic rock is only abundant in the cobble

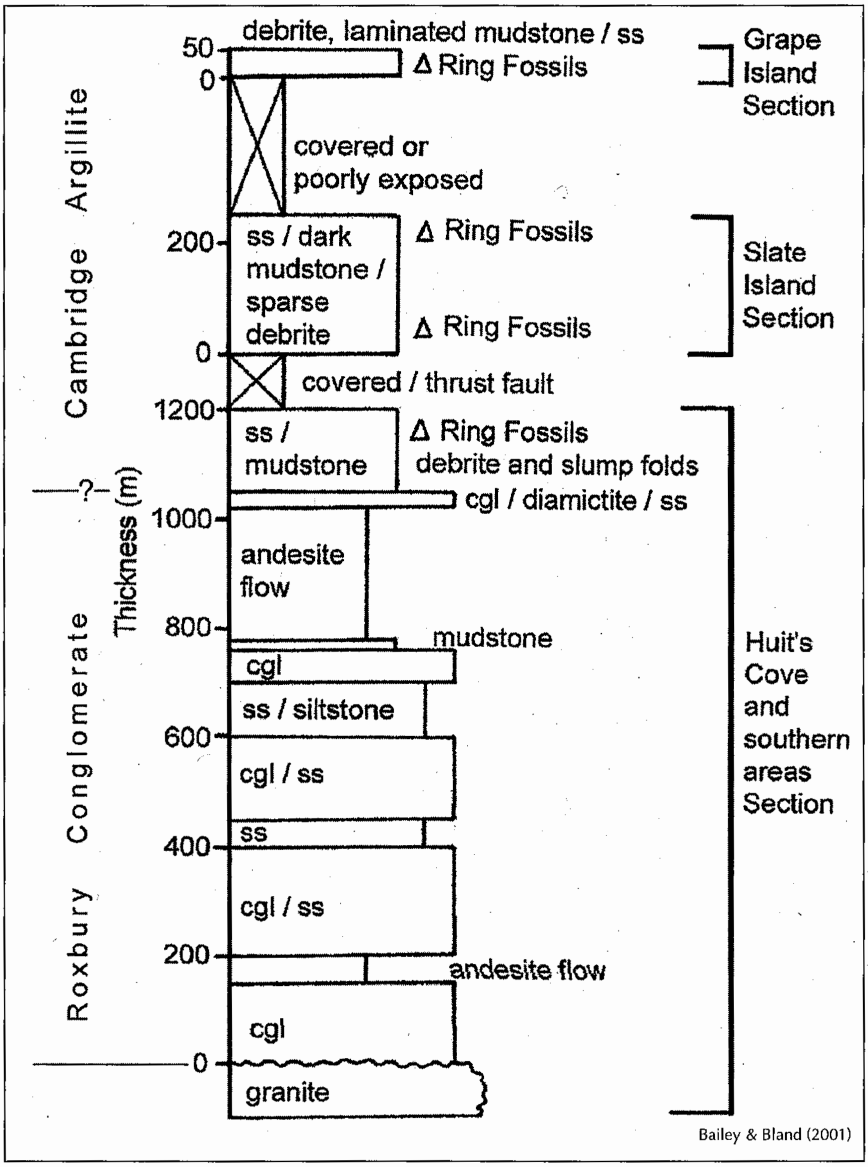


FIGURE 3-16. Generalized composite faulted stratigraphic section across the Roxbury-Cambridge boundary in Hingham.

similar to the Lynn, and 13 percent Mattapan volcanic rock, which increases to the west (Nelson, 1975a). Thompson and Grunow (2004) present a review of additional locations of conglomerate lithology. No clasts of the Quincy Granite are found in the Roxbury, which demonstrates that the granite is younger. Argillite, sandstone and shale similar to that found in the Cambridge Argillite, altered basalt and andesite of the Brighton Basalt and associated tuff beds are interbedded or interfinger locally with the conglomerate. It also contains scattered interbeds of sandstone of variable composition and gray to maroon silty sandy argillite that may be transitional to argillite.

conglomerate. The clasts consist of 85 percent porphyritic felsite, 5 to 10 percent Dedham Granodiorite and Westwood Granite, and 5 percent miscellaneous rock types at the south edge of the basin where the source must have been predominantly volcanic rock of the Mattapan, now largely removed (Chute, 1966). At the southwest edge of the basin the clasts are 42 percent quartzite from the Westboro Formation, 25 percent Dedham, 10 percent siltstone and shale, 10 percent felsic volcanic rock

The conglomerate generally appears massive, with few if any bedding-plane partings, although variation in clast size shows layering in large exposures. In weathered outcrops, crude stratification may be apparent because of the alignment of the long axial planes of pebbles and of partings that develop parallel to these planes, along with siltstone and sandstone partings and lenses. Thick gradational beds are locally present, with conglomerate at the base grading upward into sandstone or finer conglomerate at the top (Dott, 1961). Jointing is sparse and outcrops form large, steep-sided monolithic knobs.

The upper part of the unit, as seen in the City Tunnel and along the south shore, is interbedded with lava flows and tuff (Tierney, 1951; Crosby, 1880; Grabau & Woodman, 1898; Bell, 1975a & 1975b). The interbedded argillite (see Figure 3-16) displays a variety of soft sediment deformation (Bailey & Bland, 2001). This interbedded section may constitute an informal upper member above a non-volcanic lower member. The thick lower conglomerate apparently pinches out to the east along the south shore, where this upper member rests on granite and seems to form the entire formation. The section on the south shore is approximately 300 meters (1,000 feet) thick (Bailey & Bland, 2001).

The Roxbury Conglomerate sits unconformably over both the Mattapan Volcanic Complex and the Dedham Granodiorite. Its contact with the Mattapan appeared to be a disconformity representing only brief time to LaForge (1932). However, the overlap across small, thin remnants of Mattapan and onto the Dedham (Chute, 1966; Kaye, 1980b), coupled with abundant clasts of Mattapan forming a dominant part of the Roxbury, indicates a more significant unconformity, although the break in time need not be great. The Roxbury appears to be dominantly a terrestrial fan deposit off mountains to the south and interfingering northward to some degree with water laid sandstone and argillite. Interbedded conglomerate and argillite of the transitional facies is displayed at many places along the south side of the basin (Crosby, 1880; Kaye, 1980a; Bell, 1975a & 1975b). As Crosby (1880) pointed out, it was very "probable that these rocks [Roxbury and Cambridge] are in part contemporaneous deposits, slate in the deeper water and conglomerate in the shallower being formed simultaneously. In other words, the deposition of the conglomerate began first, but had not entirely ceased in some parts; so that chronologically the two deposits overlap, and have not everywhere the same relative thickness." Kaye (1980a) felt that the Roxbury Conglomerate interfingered northward with the apparent lower half of the Cambridge Argillite. However, the lack of Brighton Basalt dikes in the Cambridge and the distribution of the argillite on Kaye's (1982b) map suggest that only the basal part of the Cambridge Argillite is a normal facies change and that much of the Argillite is essentially transgressional over the conglomerate and onto the Mattapan Volcanic Complex. The contact is placed where the proportion of conglomerate becomes subordinate to that of the fine-grained strata above.

Estimates of the thickness of the Roxbury Conglomerate vary greatly due to uncertainty about fault repetition, but it may attain a thickness of 365 meters (1,200 feet) (LaForge, 1932), although Nelson (1975a) thought it might be three times that. However, the section along the south shore in Hingham to Hull appears much thinner. The Roxbury appears thin where it overlaps onto the south side of the basin and thickens away from the edge.

Cambridge Argillite. The Cambridge Argillite is the most widespread rock type in the Boston area (Kaye, 1980a), particularly in the northern, eastern, and offshore parts of the basin (see Figure 3-12). It underlies most of downtown Boston, where it is covered by glacial deposits and only exposed in a small area north of Beacon Hill and more extensively on the outer islands where the glacial material is stripped off (see Figure 1-18). The formation is best described as massive to laminated siltstone, mudstone and claystone that are now mostly slightly metamorphosed to an argillite (see Figures 3-17, 3-18 & 3-19). A former designation as slate was a misnomer since it lacks true slaty cleavage. However, some slaty argillite underlies the Boston Company Building on Court Street in downtown Boston. The argillite contains varying amounts of very fine-grained sericite and chlorite — minerals that are characteristic of very low-grade metamorphism. The argillite is usually found to be medium-gray to almost black, predominantly massive to thinly laminated mudstone with occasional ash beds in the northern part of the basin, but becomes reddish- to purplish-gray and then gray and greenish-gray to the south. The very dark-gray argillite occurs at several horizons. Interbeds of tuffaceous argillite, calcareous argillite, sideritic argillite, gypsiferous argillite, pebbly argillite, siltstone, sand-

(see color version on page 451)

FIGURE 3-17. Cambridge Argillite at the Somerville Quarry, Somerville.

stone, tuff, limestone and conglomerate are locally present. Some sideritic argillite is light colored and has been described as a claystone. The pebbly argillite is commonly described as conglomerate and it locally grades to conglomerate, but it is in slumps and different from the actual conglomerate interbeds present to the south (see Figures 3-20, 3-21 & 3-22).

The entire length of the Inter-Island Tunnel between Nut Island and Deer Island is in Cambridge Argillite and illustrative of the lithologic variations (Sverdrup, 1990a & 1990b). The argillite along the tunnel is found to form five apparent blocks, which have varying bedding orientation, characterized by different stratigraphy, but whose relative relations are not known. The blocks are, from north to south:

- massive to regular bedded medium-hard to hard gray argillite and sandy argillite that extends from Deer Island to near Long Island;
- regularly bedded, hard, gray sandy argillite and fine-grained sandstone under Long Island;
- massive to regularly bedded, medium hard to hard, green banded, gray, purple, and black argillite, tuffaceous argillite and sandstone from south of Long Island to Rainsford Island;
- massive to regularly bedded, medium hard to hard, light- to dark-gray argillite, sandy argillite and sandstone grading southward to massive to gray and white beds with local 7 centimeter (3 inch) lenses with pebbles, between Rainsford and Peddock's islands; and,
- regularly bedded, medium hard to hard, gray argillite, purple argillite with tuffaceous layers, and sandy argillite from Peddock's Island to northern Nut Island.

Many dikes and sills also are present, as well as varying amounts of calcite and quartz veins.

In the section continuing to the south through the Braintree-Weymouth Tunnel the 3,216 meters (10,550 feet) of Cambridge contains 75 percent dark-gray and locally sandy argillite, 18 percent light- to medium-gray argillaceous sandstone, 2 percent very light-gray to buff medium to coarse-grained quartzite, and 4 percent mafic dike rock (derived from Deere *et al.*, 2004). The formation in the Braintree-Weymouth Tunnel is two parts, separated by a fault sliver of Roxbury Conglomerate, with the northern part containing more of the coarser clastic material and appearing to represent shallower conditions of deposition than the southern fault block.

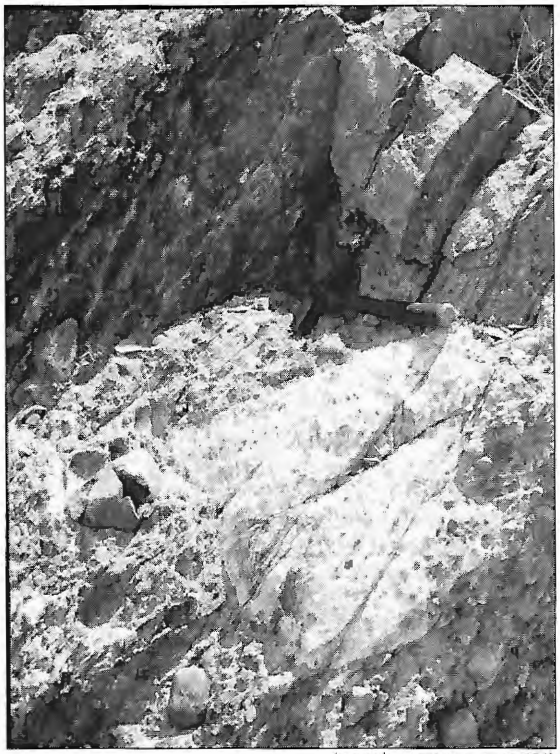
Bedding in the argillite ranges from laminated through thin-bedded to locally massive 1.5 meter (5 foot) beds. Beds usually are 0.5 to 5 centimeters (0.3 to 2 inches) and may be bundled together in units. Features that can be seen in the argillite include: graded-bedding, pinch-and-swell bedding, small-scale cross bedding, oscillation and interference ripple marks, scour marks, slump structures and contorted zones, and load clasts (see Figures 3-20, 3-21 & 3-22). The graded beds usually have a coarse silt or sand base and micaceous top or rhythmically

(see color version on page 452)

FIGURE 3-18. Thin-bedded, laminated Cambridge Argillite on Grape Island.

(see color version on page 452)

FIGURE 3-19. Thin-bedded Cambridge Argillite capped by gently dipping diabase dike at Little Brewster Island.



(see color version on page 453)

FIGURE 3-20. Slump deposit of conglomerate with tuff block and Cambridge Argillite at Squaw Head, Squantum, Quincy.

interbedded light and dark layers suggestive of turbidites. Bedding-plane partings, however, are rare, and fresh rock commonly breaks across bedding. Fine cross-bedding in the Malden Tunnel indicates deposition from the south (Billings & Rahm, 1961 & 1966). The Cambridge in the Braintree-Weymouth Tunnel at the south side of the basin has distinct bedding, transitions to argillaceous sandstone and lithic sandstone with local cross-bedding suggestive of shallower conditions than typical for the formation (Deere *et al.*, 2004). The bedding features indicate that the rock formed by pulses of mud settling out of suspension and small turbid flows accompanied by generally small, but locally large penecontemporaneously deformed or slumped beds. The slumps would have mainly slid down slope toward the deeper part of the basin, but some slumps may have slid toward faults from block rotation during earthquakes.

Interbedded with the argillite are lenses of fine- to coarse-grained sandstone, which in many places form a transition between conglomerate and argillite. The sandstone has many shades of gray and, in places in the south, grades from gray to red. Well-bedded green, maroon and light greenish-gray tuffaceous argillite and sandstone also occurs as interbeds. The sandstone varies in composition from dominantly quartz to as much as 30 percent non-quartz minerals, including feldspar, sericite, chlorite and lithic material. Some apparent fine-grained quartzitic sandstone is the result of shearing. Other gritty sandstone is the result of soft-rock alteration of quartzite in which secondary sericite and kaolinite replace much, or all, of interstitial quartz overgrowths. Bedding is generally absent or indistinct, but local cross-bedding is present and bed tops may have ripple marks.

Two sandstone units are identified separately: the Tufts Quartzite, at Tufts University on Powder House Hill in Medford, and the Milton Quartzite (Billings, 1979) in the Quincy-Milton area. The 12 meter (40 foot) thick red, yellow, green quartzite at Tufts is considered to lie in a syncline and be near the top of the Cambridge by LaForge (1932). The limited exposure of the Tufts and lack of control of its stratigraphic position renders its usefulness as a member very doubtful but it may be a mappable bed. Some small quartzite bodies mapped by LaForge (1932) in the northern edge of the Quincy Granite were called the Milton Quartzite by Billings (1929). This light- and dark-gray fine- to medium-grained quartzite lies west of both surface and subsurface exposures of similar quartzite of the Weymouth Formation, which is intruded by the Quincy, and not part of the Cambridge Argillite (Chute, 1969; Carnevale, 2007). Other quartzitic sandstone interbeds in the northern part of the Cambridge were thought by Kaye (1984a) to be similar to the Westboro Formation, which is primarily quartzite, schist and amphibolites, and lies nearby, just north of the basin. However, the Westboro is at least 50 million years older, because it is intruded by the Dedham Granodiorite and other granites of the batholith (Bell & Alvord, 1976; Bailey, 1984), and is very different in sequence, thickness, metamorphic grade and degree of deformation.

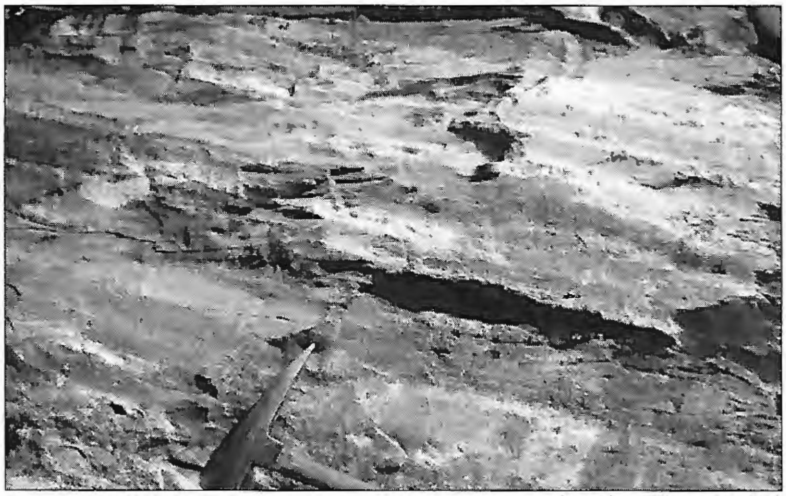
The Cambridge Argillite is found overlying various parts of the Roxbury Conglomerate

(see color version on page 453)

FIGURE 3-21. Thin-bedded, laminated Cambridge Argillite with slump folds at Rainsford Island.

(see color version on page 454)

FIGURE 3-22. Contorted laminated mudstone bed slump in sandstone of the Cambridge Argillite at Squaw Head, Squantum, Quincy.



(see color version on page 454)

FIGURE 3-23. Siltstone and mudstone of the Lower Cambrian Weymouth Formation at Brewster Road in Quincy.

and Mattapan Volcanic Complex (Kaye, 1980a) with a slight angular unconformity (as previously discussed). The upper contact of the Cambridge Argillite appears to be conformable and gradational from the similar lithology on either side, but the actual contact has not been recognized. Some tuffaceous rock of the basin is of similar color as the Braintree and Weymouth argillite, and the redbeds and quartzite found in the Cambridge could be Cambrian according to Kaye (1982a). According to Bailey (2005), about 290 meters (950 feet) of strata are exposed on Slate Island in Hingham Bay, where the beds are nearly vertical to slightly overturned and strike N72° to 80°E; Woodhouse made similar observations. The field relationships of the rocks exposed on Grape, Slate and Raccoon islands support the conclusion they are of the same Late Proterozoic age. Bailey (2005) subdivided the argillite into the following lithologies in order of abundance:

(see color version on page 455)

FIGURE 3-24. Argillaceous beds with brown cherty layers, Lower Cambrian Weymouth Formation at East Point in Nahant.

- thin-bedded laminated dark-gray mudstone and fine sandstone;
- very thinly laminated dark-gray to black mudstone;
- laminated mudstone to sandstone with cross-laminated sandstone lenses;
- graded-bedded sandstone with platy mudstone clasts overlying scour surfaces or with mudstone flames;
- slump folded and clastic mudstone-sandstone in 0.2 to 3.0 meter (0.65 to 10 foot) intervals; and,
- conglomerate with pebbles, granules and highly deformed sandstone-mudstone fragments in a sandstone to mudstone matrix forming 2 to 20 centimeter (1 to 8 inch) thick beds.

The thickness of argillite, above the conglomerate, including the sandstone and quartzite, has been estimated to be at least 700 meters (2,300 feet) and possibly 1,600 meters (5,300 feet) or more (LaForge, 1932). Because of fault offset and duplication of strata, an accurate thickness is indeterminate and Crosby (1880) thought it much less than the apparent thickness. Borings at Trinity Church in Boston's Back Bay penetrated nearly 457 meters (1,500 feet) of argillite and a diabase dike (Paulson, 2002).

Three types of microfossil acritarchs were found in strata beneath the Cambridge Argillite. The assemblage is similar to that found in European strata of Vendian, Late Proterozoic, age (Lenk *et al.*, 1982) also referred to as Ediacaran. The gypsiferous argillite in which they are found indicates deposition in a saline basin. The Ediacaran taxon *Aspidella* are present on Grape Island, Slate Island and in Hewitt's Cove in Hingham; however, it is still not clear whether these are organic or not (Clark, 1923; Bland, 2000; Bailey, 2005; Bailey & Bland, 2001). A few annelid or crustacean trails have been found in the Mystic quarries in Somerville (Woodworth, 1894b). A reported finding of trilobites on Grape Island was investigated in April 2008 by Woodhouse, who found none, nor any other mega fossil. The rock is similar to that on nearby Slate Island and is concluded to be Cambridge Argillite.

Cambrian Strata

Scattered small remnants of Cambrian (542 to 488 million years ago) strata are present in and adjacent to the Blue Hills at the south side of the basin and also in patches along the northeastern side of the Boston Basin, notably at Nahant. Other localities with strata similar to that at Nahant were found farther north in Essex County and at Jeffrey's Ledge, which lies offshore 73 kilometers (45 miles) northeast of Nahant (Sears, 1890 & 1905). Fossil-bearing clasts also are found in the sediments at Cohasset and on Martha's Vineyard (Walcott, 1893; Woodworth, 1893). These Cambrian strata are similar to the upper Cambridge Argillite and are made up of argillite, siltstone and minor limestone interbedded with increasing amounts of quartzite upwards. The composite section, from the bottom up, consists of the Weymouth Formation, Braintree Argillite, Monatiquot Formation and Green Lodge Formation. Some Early Cambrian volcanic strata are present to the north in southern New Brunswick (Landing *et al.*, 2008), but they are absent here. Details on the sequence and paleontology are given by Fletcher *et al.* (2005). The general history of the Cambrian Period was a time when sediment from low mountains to the west was carried into the sea that was advancing from the east. By the time the Boston Basin was overtopped, the relief was much lower or the uplands far enough away that only fine sediments reached the sea. Later erosion of the region from the Mid-Ordovician onward removed almost all of the Cambrian section.

Weymouth Formation. The Weymouth Formation is found in Weymouth, Nahant, Revere and Hingham on the southwest edge of Massachusetts Bay and also to the south in the Narragansett Basin (Bouve, 1893; Shaler *et al.*, 1899; Bailey, 1984; Landing, 1988; Ross & Bailey, 2001). The formation is primarily a thinly laminated argillite containing small carbonate nodules and beds and lenses of fossiliferous limestone, siltstone and fine-grained sandstone. The Weymouth is characterized by reddish and greenish-gray colors (see Figure 3-23). The red color, which may grade to gray, is considered by some to be indicative of the Early Cambrian, although some of the color could be due to effects of the Quincy Granite. The formation observed in the Weymouth-Braintree Tunnel consists of maroon to gray, very thinly-bedded to laminated argillite and siltstone with local intervals of sandstone and very light gray to buff quartzite that is locally intruded by the Quincy Granite (Davidson, 2003; Deere *et al.*, 2004). At Nahant, the formation is dark-gray, greenish-gray to black with some thin white cherty limestone (see Figure 3-24). Brachiopods, conical hyoliths, stenothecoida and aldanellids belonging to the Lower Cambrian have been found at Nahant, but no trilobites, other than in a pebble (Bailey, 1984). In the Mill Cove area of Weymouth, the type locality *Olenellus* trilobite assemblages indicative of the Early Cambrian were found as well as in loose rock to the east (Walcott, 1892). The base is not well exposed, but Kaye and Zartman (1980) were of the opinion that the formation grades into the Cambridge Argillite in the Boston Basin below. It is reported to lay

(see color version on page 455)

FIGURE 3-25. Middle Cambrian Braintree Argillite, slightly metamorphosed by Quincy Granite at Hallum Street in Milton.

uncomformably on the Proterozoic granite near King Oak Hill in northern Weymouth (Fletcher *et al.*, 2005). Crosby (1900), who saw more of the formations, thought the Cambrian was very thick, on the order of 1,000 meters (3,300 feet) or more, as did LaForge (1932), and the Braintree-Weymouth Tunnel section indicates 600 meters (2,000 feet) or more (Davidson, 2003). A recent surface measurement gives a 417 meter (1,368 foot) thickness (Fletcher *et al.*, 2005). The exposed section at Nahant (Ross & Bailey, 2001) totals 167 meters (548 feet). The base of the Weymouth at Hoppin Hill in the Narragansett Basin is considered by Landing (1988) to rest unconformably on very thin basal quartzitic sandstone that separates the unit from the underlying granite. Landing calls this sandstone the North Attleboro Formation, but it is much too minor and limited for formational or any other rank.

Braintree Argillite. The Braintree Argillite occurs along with the Weymouth Formation in a discontinuous 14.5 kilometer (9 mile) long belt of rock that stretches from the Blue Hills to Weymouth in the south and also locally in Nahant and Lynn to the north. The Braintree occurs chiefly in a limited area within and around the Quincy Granite in Quincy and Braintree. *Paradoxides*-bearing debris characteristic of the Braintree also is found on Georges Island (Crosby, 1880), but this may be from the basin border to the northwest where Crosby (1880) describes lithology similar to the known Cambrian. The Braintree is a non-calcareous green to dark-gray to black massive argillite (see Figure 3-25). It was first called a slate and was so named because the rock is thin-bedded and weathering may cause splitting along the bedding to impart a "slaty" appearance. In the Blue Hills, the Braintree is a dark-gray argillite containing thin beds of siltstone (Chute, 1969) and is marked by red and purplish beds near Fore River. The rock has been baked to a hornfels by contact metamorphism adjacent to the Quincy Granite to the degree that it was quarried for arrowheads for several thousand years. Neither the contact with the underlying Weymouth is exposed nor the top of the formation. LaForge (1932) estimated its thickness to be on the order of 300 meters (1,000 feet) and C.S. Lord measured 300 meters (985 feet) of section at the Old Quincy Reservoir (in Chute, 1969), where the Monatiquot Formation is apparently included.

It has been assigned to the Middle Cambrian (521 to 501 million years ago) because it contains the trilobite fauna *Paradoxides* that includes the largest trilobite, *Paradoxides harlani* (Geyer & Landing, 2001; Fletcher *et al.*, 2005) (see Figure 1-24). Unfortunately construction and demolition that dates back to the 1940s at the Fore River Shipyard and blasting for a new shopping center in Braintree have destroyed the type locality for *Paradoxides*. Only a remnant is left of this fossil-bearing layer. The formation is intruded by the Late Ordovician Quincy Granite.

Monatiquot Formation. The Monatiquot Formation lies conformably over the Braintree Formation and beneath the Green Lodge, with a slight unconformity in the eastern Blue Hills around Braintree. It was separated from the Braintree on the basis of the quartzite and limestone interbeds. The Monatiquot Formation consists of dark-gray shaly mudstone, thin quartzite and minor dark-gray limestone with interbedded ripple-marked quartzitic sandstone in the upper part (Lord, 1972). The formation is 100 meters (328 feet) plus thick. The contained trilobite assemblage shows a Middle Cambrian age (Fletcher *et al.*, 2005).

Green Lodge Formation. Very limited exposures of the Green Lodge Formation are present on the southwest side of the Blue Hills along Route 128 in Dedham (Rhodes & Graves, 1931; Chute, 1966). It consists of light-gray quartzite interbedded with dark-gray phyllite, most of which has light-gray siltstone laminae. The formation was dated as Late Cambrian by poorly preserved brachiopods. Chute (1966) estimated that 150 meters (500 feet) are present and Rhodes and Graves (1931) interpreted that the thickness to be not less than 300 meters (1,000 feet).

Ordovician Strata

The Early Ordovician strata (488 to 443 million years ago) have been stripped away by erosion from the Boston area, except perhaps for small scattered remnants in the Blue Hills, such as the quartzite inclusions, described by Chute (1969) in the Quincy Granite, in the northwestern Blue Hills. Their description, however, can be pieced together from the very abundant clasts preserved in the later conglomerates and glacial debris found to the south. The layers of coarse clasts of the Ordovician rock in the Pennsylvanian formations indicate nearby sources and that the region from Boston to the South Shore must have been blanketed by the Ordovician at one time. These strata are important in the light they shed on the geologic conditions existing across the Boston Basin in the Ordovician, the tightened age control on some other units and the subsequent periods of erosion. The silts and sands deposited during that time from hills to the west suggest nearer shore conditions than the finer Cambrian strata.

A great change came about in the Late Ordovician when a volcanic complex formed in the Blue Hills, after uplift and erosion, as part of the widespread Taconic Orogeny. The conduit is marked by two granitic bodies that intruded part of its early rhyolitic ash deposit of which only a remnant survives. Such ash flow deposits normally vent from a wide caldera on a large volcano. The volcanic debris, which may have covered much of Boston deeply, would have been accompanied by faulting during caldera collapse, but these faults have yet to be recognized.

Unnamed Quartzite. The few small exposures of light-gray quartzite pendants within the Quincy Granite (Chute, 1969) may be part of the Green Lodge Formation or the now-eroded overlying Lower Ordovician Quartzite. This quartzite constitutes 80 to 95 percent of the clasts in the conglomerates of the Lower Pennsylvanian strata to the south. It also occurs as reworked clasts in the Pleistocene till deposits and outwash on Cape Cod, as pebbles on beaches across Rhode Island and southeastern Massachusetts, and is likely present as small local remnants (Perkins, 1920; Woodworth & Wigglesworth, 1934). The quartzite clasts are white to medium-gray, well-sorted, mostly thin-bedded, fine-grained sandstone to siltstone, composed predominantly of quartz, and weathers slightly lighter. Thin beds, 1 to 10 centimeters (0.5 to 4.0 inches) thick and commonly graded or laminated, are seen in boulders (see Figure 3-26). The quartzite must have formed a thick unit and remnants several meters thick could easily be preserved in the Blue Hills. The rock is so similar to some beds in the Cambrian strata that it must be part of the same sedimentary sequence, which would have constituted a conformable overlying unit that may represent a shoaling from the muddier Cambrian deposits (Woodworth & Wigglesworth, 1899). Woodworth and Wigglesworth (1899) described the fossiliferous formation as composing at least three biological divisions. These divisions are: an Obolus zone of light-colored quartzite, which displays some marked cross-bedding, indicating shallow water conditions with currents, and probable interbeds of barren quartzite; a Scolithus zone of light-colored quartzite; and, a barren zone of quartzite of various colors.

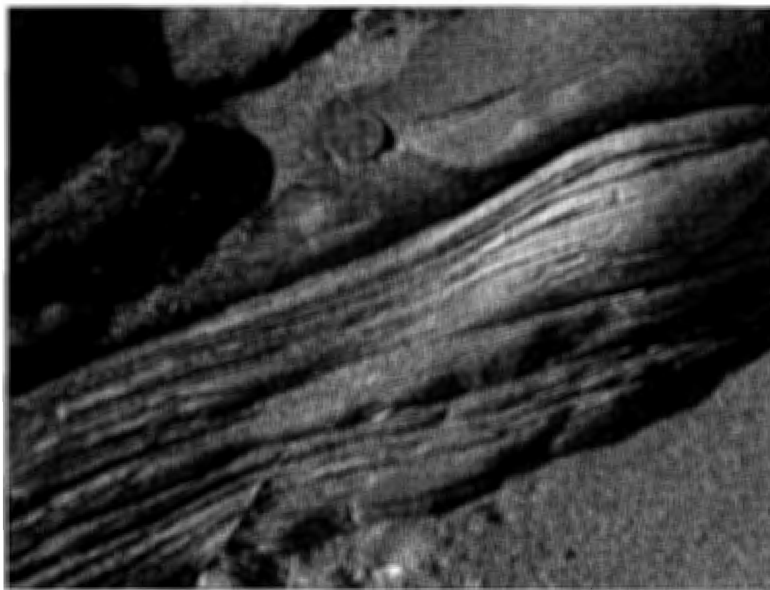


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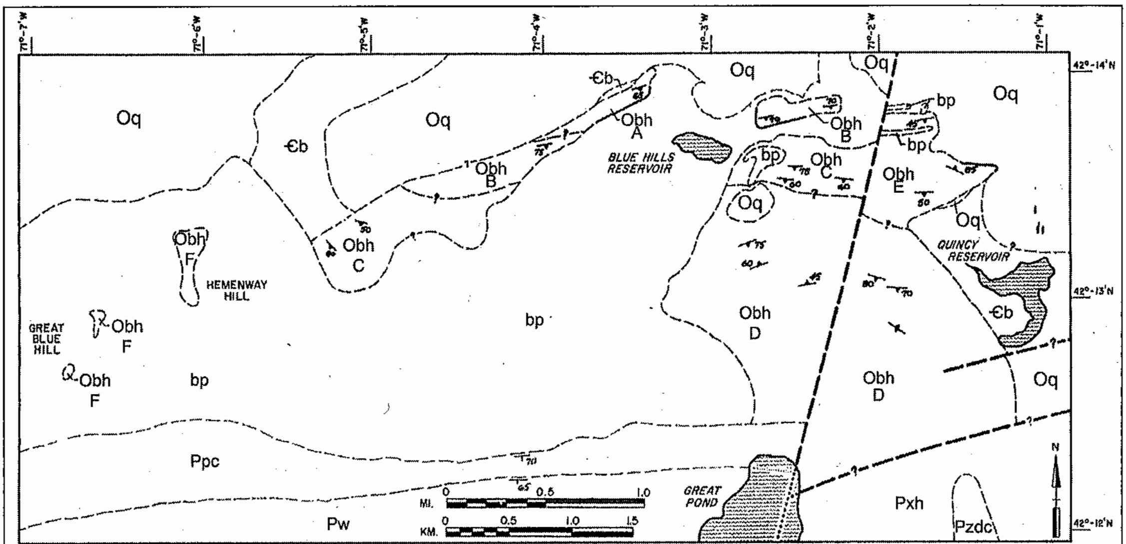
FIGURE 3-26. Ordovician siliceous sandstone and siltstone clasts in Pennsylvanian conglomerate at Sachuest Beach in Middletown, Rhode Island.

included the Ordovician. These pebbles could be from a rare interval or higher zone of dark siltstone. Because the Newfoundland fauna lay in the same general basin and the known Late Cambrian strata near Boston are not quartzite, the quartzite unit is considered Early Ordovician in age.

Blue Hills Rhyolite. Rhyolitic welded tuffs and a few flows form part of a Blue Hills igneous complex, which includes the Quincy Granite and Blue Hills Granite Porphyry in the Blue Hills (Chute, 1969; Kaktins, 1976). The rhyolite tuff comprises several remnants in the Blue Hills that form a steeply south dipping arc that is concave to the south. Chute (1969) considered the tuff part of the Mattapan Volcanic Complex as did Kaktins (1976), who described and named separate tuff units. However, since these volcanic rocks are apparently Late Ordovician in age, they cannot be part of the Late Proterozoic Mattapan and must constitute a different formation, which is herein named the Blue Hills Rhyolite from their position in the center of Blue Hills and general rhyolitic character. Six units of ash-flow tuff and rare lava of rhyolitic composition (see Figures 3-27 & 3-28) are separated and described by Kaktins (1976). Their colors vary widely from medium- to dark-gray, greenish- and purplish-gray to black and usually weather much lighter with a local brownish cast. They consist of various types of ash-flow tuff with different degrees of welding (fusing together from the heat retained in the flow), fine breccias and fine-grained flow rock. Most have the very fine layering and flattened pumice shard texture typical of welded tuff. The welded tuff is similar to the extensive Tertiary ash flow tuff of southern Nevada.

The six units described by Kaktins (1976) are herein grouped together as members of the Blue Hills Rhyolite (see Figure 3-27) in order

Remains of different species of the inarticulate brachiopods and scolithus burrows have been found in many quartzite clasts south, southwest and southeast of the Boston Basin (Easton, in Rogers, 1861; Walcott, 1898; Woodworth & Wigglesworth, 1934; Emerson, 1917). They are found from Block Island to Provincetown, with the most found on Martha's Vineyard. Walcott (1898) described *Obolus (Lingulobus) affinis* Billings, *O. (L.) spissus* Billings and *Obolus (Lingulella) rogersi.* Most workers considered the fossils correlative to those in the Potsdam Sandstone of New York (Rogers, 1861; Walcott, 1898; Emerson, 1917; Howell, in Mutch & Agron, 1963) and Late Cambrian in age, although Crosby and Barton (1880) considered them older. However, the Potsdam Sandstone of New York is now considered to straddle the Cambrian-Ordovician time boundary (488 million years ago) and Walcott (1898) matched these with species confined to Early Ordovician at Belle Island, Newfoundland. In addition, black chert pebbles in Miocene conglomerate at Gay Head on Martha's Vineyard contain corals, crinoid stems, graptolites and shells that are Silurian according to Woodworth and Wigglesworth (1934) — a designation that during that period



sgd = Diorite
wg = Border zone of the Dedham Granodiorite (Westwood Granite)
Cb = Braintree Formation
mv A-F = Blue Hills Rhyolite members – A, Great Dome Trail; B Wampatuck Hill Flow; C, Chickatawbut Road Flow; D, Pyritic Volcanic Rock; E, Pine Hill Flow; F, Hemenway Hill
qu = Quincy Granite
bp = Blue Hills Granite Porphyry
Ppc = Pondville Conglomerate
Pw = Wamsutta Formation

Modified from Kaktins (1976)

FIGURE 3-27. Geologic map of the southern portion of the Blue Hills igneous complex showing the distribution of the Blue Hills Rhyolite.

to clarify the stratigraphic relations in this area and aid in correlation. His named volcanic units are designated members and their cumulative thickness used for the minimum formation thickness. The designated south-topping type section extends eastward north of Chickatawbut Road from Randolph Avenue, passing east of the Blue Hills Reservoir to Pine Hill through the areas of the members described by Kaktins (1976). These members are from the base to the apparent erosional top: Great Dome Trail, Wampatuck Hill, Chickatawbut Road and Pyritic flow members. The position of Pine Hill and Hemenway Hill is uncertain. Their description and contacts are as described by Kaktins (1976). They are intruded by the Blue Hills Granite Porphyry and have no exposed base or top. The present aggregate measured thickness of the member is 1,190 meters (3,903 feet) and the original thickness must have been much greater. The composition of the tuff is very similar to that of the Quincy Granite and is probably an early extrusive phase of the gran-

(see color version on page 455)

FIGURE 3-28. Ash flow tuff of the Chickatawbut Road Flow Member of the Blue Hills Rhyolite at Blue Hills.

ite (Chute, 1969). Small areas of similar rhyolitic rock are described as extending westward into Westford where it was included with the Mattapan (Chute, 1966), but probably is part of the Blue Hills Rhyolite. It apparently was deposited about the same time as the Lynn Rhyolite north of the Boston Basin that is related to a volcanic center about Cape Ann.

These terrestrial (land) volcanic tuffs of the Blue Hills Rhyolite must be younger than the marine Cambrian-Ordovician strata and are intruded by both the Blue Hills Granite Porphyry and the slightly older Quincy Granite of Late Ordovician age and overlapped by Early Pennsylvanian strata (Chute, 1966 & 1969; Lyons *et al.*, 1976). The radiometric age dates of the flows and the associated granites show a range from Late Ordovician to Early Devonian (Lyons & Kreuger, 1976; Bottino *et al.*, 1970; Kaktins, 1976). These, and many other, wide-ranging age dates were reviewed by Sayer (1974) who felt that the 422 to 437 million years ago (Late Ordovician to Early Silurian) age of Zartman and Marvin (1971) was probably the closest. The very similar Cape Ann Granite also is well-dated as Late Ordovician (Zartman & Marvin, 1971; Dennen, 1991a, 1991b & 1992). Fossil evidence provides a closer control and shows that the region was uplifted and eroded prior to deposition of Silurian-Devonian strata (Gates, 1969; Gates & Moench, 1981; Barosh, 2005). The Blue Hills Rhyolite, therefore, is Late Ordovician in age and part of a regional volcanic outbreak at that time (461 to 444 million years ago).

Pennsylvanian Strata

A long stratigraphic gap exists in the Boston area between the Ordovician and Pennsylvanian (444 to 316 million years ago). The Early Silurian, Devonian and Mississippian strata in Maine and New Brunswick show that this was a time of red sandstone, shale and volcanic rock deposited on land and mixed with some near-shore limestone, with the volcanic rock tapering off in the Mississippian when coal beds first appear in the section. A thick section of this Silurian-Devonian strata is preserved in northeastern Massachusetts and Devonian volcanic rock lies in west-central Rhode Island, indicating that some was probably present around the Boston Basin before being eroded away prior to the Pennsylvanian. Also, remnants may be buried beneath the Pennsylvanian rock. In the Pennsylvanian Period, shale, sandstone and coal accumulated on land in a valley system, which extended from southern Rhode Island and off coastal New England into the Canadian Maritimes, with conglomerate along the highland borders. The Norfolk Basin (see Figure 3-29), which was part of this system, contains strata (described below) that was derived from an eroding Blue Hills and what was at that time the surrounding Ordovician strata.

Pondville Conglomerate. The Pondville Conglomerate forms the basal Pennsylvanian strata in the Norfolk Basin south of the Blue Hills. It was divided into two members (see Figure 3-29) by Chute (1966). The lower member consists of cobble and boulder conglomerate made up of quartzite, volcanic rock and granite clasts in an arkosic sandstone matrix. The upper member (see Figures 3-30 & 3-31) consists of gray coarse-grained arkosic sandstone and interbedded granule to pebble conglomerate (Chute, 1966; Stanley, 1968). The lower member rests unconformably on the weathered surface of the Blue Hills Granite Porphyry and grades into the upper member, which, in turn, grades into the overlying Wamsutta Formation. The lower member of the Pondville is 300 to 520 meters (1,000 to 1,700 feet) thick and the upper is 180 to as great as 460 meters (600 to 1,500 feet) thick (Chute, 1966) for a total in the estimated range of 480 to 900 meters (1,600 to 2,950 feet). The Pondville is Early Pennsylvanian on the basis of contained plant fossils (Lyons *et al.*, 1976) and noted for the large trunks of Calamites at Canton Junction.

Wamsutta Formation. The Wamsutta Formation is a red arkosic unit found in the Norfolk Basin and northwest corner of the Narragansett Basin and laps up onto the Blue Hills. The formation (see Figure 3-32) consists predominantly of red, non-marine, fined-grained, cross-bedded arkosic sandstone with interbeds of red shale, gray granule and pebble conglomerate, and minor purple and green shale, green sandstone and light-gray shaly limestone (Woodworth & Wigglesworth, 1934; Chute, 1966 & 1969). However, it grades into

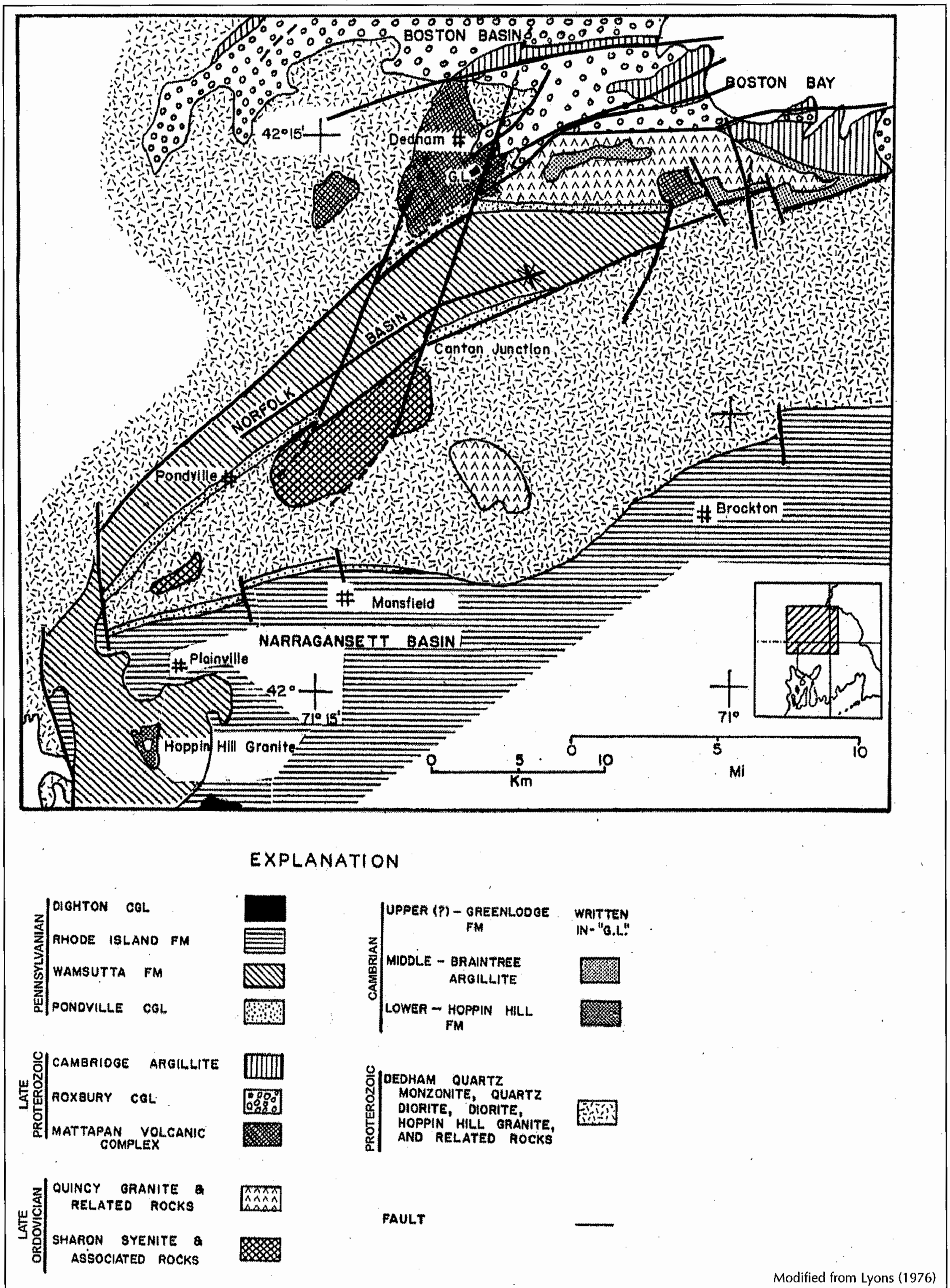


FIGURE 3-29. Map of the Norfolk Basin showing stratigraphy and structural relation with the southern border of the Boston Basin.

(see color version on page 456)

FIGURE 3-30. Pondville Conglomerate, upper right, overlying Blue Hills Rhyolite volcanic rock, left side, along an irregular contact in the Norfolk Basin on the north side of Route 128 in Milton.

(see color version on page 456)

FIGURE 3-31. A close-up view of Pondville Conglomerate just above lower contact, at Routes 128 and 28 in Quincy.

gray rock locally. Pennsylvanian strata also lie offshore of the bay to the northeast as indicated by pieces of silicified wood found at Cape Cod (Kaye, 1964c). Red rhyolite and basalt flows occur in the northwest corner of the Narragansett Basin (Woodworth & Wigglesworth, 1934; Quinn & Oliver, 1962; Quinn, 1971; Maria & Hermes, 2001). No top is present in the Norfolk Basin, but to the south in the Narragansett Basin it is reported to grade into the Rhode Island Formation (Quinn & Oliver, 1962). Interfingering facies changes occur both in the bottom and top of the unit. The lower part of the Wamsutta is partly equivalent in age with the earlier Pondville and the upper part with the Rhode Island Formation (Lyons *et al.*, 1976). About 900 meters (3,000 feet) is estimated to remain in the Norfolk Basin by Chute (1966), but Shaler *et al.* (1899) had earlier considered it much thinner.

The Wamsutta appears to be derived from highly weathered granite adjacent to the Pennsylvanian Basin, which also explains the lack of granitic clasts in the basal Pondville Conglomerate (Woodworth & Wigglesworth, 1934). Granite clasts are introduced later, with increased activity along the borders of the basins. The deposition of the Wamsutta is thus indicated to have been preceded by a long intermittent period (444 to 318 million years ago) of subaerial weathering that is the main reason for the lack of Mid-Paleozoic strata. Some apparently intrusive felsite at Diamond Hill in Rhode Island might be a vent that supplied some of the volcanic material (Quinn, 1971).

Most early workers considered the Wamsutta to be Devonian due to its red arkosic nature similar to the Devonian Old Red Sandstone in Ensgland (E. Hitchcock, 1841; Lyell, 1845a & 1845b; C.H. Hitchcock, 1871), but since 1880 it has been dated as Carboniferous (combined Mississippian and Pennsylvanian) in age, from the nature of the associated

(see color version on page 456)

FIGURE 3-32. Red sandstone beds of the Wamsutta Formation, southbound lane of Route 24 just south of Route 128 in Randolph.

numerous plant fossils (Crosby & Barton, 1880; Foerste, 1887, in Woodworth, 1899; Woodworth, 1894c; Knox, 1944). Calamites and Cordaites are found in the Wamsutta (Woodworth & Wigglesworth, 1934) and many other plants in the interfingering Pondville Conglomerate and Rhode Island Formation. It still was tempting to correlate it with the Silurian-Devonian redbeds in northeastern Massachusetts and a recent Late Devonian radiometric age date from the unit by Thompson and Hermes (2003) has revived some discussion for the Devonian assignment. However, the consistent Pennsylvanian age given by the many plant studies make this age assignment extremely doubtful. The plant fossils in the stratigraphic sequence show the Wamsutta to straddle the Early-Middle Pennsylvanian boundary (Lyons *et al.*, 1976; Oleksyshyn, 1976).

Cretaceous & Tertiary Strata

The region remained high and red shale, sandstone and conglomerate were deposited in scattered basins around Boston in the Late Triassic and Early Jurassic (see Figure 2-29). These were almost all stripped away before fringing coastal plain deposits formed in the Atlantic Ocean that rose a little higher than present. The highly weathered land contributed clean clay, silt and sand. These deposits only remain locally now: on the coast just south of Boston, apparently at a few locations in the city itself and possibly other thick deposits offshore.

Coastal Plain Strata. Test borings in isolated areas of Boston and surveys of one outcrop have encountered strata that appear to be patchy remnants of Late Cretaceous (100 to 65 million years ago), Eocene (56 to 34 million years ago) and Miocene (23 to 5 million years ago) sediment. These borings indicate that coastal plain deposits of these ages, such as the remnants seen along the shore south of Boston at Scituate, at Marshfield and Duxbury, and at the larger section on Martha's Vineyard, may occur as patches within the basin as well. The strata described by Bowman (1905 &

1906) as apparently Cretaceous to Miocene at Third and Fourth Cliffs in Scituate, and those not far to the south at Marshfield where Hitchcock (1833 & 1841) first noted Miocene greensand (W.O. Crosby, in Upham, 1890), show the type of sediments that may occur in the Boston Basin. At Third Cliff, a couple of meters (6 feet) of very pure light yellow clay that grade up into 7.6 meters (25 feet) of yellow and white fine- to coarse-grained cross-bedded sand, with glauconite and sponge spicules, is probably of Late Cretaceous age. These strata are unconformably overlain by 3 meters (10 feet) of dark red coarse-grained cross-bedded sand, with patches of black sand at its base, of presumably Tertiary age. This section is cut into by a channel filled with dark-green sand and clay that are capped by till. At Fourth Cliff, 0.3 to 0.6 meters (1 to 2 feet) of coarse black sand of smoky quartz and biotite, 3 meters (10 feet) of coarse dark-red sand and 3.7 meters (12 feet) of dark-green sand and clay are above the Cretaceous. The highly glauconitic Miocene greensand in near-horizontal beds rests on granite over more than a square mile to the south in Marshfield and matches the lithology and fossils of a similar bed at Gay Head (Shaler, 1890; Dall, in Woodworth & Wigglesworth, 1934). The missing underlying beds probably reflect the coastal Oligocene uplift. These strata and those in Boston are correlated with ones that appear so clearly in the Gay Head (Aquinnah) cliffs of Martha's Vineyard, where blocks of coastal plain sediments were thrust up by an advancing glacial ice front, as happened at Beacon Hill (Woodworth & Wigglesworth, 1934; Kaye 1964a & 1964b).

One of six borings for the Boston Common Garage in 1960 drilled into 3 meters (10 feet) of what was described by Kaye (1961) as coarse quartz sand in a white clay matrix. This sand lies below 26 meters (85 feet) of Pleistocene strata and above the argillite at an elevation of roughly –21 meters (–70 feet) MSL. The sand unit was considered similar to the kaolinic quartz sand of the late Cretaceous Raritan Formation found on Martha's Vineyard, Block Island, Long Island and New Jersey. Kaye was familiar with both the Raritan as well as kaolinized argillite that might look similar, so his assignment is considered correct. Cretaceous clay also was described in the boring(s) at the White Fuel Company's location in South Boston by Donald Reed of Haley & Aldrich and Kaye, and an unconfirmed exposure of Cretaceous clay was reported by Kaye along the Lynn shore north of Boston. Drilling near the old Boston Neck encountered gray-white shale and some sandstone, which Pearsall (1937) suggested was Cretaceous or Tertiary strata filling an ancestral Charles River channel (Upson & Spencer, 1964). However, Kaye (1982b) considered this a tuffaceous part of the Cambridge Argillite. Boulders with Eocene fossils found in the Pleistocene at Truro on Cape Cod were considered by Crosby (1881) to be from a deposit in the Boston Harbor. However, the deposits along the south shore, near Scituate and Marshfield, would lie near the same pathway. This also applies to the source of the soft limestone boulders with well preserved Cretaceous fossils reported in the drift of Cape Cod.

Another sequence that was reported as being very similar to the Raritan by F.G. Clapp (1907) was from one of the borings in downtown Boston for the Ames Building, at the corner of Tremont and Court streets. This 41.5 meter (136 foot) section of light gray to white clay, occurred between the Pleistocene and the argillite at elevations of –13.5 to –55 meters (–44 to –180 feet) MSL. But Woodhouse observed kaolinized argillite at similar depths in test borings drilled in the immediate area for the nearby Boston Company Building on Court Street, the New England Merchants Building on Tremont Street and the 60 State Street building. It is, therefore, more likely that altered argillite underlies the Ames Building.

Intrusive Rock

The Boston Basin has been intruded by considerable igneous rock throughout its history. These intrusions were molten igneous bodies that flowed along fractures or penetrated the country rock. The largest bodies are the two Late Ordovician granites that served as volcanic conduits in what is now the eastern Blue Hills. The rest are dikes, sills and small plutons of predominantly basaltic and diabasic composition that invaded the basin during

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FIGURE 3-33. Amygdaloidal basalt of the Brighton Basalt (Melaphyre) at Wiltshire and Chestnut Hill streets in Brighton.

periodic times of extension since its inception. They range in age from ones associated with the pre-Cambrian Mattapan Volcanic complex to the Cretaceous with the pre-Late Ordovician intrusions being noticeably altered. The dikes are almost all vertical or steeply dipping, and they form several sets and follow fault zones.

Brighton Basalt (Melaphyre). Altered basalt and andesite, referred to early as melaphyre in the Boston Basin, occur as small stocks, dikes and sills that intrude the Roxbury Conglomerate as well as flows interbedded within the formation. The Brighton Basalt was described and named the Brighton Melaphyre by LaForge (1932), who also included similar dikes found elsewhere (see Figure 3-33). (The term *melaphyre* is now confusing to many and the more familiar rock type name, basalt, is used in this section for clarity.) The Brighton apparently represents one or more resurgence of the volcanic activity at, or adjacent to, the southern border of the Boston Basin distinctly later than the Mattapan Volcanic Complex and has the same Late Proterozoic age as the Roxbury Conglomerate. The intrusive portion of the Brighton Basalt apparently acted as feeders for the flows and associated beds of tuff and breccia found interbedded in the Roxbury. It is a little unusual since it is both an intrusive and interbedded rock, which could be treated as a stratigraphic unit. However, its extremely variable stratigraphic thickness and placement makes it difficult to be described as a member of the Roxbury and it is best treated as an intrusive igneous unit. The Brighton Basalt is found across the western and southern edges of the basin and was well exposed in the City Tunnel and City Tunnel Extension. It occurs interlayered with conglomerate and argillite along the shore from Hingham to Hull (Crosby, 1893 & 1894; Bell, 1975a & 1975b) where it has been repeatedly described in field guides (Crosby, 1895; Bailey, 2001; Ault, 2003), and the same relations occur at the western border of the basin (Tierney, 1950b & 1951; Tierney *et al.*, 1968; Nelson, 1975a; Kaye, 1980a).

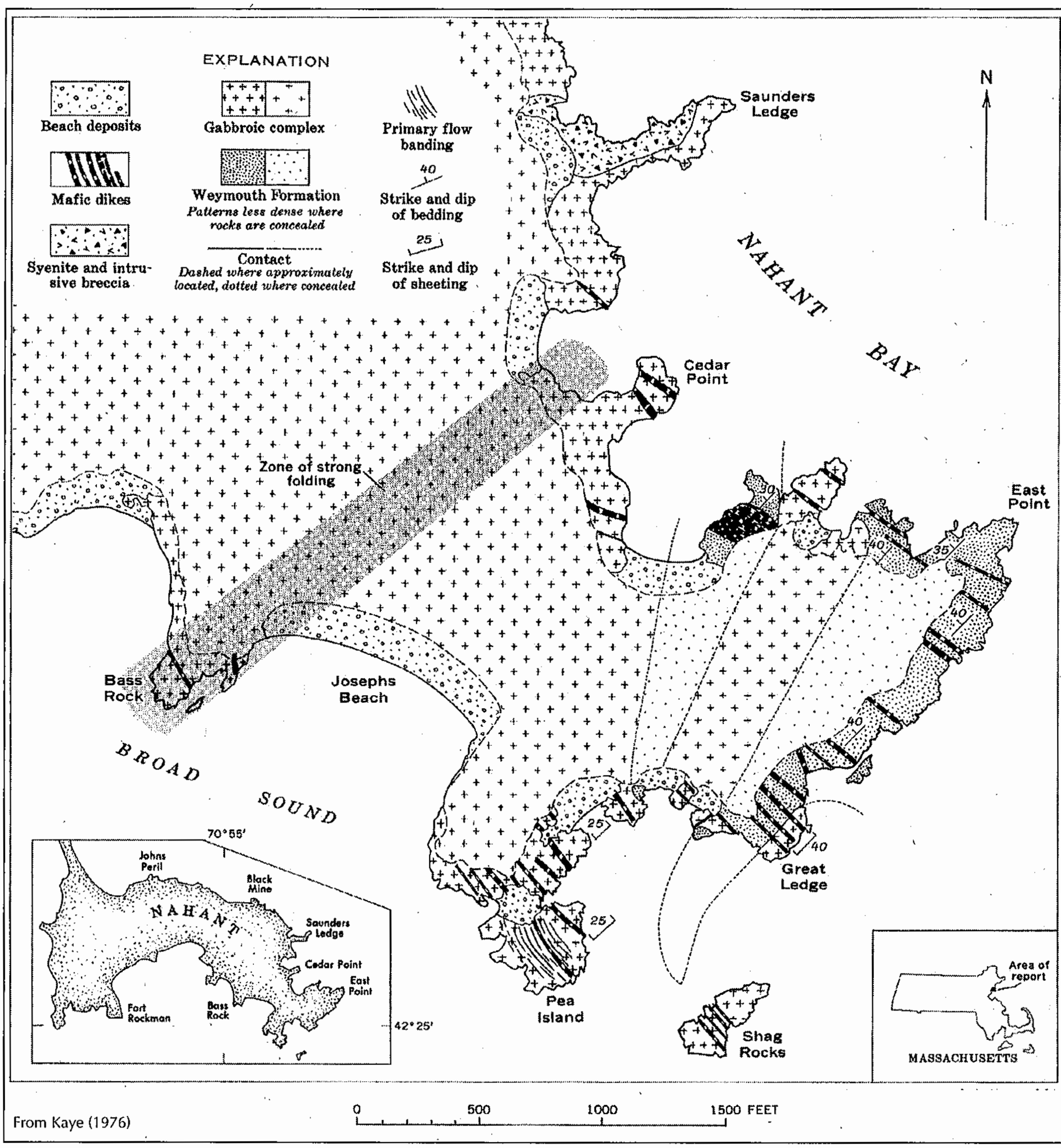

FIGURE 3-34. Geologic map of southeastern Nahant.

The Brighton is an altered greenish-, brownish-, reddish-, bluish- purplish-dark-gray or black amygdaloidal (mineral-filled almond-shaped vesicles) basalt and andesite, which occurs as generally porphyritic, massive, layered, brecciated flows, spilitic pillow lavas, feeder pipes and dikes (LaForge, 1932; Nelson, 1975a; Kaye, 1980a). The typical basaltic rock of the Brighton seen in the tunnels is a dark-green to a yellow-green, locally brown to black medium-grained rock, which in places is strongly mottled in shades of green and red (Tierney *et al.*, 1968; Billings & Tierney, 1964). It consists chiefly of albite, hornblende, chlorite, epidote and calcite. Small phenocrysts of kaolinized calcic feldspar are present in places. Tiny amygdules also are locally abundant in diffused irregular bands and filled by calcite, epidote, chlorite or quartz. Flow layering is marked by alternating bands of slightly different color and composition. Basaltic lapilli and crystal tuffs are commonly associated with it.

LaForge (1932) noted that "[t]he interbedded layers range in thickness from a few feet to several hundred feet and in length from 100 feet or less to more than a mile." Nelson (1975a) estimated a thickness of 1,070 meters (3,500 feet) at the west edge of the basin, but this area has very few outcrops and many unmapped faults and may be much less. Thickness at the west edge of the basin is clearly more than at the eastern shore where it occurs only as one or two flows and some tuff beds (Crosby, 1880; Stone & Webster, 1995). The stocks in the City Tunnel Extension reach perhaps 550 meters (1,800 feet) across (Billings & Tierney, 1964). The flows lie close to the top of the Roxbury all along the south side of the basin (Crosby, in Grabau and Woodman, 1898; Bell, 1975a; Nelson, 1975a). The Brighton Basalt is not found to intrude the Cambridge Argillite, but is found interbedded in the Roxbury Conglomerate just below the Cambridge contact in Hull and Hingham.

(see color version on page 457)

FIGURE 3-35. Nahant Gabbro cut by a nearly contemporaneous diabase dike that is offset at East Point in Nahant.

Nahant Gabbro. Nahant and Little Nahant at the northeastern edge of the basin are formed chiefly of gabbro (see Figure 3-34). Similar bodies are intersected by the tunnels in the harbor and geophysical anomalies northeast of Nahant may indicate others (see Figure 3-12). The gabbro is a medium- to coarse-grained, dark-gray to black rock that varies to leuco-gabbro, olivine gabbro, pyroxene gabbro and syenite (see Figure 3-35). In addition, porphyritic tonalite is present on Little Nahant (Kaye, 1965; Ross & Bailey, 2001). Locally, it displays flow foliation and compositional layering and contains some intrusive breccia (Kaye, 1965). It invades the Weymouth Formation with sharp contacts, which generally parallel the bedding of the Weymouth that strikes northeast and dips 25 to 40 degrees to the northwest. It is cut by two prominent joint sets: one parallel to the contacts and the other strikes northwest with a steep dip.

The Nahant Gabbro is Late Ordovician in age. It is younger than the Early Cambrian strata of the Weymouth Formation, which it invades, and is cut by numerous basaltic dikes of probable Jurassic age. The gabbro was dated in the range of 493 (±31) to 461 (±35) million years ago, latest Cambrian to Late Ordovician, by Zartman and Marvin (1971) using Rb/Sr. Sills on its east edge are correlated with it by Kaye (1965), but found different by Ross and Bailey (2001), who dated one as 445 (±6) million years using 40Ar-39Ar. Structural features also indicate a Late Ordovician age. The Nahant Gabbro (see Figure 3-36) is crossed by a zone of very small wave-like folds, which appear to be essentially drag folds, developed in a shear zone associated with a northwest-dipping, N60°E-striking thrust fault (Kaye, 1965). Similar drag-like folds are seen in the Cambrian strata beneath one northeast-trending gabbro sill on East Point, Nahant (Ross & Bailey, 2001). Small-scale drag folds are commonly associated with thrust faults in the region. The thrust causing the drag folds would be part of the set in the region that both controlled and offset the Late Ordovician Andover Granite to the west and forms the nearby North Boundary Fault of the Boston Basin. The thrusting apparently ended by the Silurian (444 million years ago) when extensional faulting was underway. The com-ite, and which displays auto-injection and intrusive breccia locally. It is closely associated with the Cape Ann Granite to the north (see Figure 3-12) where the two rocks invade one another and both have a Late Ordovician age (Zartman & Marvin, 1971; Dennen, 1991a, 1991b & 1992).

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FIGURE 3-36. Nahant Gabbro, sheared with drag folds.

mon pre-Late Ordovician altered basic dikes are absent from the gabbro.

The compositional and structural variation of the gabbro strongly indicates it is an isolated, but more uniform, part of the Salem Gabbro-diorite, which lies to the north on the mainland. The Salem is a highly variable dark-gray to black basic intrusive rock that ranges from fine-grained gabbro to medium- to coarse-grained, equigranular to foliated dior-

Quincy Granite. The Quincy Granite, along with the Blue Hills Porphyry and associated flows of the Blue Hills Rhyolite, occur in the Blue Hills and have been referred to as the Blue Hills igneous complex (Chute, 1966 & 1969). The complex forms a lens-shaped body that extends between the Neponset River on the west and Braintree on the east. It is overlapped on the south by strata of the younger Norfolk Basin. The Quincy Granite (see Figure 3-37) is a medium-gray to dark-bluish-gray medium- to coarse-grained equigranular massive rock that locally has pink, red or dark green hues due to hydrothermal alteration (Chute, 1969). It is part of a line of riebeckite granites that extends from northeast Rhode Island to Cape Ann (Quinn, 1971) (see Figure 2-21) and makes a desirable building stone (see Figure 3-38) that was very extensively quarried (Williams, 2009). The Quincy both intrudes Cambrian strata and is intruded by the Blue Hills Granite Porphyry, and occurs as clasts within the Early Pennsylvanian Pondville Conglomerate. Radiometric ages indicate a Late Ordovician age, 450 (±25) million years ago similar to the Cape Ann Granite (Zartman & Marvin, 1971).

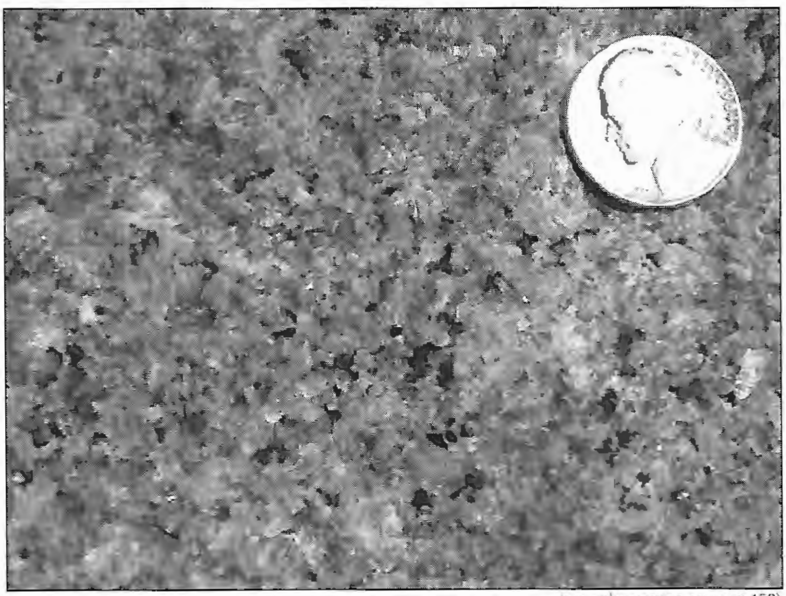

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FIGURE 3-37. Quincy Granite closeup at the Granite Rail Quarry in Quincy.

Blue Hills Granite Porphyry. The Blue Hills Granite Porphyry underlies most of the southern half of Blue Hills, where it is part of the same riebeckite granite complex as the Quincy Granite and invades both the Quincy Granite and Blue Hills Rhyolite (see Figure 3-27). The Blue Hills Granite Porphyry is a medium-gray to bluish-gray equigranular massive fine- to medium-grained granite that weathers lighter. Phenocrysts of perthite, quartz and riebeckite constitute 60 to 80 percent of the rock (see Figure 3-39) in fine-grained groundmass (Chute, 1966 & 1969).

This dark granite was considered a border phase of the Quincy Granite (Crosby, 1900), but Chute (1966) found xenoliths of Quincy within it and mapped the porphyry as a separate unit. However, this intermixing could be local. Loughlin (1911) explained the presence of the porphyry only on the south side of the Quincy as being due to the tilting of Blue Hills to the south and its erosion on the uplifted side. The porphyry along with the Quincy Granite and the Blue Hills Rhyolite are all part of the same volcanic episode and would be nearly contemporaneous. The Quincy probably invaded the Early Ordovician quartzite and the porphyry is unconformably overlain by the Early Pennsylvanian Pondville Conglomerate. The Blue Hills Porphyry has a Late Ordovician radiometric age (Zartman & Marvin, 1971).

FIGURE 3-38. Quincy Granite at the West Quarry in Quincy. (Courtesy of Thomas Crane Public Library, Quincy.)

Dike & Sill Rock. The rocks of the Boston Basin and adjacent areas are interlaced with a bewildering variety and number of dikes and sills of various ages and trends. They have been the subject of considerable study by many early to present geologists (Lane, 1888; Tarr in Shaler, 1889; Emerson, 1917; Crosby, 1905; LaForge, 1932; Chute, 1966; Ross, 1981, 1984 & 2001; Bailey, 1984; Kaye, 1965 & 1986; Ross & Bailey, 2001). They range from 2.5 centimeters to almost 168 meters (1 inch to 550 feet) in thickness and 1 meter to more than 6.4 kilometers (3 feet to more than 4 miles) in length (LaForge, 1932; Kaye, 1980a). The compositions, trends and ages of the dikes vary from place to place and a comprehensive regional study is yet to be done despite some excellent local studies. Differences in terminology and description make it difficult to combine studies. The great majority are basic rock and the chief division noted in the basin is

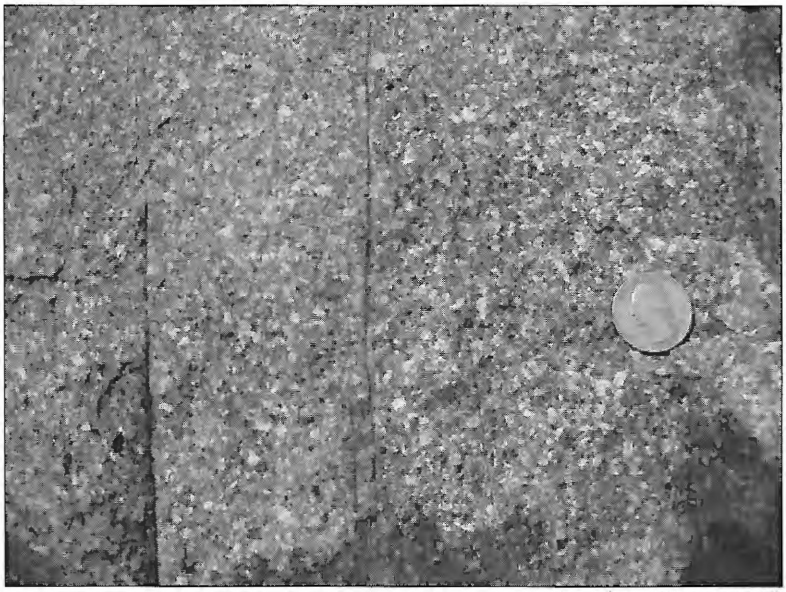

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FIGURE 3-39. Blue Hills Granite Porphyry at Blue Hills.

between altered and unaltered diabase dikes. The typical situation in the basin is well illustrated by the maps and stereographic diagrams prepared for geologic investigations for several tunnel reports. However, these hard, dense dikes tend to weather and, therefore, are under-represented in natural outcrop. Core from boreholes and the available outcrops show that, at places, sills are more numerous than dikes; while in others, dikes are clearly dominant, but overall steeply dipping dikes predominate. The dikes usually are straight, but some may be highly irregular.

The felsite dikes that are common in the areas of the Mattapan Volcanic Complex in the northern Norwood quadrangle may be the earliest since they are not known to cut the Roxbury Conglomerate (Chute, 1966). Most are probably rhyolitic and are purplish-, reddish-, greenish-gray to gray slightly porphyritic dikes that weather lighter and range up to 6 meters (20 feet) in width. Dark basic rock types are the most common and include diabase, lamprophyre and basalt, which are described by a confusing array of terms. At least fifteen petrographicly distinct rock types occur, most of which can be categorized as diabase, lamprophyre or keratophyre (Kaye, 1980a). The most commonly encountered ones on the surface in central and eastern Massachusetts are the fresh very dark-gray to black "Triassic" diabase dikes. However, fine-grained greenish-gray altered diabase is more common locally in the Boston Basin. Important also is a medium- to light-gray aphanitic trachyte that intrudes the argillite, mostly in the form of sills. Most sills are of a much altered, fine-grained trachyte (Bostonite) of medium-gray color and they resemble massive argillite in appearance (see Figure 3-19), but are harder

(see color version on page 458)

FIGURE 3-40. Curved greenstone dike cutting the Cambridge Argillite (on the right) at the southeast end of Calf Island.

(Kaye, 1980a). The trachyte is easily overlooked for this reason in both outcrop and tunnel mapping. Other more locally occurring basic dikes are associated with the Mattapan Volcanic Complex and the Brighton Basalt, which forms dikes and sills in the Roxbury Conglomerate. In addition, some felsic dikes related to the Quincy Granite occur in the Blue Hills.

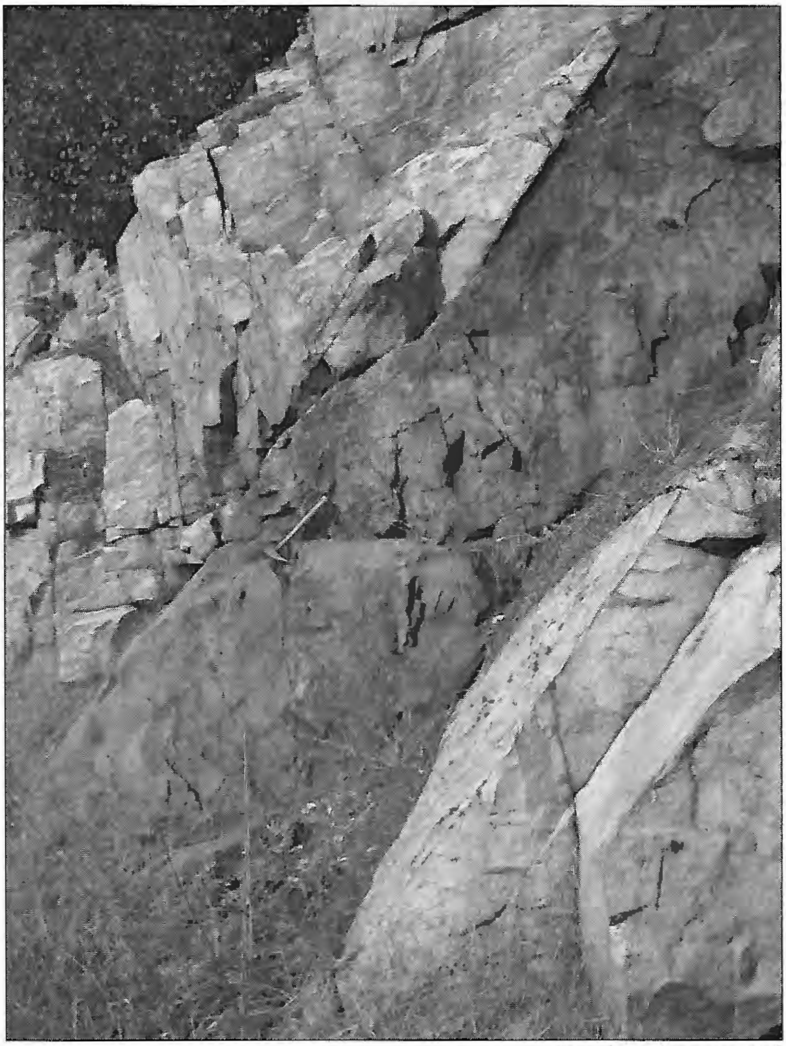

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FIGURE 3-41. Greenstone dike cutting Late Proterozoic Dedham Granodiorite on Route 128, near Exit 16, west of route 109 in Dedham.

Many fine-grained basic dikes and sills across the Boston Basin are altered to slightly greenish-gray to green from the development of chlorite and epidote, and may weather to light- to medium-brown. Irregular fine-grained dikes and masses in the bedrock portion of the Wellesley Extension Interceptor Tunnel at the west edge of Dedham were much altered to green as the adjacent Dedham Granodiorite was changed to red for a striking contrast. These dikes and masses were found to be diabase by spectrographic analysis by W.H. Dennen. Such altered diabasic dikes are described to be in rock in, and adjacent to, the basin west to the Bloody Bluff Fault (see Figures 3-40 & 3-41). The alteration makes it difficult to distinguish the different rock types and the old designation of greenstone for altered basic rock is useful. These altered dikes are more than one age, but the degree of alteration may not indicate their relative ages. In the Blue Hills, the oldest of two sets of dikes and sills, which cut the Cambrian strata and are cut by a few aplite dikes, are altered to greenstone (see Figure 3-41), but less so because of more sodic feldspars than a second set of dikes, which are much altered to epidote, chlorite and albite (Chute, 1966 & 1969). LaForge (1932) found his youngest set of altered dikes to cut the Cambrian strata and noted the scarcity of dikes in the Quincy Granite. Clasts of greenstone occur with those of the Ordovician siltstone and sandstone, which form Pennsylvania conglomerate in the Narragansett Basin, and indicate dikes had invaded these rocks and were subsequently altered before being eroded with them. No altered dikes are seen cutting the Late Ordovician intrusive rock around the basin, and the alteration apparently accompanied the Late Ordovician intru-

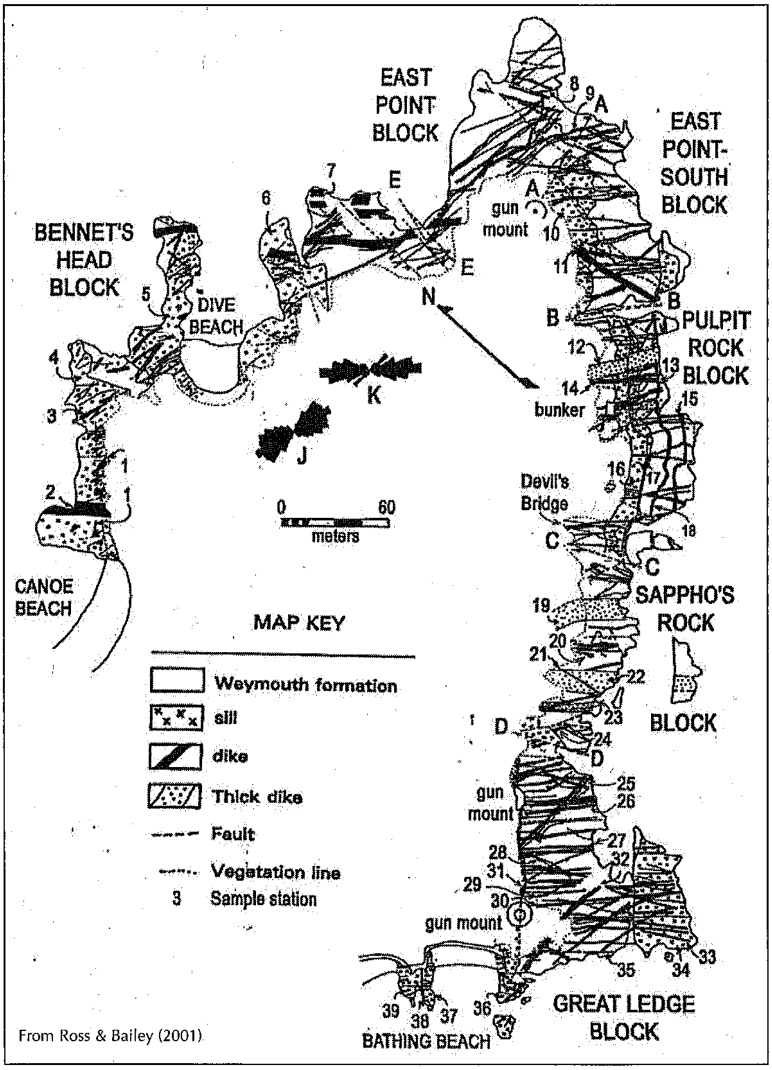


FIGURE 3-42. Map showing the diabase dike complex at East Point in Nahant.

sions of the Cape Ann and Quincy Granites and the Salem Gabbro-diorite.

The Cape Ann Granite on the north side of the basin is cut by many unaltered basic dikes that are of the same age (about 477 million years ago) or only slightly younger (Dennen, 1976, 1981 & 1992). Some dikes invaded the still mushy granite, which in turn squeezed into the dike rock (see Figure 3-35). They average slightly less than 1 meter (3 feet) in thickness (Dennen, 1976). Many of these dikes are basalt and apparently related to the Salem Gabbro-diorite and Nahant Gabbro (see Figure 3-42). Other aplite, pegmatite, syenite and rhyolite dikes of mutually intrusive sets of the same general age also are present. Near the Quincy Granite are apparently related dikes of light-gray or yellowish-gray porphyritic rhyolite, composed chiefly of quartz and kaolinized feldspar that cut the older rock (LaForge, 1932; Chute, 1966). Some of these dikes probably extend into the basin strata. These dikes may include those around the Nahant Gabbro, which appears to be related to the Salem (see Figures 3-35 & 3-42). The many petrologic variations present in the basic dikes at Nahant (Ross & Bailey, 2001) are consistent with the characteristically variable texture and composition of the Salem. Some dikes in the Medford area also are related to the Salem, but most occurred much later.

Fresh dark-gray to black north-south-trending diabase dikes form the youngest dike set. These dikes are found throughout the Boston Basin, its extension to the west and in the area to the south. The largest of such dikes known in the Boston Basin, the Medford Dike (see Figure 3-43), is a near vertical and strikes N19°E across the basin, reaching 171 meters (560 feet) in width, and continues into the older rock to the north. The dike is well exposed just beyond the Northern Border Fault in the Interstate 93 road cut at South Border Road. This area has been described in a great many field guides over at least the past one hundred and thirty years (Hobbs, 1888; Ross, 2001). This dike, and others in Somerville, contains fragments of the basement rock and the basin fill that have been carried through the argillite (see Figure 3-44). The Medford Dike is a fresh mottled light- and dark-gray, fine- to coarse-grained diabase and is dated at 190 (±6) million years (Ross, 1981), making it Early Jurassic in age rather than Triassic. The Medford Dike is similar in width to the large Higganum diabase dike that trends northeast across the central part of the state and that is dated at about 200 million years old. Equally large north-trending basic dikes are indicated by elongate magnetic anomalies southeast of Boston (see Figure 3-45). The Medford Dike is crossed slightly obliquely by a north-trending diabase dike and is considered separate from the ubiquitous smaller fresh fine-grained diabase dikes that center about N10°E. These north-trending dikes are found throughout the basin and range in width from 1 centimeter to 12 meters (0.2 inch to 40 feet) and in length from 1 to 800 meters (3 feet to half a mile) (LaForge, 1932). Many have well developed columnar jointing (see Figure 3-46), which along with chilled borders is indicative of rapid cooling upon invading relatively cool rock. This columnar jointing is compared with the greenstone dikes that normally do not have these features, showing that they invaded hot rocks and cooled slowly (se Figure 3-41).

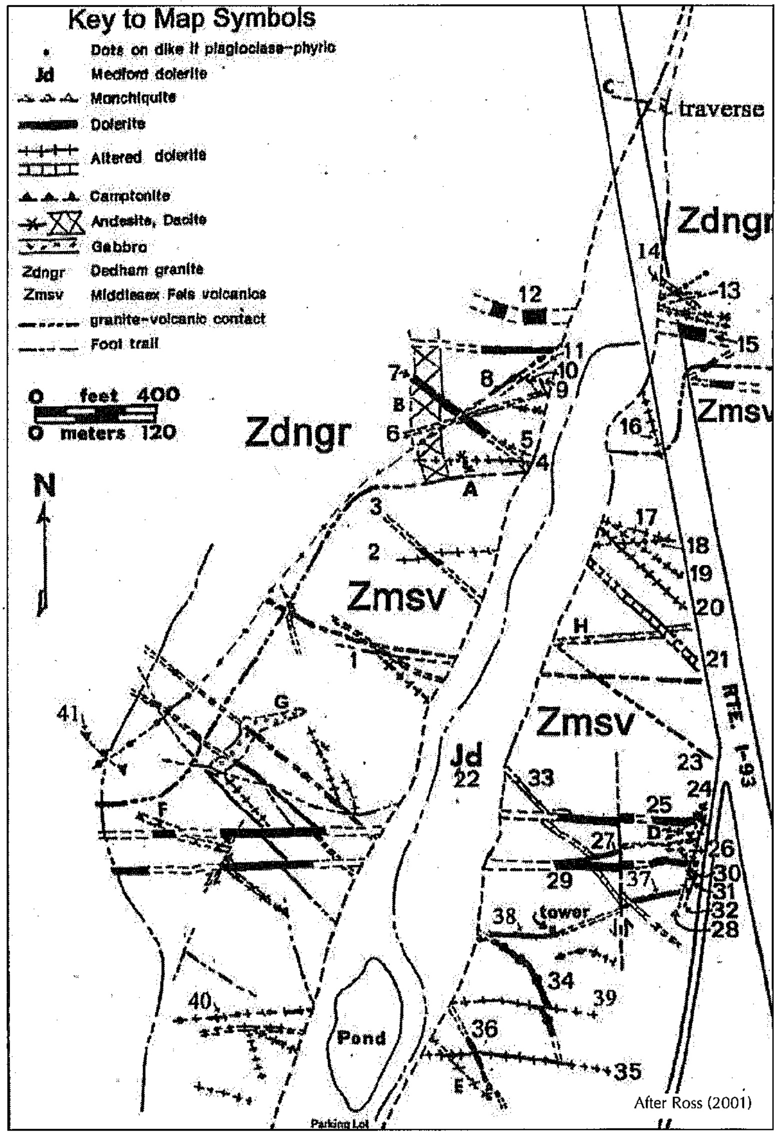


FIGURE 3-43. Map of the Medford Dike at the northern border of the Boston Basin in Medford.

Fresh dikes and sills are very common and are of various trends in the harbor islands (see Figure 3-19). Most of the small diabase dikes west and northwest of the Boston Basin also trend to the northeast. They might be older than the north-south ones in the basin since they follow an older set of faults, but their ages could overlap. The principal dike trends vary from place to place and reflect local structural control at the time of their intrusion. Most dikes are found to follow faults, where they are examined closely, as at Nahant (Bailey, 1984) and in tunnels, and thus provide structural data where none are recorded. However, the type of movement along the fault may vary over time and caution is needed since dikes may form under extension along faults that had initially formed under compression. Some

(see color version on page 459)

FIGURE 3-44. Gabbro dike from Porter Square Subway Station in Cambridge with fragment of granite. (Photo courtesy of Allen Hathaway.)

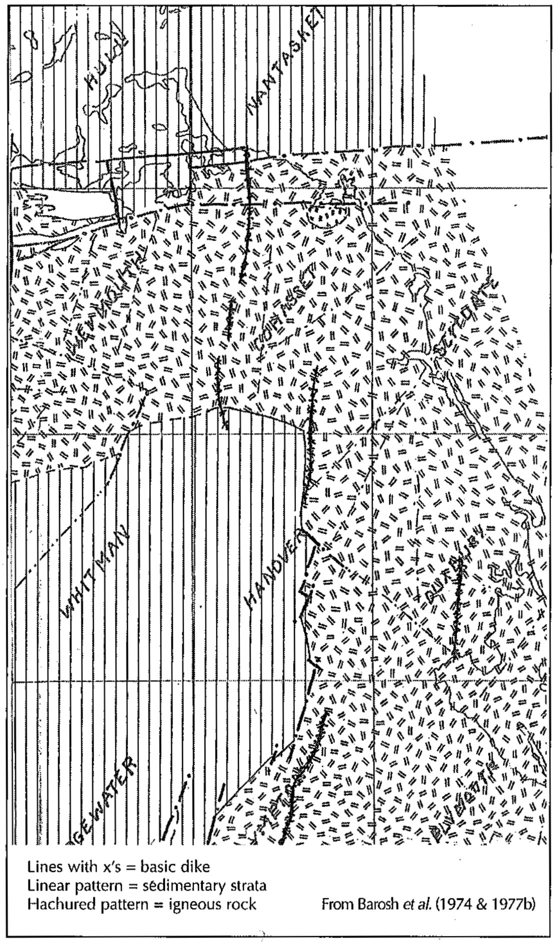


FIGURE 3-45. Large basic dikes indicated by linear aeromagnetic anomalies south of the Boston Basin.

irregular intrusions also appear to be pipes at fault-intersections (Kaye, 1980a). Diabase dikes commonly have slickensides, and adjacent wall rocks show shears, fractures and drag — all evidence that they intruded faults. The Medford Dike follows a breccia zone (Crosby, 1880) that has little offset (Billings, 1929). Rarely do dikes have any foliation, but many dikes (see Figure 3-47) do exhibit gouge, shears or fracturing from reactivation of the faults they intruded (LaForge, 1932; Kaye, 1980a; Barosh & Woodhouse, 1990).

The dikes in the Boston Basin commonly form a roughly rectilinear north-south east-west pattern, but in places the majority strike northwest or northeast. The variety of trends is well displayed at Medford and Nahant (see Figures 3-42 & 3-43). LaForge (1932) found that, in general, the dikes formed four sets, which are, in order of age: an older east-west set, a northwest-trending set, a younger east-west set and a north-south set. The first three sets are altered and the second and third sets are about the same age. The dikes in the northern part and north of the basin mostly trend northwest (Ross, 1981 & 1984; Bailey, 1984). On East Point, Nahant, 95 percent of the dike swarm present strike northwest and the remainder between northeast and east, with the sills striking northeast and dipping 30 to 57 degrees northwest (Ross & Bailey, 2001). Lane (1888) found four groups among the 526 dikes he measured on Nahant and Little Nahant: N7°W, N45°W, N80°W and N50°E. Near the north-northeast-trending Medford dike to the west, the great majority of dikes strikes northwest and are cut by some east-west and rare northeast-trending dikes (Ross, 2001). On Cape Ann, the strike of 361 mafic dikes of the same age or only slightly younger than the granite, is predominantly north-northwest (Woodward, in Shaler, 1889; Dennen, 1981).

The fresh diabase dikes at the west edge of the basin trend northwest, northeast and east-west (Nelson, 1975a), but farther west Crosby (1904) found them to trend north-south across east-west trending altered dikes along the western portion of the Weston Aqueduct in Weston. The north-south dikes also are prominent at the south edge of the basin and across the Narragansett Basin (see Figure 3-45). Those dikes that are visible are fresh diabase and apparently follow late Mesozoic faults that cut Pennsylvanian strata of the Narragansett Basin and the Late Triassic-Early Jurassic Watch Hill Fault Zone. These dikes cut two older altered approximately east-west sets in the Hingham-Hull area, as well as melaphyre dikes (Crosby, in Grabau & Woodman, 1898).

FIGURE 3-46. Jurassic diabase dike with columnar jointing at Route 128, Exit 16 west of Route 109 in Dedham.

The type, amount and condition of dikes present in the harbor are shown well along the alignment of the Inter-Island Tunnel between Deer and Nut islands (Sverdrup, 1990b). Vertical boreholes encountered abundant diabase dikes and some basalt bodies that are 9 to over 30 meters (30 to 100 feet) in width. The diabase is fine-grained, dark-gray to greenish-gray. The greenish, altered variety may have quartz and calcite veins. Slickensides are usually found in the diabase and the dikes are adjacent to faults or are themselves highly sheared and broken. The basalt is generally a fine-grained, dark to yellow-green rock forming irregular bodies. Felsite dikes, 3 to 4.5 meters (10 to 15 feet) thick are found below Nut Island, and smaller red dikes scattered in the argillite elsewhere. These dikes are probably related to the nearby Late Ordovician Quincy Granite. In addition, quartz and calcite veins cut the rock.

The dikes are of at least five different pre-Mesozoic ages, plus the "Triassic" diabase

(see color version on page 459)

FIGURE 3-47. North-trending diabase dike with columnar jointing and with fault gouge along its border at the Wellesley Extension Intercept Tunnel in Dedham.

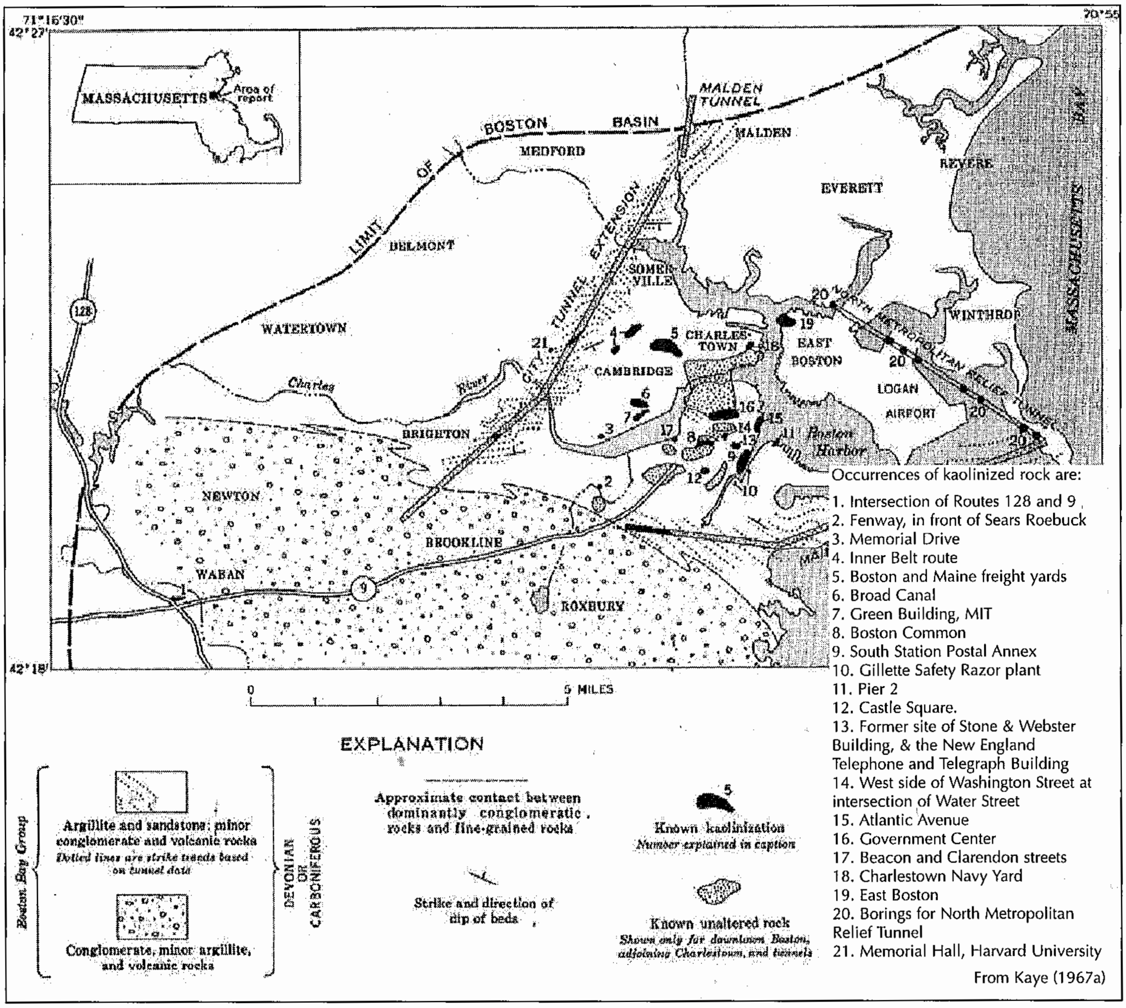


FIGURE 3-48. Map of the Boston area showing the areas of known kaolinized rock, the bedrock tunnels and the generalized geology of the Boston Bay Group.

dikes, which McHone (1978 & 1984; McHone & Butler, 1984) found to be of different ages in the region. In addition, Cretaceous felsite dikes are associated with the volcanic stocks in southern New Hampshire (Eby, 1984) and similar ones occur west of Cape Ann. Reported ages can be confusing and vary as the considered ages of the Boston Basin strata varied. However, with proper attention, the ages can be worked out. Radiometric ages of dikes yield a spread of 573 (±5) to 190 (±6) million years ago (Zartman *et al.*, 1970; Ross, 1981, 1984 & 2001; Ross & Bailey, 2001), and the north-trending dikes and some east-west ones are younger with an age of 146 to 100 million years ago (Early Cretaceous). It is reported to be difficult to date basic dikes because the use of radiometric methods depends on when initial decay began and whether the "clock was restarted" due to recrystalization. Therefore, many dates may not be too reliable in the region (McKinley, 1980; McHone, 1992). For the most part, in and adjacent to the Boston Basin stratigraphic relations and fossil dates demonstrate that in the Late Proterozoic rhyolitic felsite dikes and a few basic dikes are associated with the Mattapan Volcanic Complex, as well as basic dikes feeding the Brighton Basalt. Many diabasic dikes formed during the Cambrian to Late Ordovician. Suites of basic and rhyolitic dikes formed during the Late Ordovician. A few scattered dikes possibly reached the basin from nearby volcanic sources during the Silurian, Devonian and Pennsylvanian. Fresh diabase dikes formed at different times in the Mesozoic, and rare rhyolitic dikes intruded during the Cretaceous to the north of Boston. This large group of dikes demonstrates a long period of extensional stress in the area, with the stress alignment varying both in time and place in order to produce a confusing array of dike trends.

Rock Altered by Intrusions. Altered Cambridge Argillite was first considered Cretaceous clay in early encounters, but this practice soon changed. Clapp (1907) described 41.5 meters (136 feet) of light gray to almost white clay found between till and the Cambridge Argillite at a depth of 13.5 meters (44 feet) beneath the Ames Building in downtown Boston as very similar to samples of the Raritan Formation from Long Island. It varied from very soft and putty-like material to hard as a rock, and chemical analysis indicated that it was pure clay. Clapp also cited other deep borings in central Boston and on Spectacle Island that encountered similar material. Crosby (1903) had earlier suggested such soft white deposits were pre-Pleistocene and called attention to the fact that under the new Cambridge site for MIT, the normal argillite was "rotted to a whitish and more or less plastic clay" (Worcester, 1914). Since then, this type of alteration has been found at many places in the Boston Basin (see Figure 3-48). Woodhouse has encountered it in samples of borings he has observed in central Boston. The alteration occurs in all types of sedimentary rock, including conglomerate. The altered conglomerate is well exposed in several places, but for the most part these softened rocks lay deeply buried (see Figure 3-49). In places, secondary alteration has changed the hard argillite rock into a soft, bleached white, silty aggregate that can be dug with a hand shovel. These changes are due to the formation of sericite and kaolin at the expense of all primary minerals, including quartz (Kaye, 1979).

(see color version on page 459)

FIGURE 3-49. Kaolinized Roxbury Conglomerate at Blue Hill Avenue at Franklin Field in Dorchester.

The argillites, particularly the maroon and green tuffaceous argillites, seem to be most widely affected, especially under parts of downtown Boston, the Back Bay and the lower Charles River, where the cause-and-effect relationship of low topography and deep bedrock with altered rock is notable. The altered argillite varies from light-gray to dark-green in color. Soft rocks were the most deeply eroded ones during Pleistocene and earlier, and are thought to underlie most of the larger lowlands in the basin. The alteration is present in zones reaching in excess of 91 meters (300 feet) below the surface. Kaye (1967a) noted that the alteration appeared limited to certain beds, and thought the common association of igneous rocks also might suggest a genetic relation, but later Kaye (1984b) found a closer relation with shear zones, faults and dikes and a lesser one to stratigraphic horizons. However, the suggestion that it follows tuffaceous horizons in the argillite that were rapidly altered after their eruption (Hager & Stewart, 1995) does not match their relation to the surface of the argillite and lacks an origin. The cause of this soft-rock alteration is conjectural and could be either the result of hydrothermal activity or deep lateritic weathering during Tertiary time

(Kaye, 1961 & 1967a). Kaye favored weathering similar to that forming bauxite, and being the result of early deep weathering as altered clasts occur in the Tertiary deposits of Martha's Vineyard. If it were due to hydrothermal alteration, this could have occurred when the basic dikes in the basin were altered by the Late Ordovician intrusions and volcanic activity.

The altered rock tends to be restricted to certain beds as noted by Rahm (1962) and Billings and Tierney (1964) in the tunnels under Boston constructed by the Metropolitan District Commission. In the tunnels studied — the City Tunnel Extension and the Main Drainage Tunnel — soft rock was limited to certain beds or groups of beds. However, because tunnel observations are limited by the height of the tunnel, about 4 meters (13 feet) for the Boston tunnels, the alteration might cut across planes of stratification out of view (Kaye, 1967a). In the western 1,310 meters (4,300 feet) of the Main Drainage Tunnel beneath Roxbury, altered argillite, called "shale" in the tunnel reports, and sandstone are interbedded with massive conglomerate and arkose, some of which appear from the description to be altered. Three diabase dikes and sills cut the soft rock (Rahm, 1962). Billings and Tierney (1964) also found "shale" in two places in the City Tunnel Extension. A section 12 meters (40 feet) thick of soft kaolinized argillite, interbedded with thin quartzite, purple argillite, sandstone and conglomerate, occurs in the tunnel south of the Charles River in Allston at a depth of about 69 meters (225 feet) below the top of the bedrock surface.

The deepest recorded occurrence of alteration beneath the surface of bedrock is reported to be 91 meters (300 feet) from the City Tunnel Extension under Cambridge (Billings & Tierney, 1964). The altered rock obviously extends below the tunnel level to an even greater depth. No borings yield unequivocal evidence of having reached the base, or maximum depth, of a particular kaolinized zone.

Some indirect evidence suggests that most alteration dies out at relatively moderate depths. The distribution of altered rock is much more restricted in the Main Drainage Tunnel and the City Tunnel Extension than it is under the Shawmut Peninsula and adjoining Cambridge. The average elevation of the rock surface in the altered zones is about –30 meters (–100 feet) MSL, whereas the elevation of the tunnels ranges from –88 to –116 meters (–290 to –380 feet) MSL. However, because the tunnels do not pass under the highly altered zone of Boston and Cambridge, it cannot be demonstrated that the sparseness of alteration in the tunnels bears on the depth of bedrock alteration. In addition, altered argillite is abundant at an elevation of –85 meters (–280 feet) MSL in the North Metropolitan Relief Tunnel. This discussion is based largely on the results of geological mapping of four bedrock tunnels in the greater Boston area, constructed, between 1948 and 1960 under the supervision of the Construction Division of the Metropolitan District Commission. These four bedrock tunnels total slightly more than 32 kilometers (20 miles) in length.

Unconformities

The Boston area has undergone deep erosion at various times in its history that has produced a number of unconformities, most of which follow tectonic activity. An unconformity may be angular or erosional. It is a surface that separates two strata and represents an interval of time in which either tectonic activity such as uplift occurred and produced an angular unconformity or deposition stopped, erosion removed some sediments and rock, and then deposition resumed (erosional unconformity). They are as important as the strata in understanding the correlation of strata, the sedimentation, history and structure in the region. There are Late Proterozoic unconformities under and over the Mattapan Volcanic Complex, a partial pre-Early Cambrian unconformity, and a Late Ordovician unconformity. Further, an unconformity occurs before the Silurian and composite unconformities exist in the pre-Pennsylvanian and pre-Pleistocene. The composite unconformities represent the cumulative effects of different erosional periods, which are not easily separated in this region.

Two unconformities of different character that stand out as being of paramount importance in the region in representing periods of erosion are the pre-Mattapan Late Proterozoic and a very long one expressed by several phases since the Ordovician (post 488 million years ago). The former represents a great, rapid uplift following the principal phase of plate collision and the latter a general and sustained uplift of the region after the last phase of plate collision. Over this later long period, extensional basins and coastal transgressions formed local unconformities but some intervening areas could have been exposed the entire time.

Pre-Mattapan Late Proterozoic. A period of profound erosion occurred near the end of the Late Proterozoic that removed over 10 kilometers (6 miles) of rock to uncover the Dedham Granite and metamorphic rock in a relatively short time before the Mattapan volcanic rocks were spewed out on the surface. It is the greatest unconformity in New England and marks the rise of the land after the first great collision of Gondwana and Laurentia. This surface would have had considerable relief, but subsequent erosion has destroyed almost all of it. Moderate relief is preserved on the south side of the Boston Basin where the patchiness of the Mattapan volcanic rock reflects the irregular surface (Chute, 1966). Erosion at this time had just stripped the rock down to the outer part of the Dedham Granodiorite near Boston and much of its finer grained northern border facies, the Westwood Granite, is preserved. Later erosion has removed most of the Mattapan on the west side of the basin.

Kaye (Kaye & Zartman, 1980) reported one exposure with an apparent gradation of Mattapan rock into the Late Proterozoic Dedham Granodiorite. He interpreted this as an intrusive contact, making the two rocks in part contemporaneous. The gradation is apparently due to either shearing, which he noted as being present, or weathering at the top of the granite, which LaForge (1932) also mentioned as being present beneath the later Lynn volcanic rocks, and is not an intrusive contact. Such gradation from a weathered rock into an overlying deposit is not unusual.

Pre-Roxbury Late Proterozoic. Prior studies have mentioned some erosion and local disconformities at the base of the Roxbury Conglomerate, but the general distribution of the rocks below shows this break to be a major erosional one. The Mattapan volcanic complex had extended into the adjacent area outside the basin, but erosion after its deposition removed most of it. The Mattapan wedges out now to the east beneath the Roxbury, yet the predominance of clasts of volcanic rock in the Roxbury farther east demonstrates that the Mattapan had been present and removed making a significant unconformity beneath the conglomerate. The Roxbury also overlaps different units of the Mattapan at the west end of the basin (Nelson, 1975a).

Pre-Cambridge Late Proterozoic. The base of much of the Cambridge Argillite is shown to rest on progressively older rock to the south within the Boston Basin on Kaye's (1980a) map. This map indicates an unconformity, but one that probably dies out basinward where the sedimentation was probably continuous. The base of the Cambridge thus appears to first intertongue with the Roxbury Conglomerate to the south at some distance into the basin, then the argillite transgresses to form an unconformity, with a creeping shoreline, southward over the alluvial fans of the underlying conglomerate. The upper part of the Cambridge Argillite subsequently intertongues with younger fans of the conglomerate close to the south side of the basin. The unconformity would merge with the general older erosional surface to the south.

Pre-Early Cambrian. The Early Cambrian strata apparently rest conformably or with only a slight disconformity (showing a minor break in sedimentation) on the Cambridge Argillite in the Boston Basin, but where it spills out of the basin to the north and south, it lies unconformably on the eroded surface of the Late Proterozoic batholithic granite. It is unconformable on the granite in both Weymouth off the southeast side of the basin and Hoppin Hill farther south (Shaler *et al.*, 1899; Fletcher *et al.*, 2005). Remnants also exist at several places on the ancient rock north of the basin (Sears, 1905). This unconformity represents the cumulative effects of the previous two erosional periods mentioned above and marks the general Cambrian transgression westward over the land.

Pre-Late Ordovician. The Late Ordovician terrestrial volcanic flows in the Blue Hills followed marine deposition of the Cambrian and Early Ordovician strata of which only small remnants exist. This change from the marine depositional environment represents uplift and erosion of these newly deposited strata prior to the eruptions and shows the onset of the Taconic Orogeny. North of the Boston Basin there is a similar unconformity where the contemporaneous Late Ordovician Lynn Rhyolite is over Late Proterozoic rock (Dennen, 1991a).

Pre-Silurian. The contact between the unmetamorphosed Silurian-Devonian Newbury volcanic rock and redbed strata, and the underlying Late Proterozoic granite and highly metamorphosed strata in the Nashoba Terrane, cannot be seen in northeastern Massachusetts, but must represent a profound unconformity. It marks the rise of Pangea after it was consolidated at the end of the Ordovician. The unconformity also existed toward the Boston Basin to the south as shown by small patches of the redbeds resting on the Cape Ann Granite (Bell *et al.*, 1977 & 1993). Fossils found at the base of this volcanic redbed sequence in Maine date it as Early Silurian and the unconformity developed earlier (Gates & Moench, 1981).

Pre-Pennsylvanian. The unconformity beneath the Early Pennsylvanian Pondville Conglomerate on the south side of the Boston Basin is the cumulative result of the periods of uplifts and erosion since the end of the Early Ordovician. The Early Ordovician quartzite was still around much of the area before it was stripped off and deposited in the Pondville Conglomerate, along with the Late Ordovician volcanic rocks and any remaining Silurian strata in the area. The unconformity at the base of the Early Pennsylvanian Pondville Conglomerate over the Late Ordovician Blue Hills Granite Porphyry is well displayed along the north side of Route 128 at the south side of the Blue Hills. In some places, joint-bounded blocks of porphyry gradually change upward into rounded shapes from spheroidal weathering and become the basal boulders of the conglomerate in such a way that the contact appears gradational (Crosby, 1900). The long period of weathering before the Pennsylvanian deposition is indicated by the red debris and lack of cobbles and boulders forming the basal Pennsylvanian deposits away from the source of volcanic material (Woodworth & Wigglesworth, 1934).

Pre-Late Triassic. A regional uplift across southern New England and areas now offshore created a broad rolling land area prior to the development of basin-and-range topography across the region and the deposition of redbeds and basalts in grabens during the Late Triassic. Broad grabens exist to the east and west, but only the small Peabody Basin is known to record this unconformity onshore near Boston. This uplift had unroofed the Permian-Middle Triassic Narragansett Pier Granite to the south while tilting the region to the north before these grabens formed.

Pre-Cretaceous. After the extensional faulting of the Late Triassic and Early Jurassic as the North Atlantic rift began to open, the initial ocean transgressed to form salt deposits in the basins and start a widespread unconformity. The land had worn down to an eastward slope and the uniform upland elevations of central Massachusetts are thought to be remnants of this seaward slope (Alden, 1924), but such a slope is harder to discern in eastern Massachusetts. This period of erosion is sometimes referred to as the Post-Rift or Breakup Unconformity, which forms the base of the Coastal Plain deposits as they extended onto the land (Grow, 1981). The unconformity at present remains almost entirely offshore.

Pre-Pleistocene. Periods of erosion after the Middle Jurassic and prior to the Pleistocene, which includes the Cretaceous and Tertiary, in eastern New England and the Maritimes cannot be separated on-shore around Boston. The principal surfaces due to these periods developed within the Tertiary deposits seen offshore in this region and are due to fluctuating sea level. The many resulting small unconformities are present in the upper edge of the Coastal Plain deposits (see Figure 2-35). One is displayed onshore beneath the Miocene sediments near Marshfield and a few other spots, but inland they merge into a larger general surface of erosion. The relief on the buried pre-Pleistocene surface is very important to the understanding of the Pleistocene deposits in the Boston area.

Structure of Boston Basin Bedrock

A full discussion of the structure of the Boston Basin would require the compilation of the geologic maps of Kaye and Bell with the subsequent tunnel and borehole data added. The resulting map would probably be the most detailed city geologic structure map in the United States and would demonstrate well the structural relations. The discussion below provides an overview with some examples. It should be pointed out that the data from actual field mapping has been consistently additive over the years to increasingly clarify what was found before. The general structure is known now, although many local problems remain due to the myriad of faults and complex stratigraphic relations; however, no major surprises are expected.

The Boston Basin was first considered a simple synclinal feature, but is now known to be a complex asymmetrical rift basin characterized by ubiquitous faults and few folds (Kaye, 1982a). The basin is a fault trough whose northern side is cut off by a later reverse fault and whose southern side is bordered by a subsequent south-tilted block, which forms the Blue Hills and Norfolk Basin that merges eastward into the Boston Basin (see Figure 3-50). The faults mainly formed during four periods:

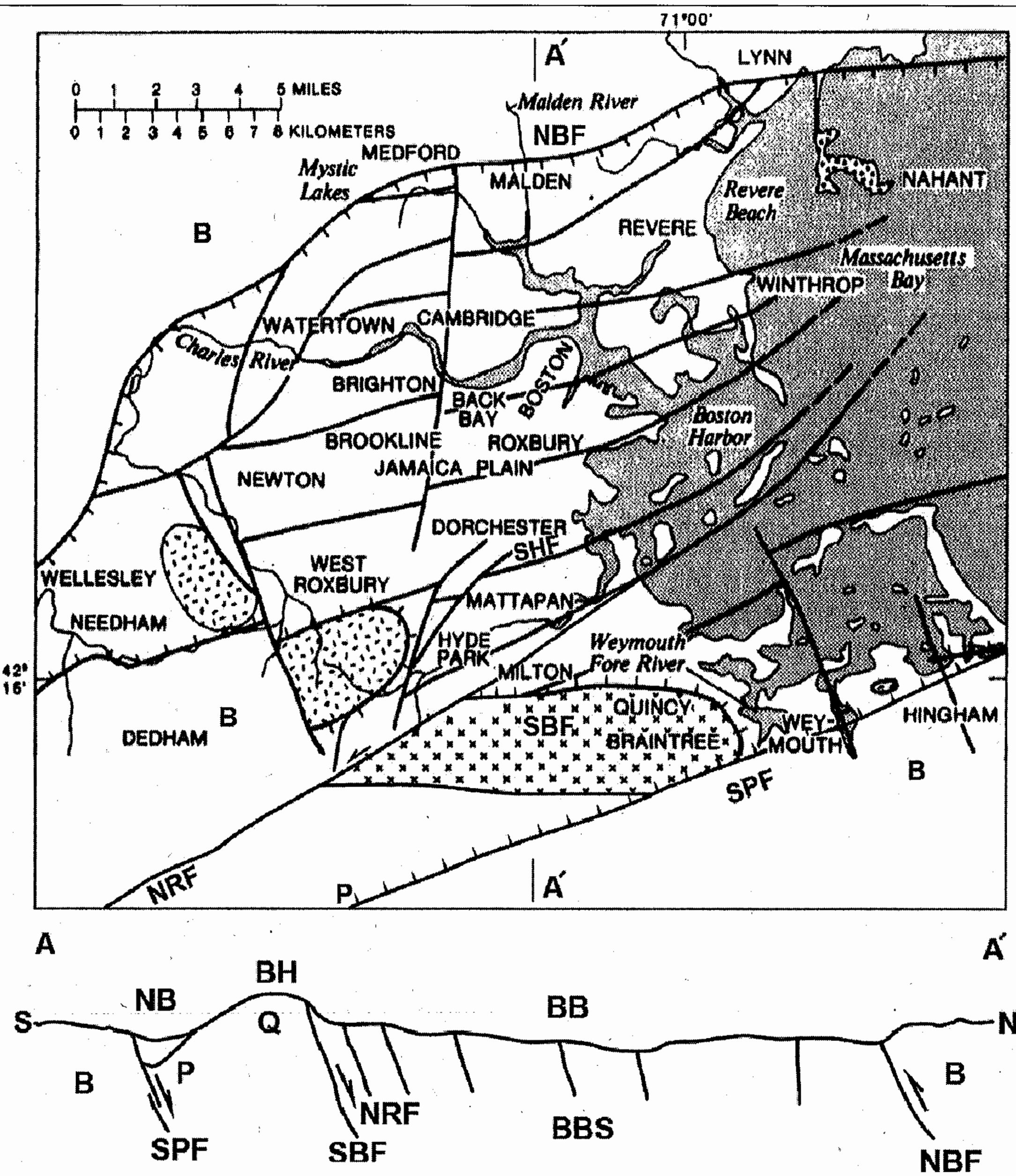
- east-trending Late Proterozoic normal faults (in which the block above the fault has moved downward relative to the block below), which are chiefly along the southern side of the basin and initiated basin growth;
- northeast- to east-trending Late Ordovician thrust faults, which are more prominent on the north side of the basin and obscure the slightly younger Late Ordovician caldera faults;
- northeast-trending Pennsylvanian to Early Jurassic normal faults, which are concentrated in the southern part of the basin; and,
- north- and northwest-trending Jurassic to Holocene faults across the basin.

Between these periods of offset there were other times of extensional faults that controlled many diabase dikes.

The east-tilting Boston Basin is deformed by a series of long, east-west to northeast-trending longitudinal faults of large displacement, with each intervening block containing a single group of strata with a similar dip or a rare fold. The basin formed north of an active latest Proterozoic zone of normal faults and was then thrusted over on the northwest and sliced up by longitudinal faults with considerable strike-slip movement during the Ordovician. The basin shows a strong north-south structural and stratigraphic asymmetry and was intruded by volcanic rock and granite along its southern side. The lower stratigraphic units are more prominent to the south where they terminate irregularly against some of the original border faults with the granitic basement, whereas the higher units end abruptly to the north against the later Northern Boundary Fault, which forms a prominent bluff. The present distribution of strata within the basin is due chiefly to a combination of the depositional pattern related to the southern border faults, fault repetition and an easterly tilt.

The basin subsequently suffered offset from both Pennsylvanian and Mesozoic and perhaps other times of normal faulting and rotation. The numerous dike-sets present attest to many periods of extension in the basin. Many of the early structures have been reactivated in various ways and their origin may be difficult to ascertain. The original configuration of the Boston Basin would have been linear with volcanic and coarse debris grading northward away from a ridge into marine waters (see Figure 3-10). The shape is greatly changed now due to the disappearance of its northern and western sides against a border fault and a shortening of the original length of the basin from right-lateral offset.

Kaye (1980a) shows that the Boston Basin is cut by at least eight large east-northeast-trending longitudinal faults, most of which are 15 kilometers (9 miles) or more in length (see Figure 3-51). Other longitudinal faults continue westward beyond the basin to the Bloody Bluff Fault Zone and makes a structural feature at least 50 kilometers (33 miles) long (Nelson,



Heavy line = generalized major fault
Hachured = inliers of plutonic rock, Dedham Granodiorite
Crosses & Q = Quincy Granite
Triangles = Nahant Gabbro
P = Pennsylvanian strata

NBF = Northern Boundary Fault
SBF = Southern Boundary Fault
SPF = Straits Pond Fault
B = granite & metamorphic rock basement
NRF = Neponset River Fault
NB = Norfolk Basin

BH = Blue Hills
BB = Boston Basin
BBS = Boston Basin strata
SHF = Squantum Head Fault

Modified from Kaye (1978)

FIGURE 3-50. Simplified map and north-south section of Boston showing the limits of Boston Basin (ticked line).

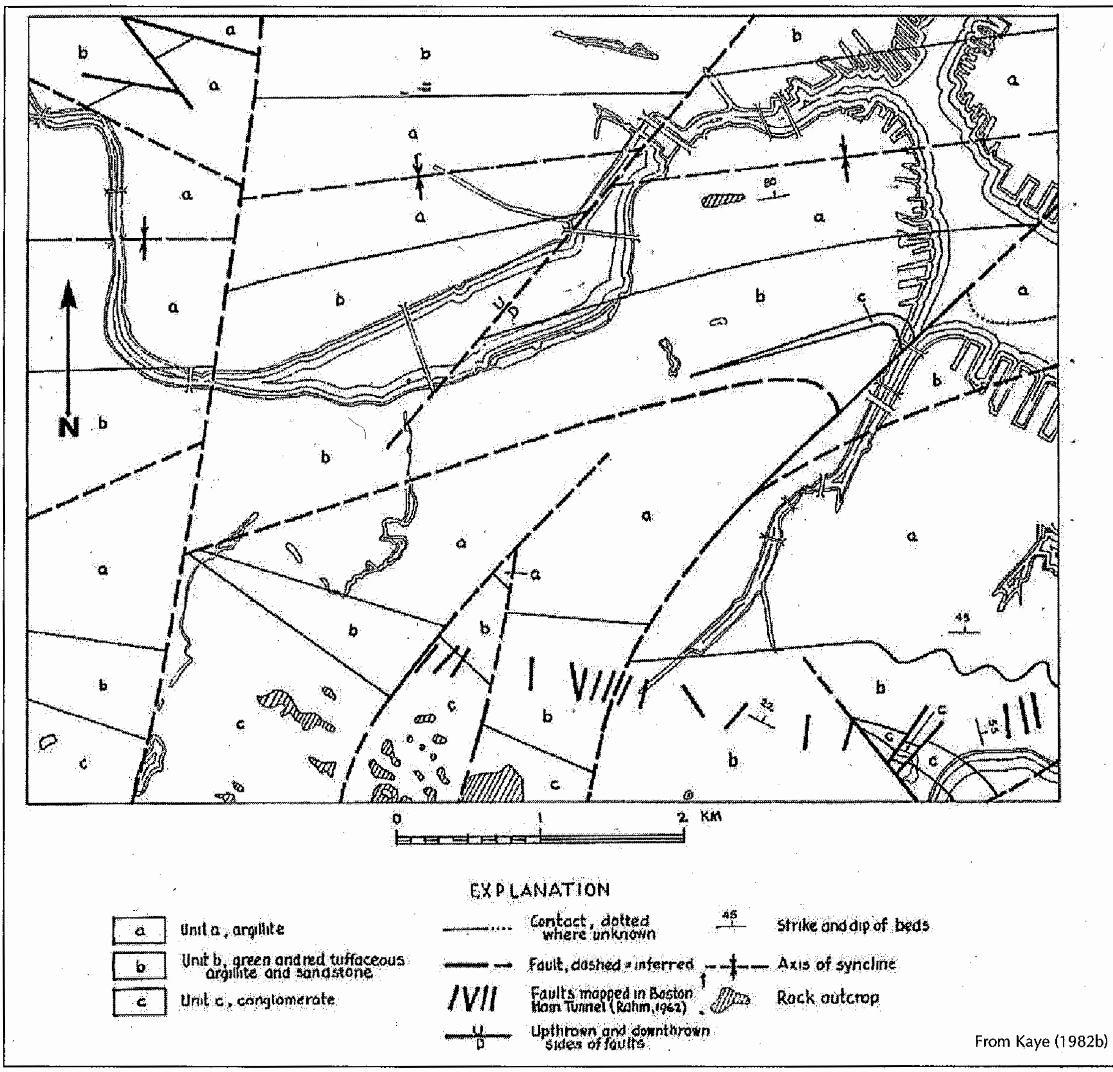


FIGURE 3-51. Bedrock geologic map of the central Boston portion of the Boston South quadrangle.

1975a & 1975b; Barosh, 1977a & 1977b). The basin fill appears to end to the east in the inner Massachusetts Bay, where the drowned bedrock surface has numerous east-northeast lineaments (see Figure 3-52), but here too, there are indications that the faults continue seaward (Ballard & Uchupi, 1975; Ackerman *et al.*, 2006; Barnhardt *et al.*, 2006). The longitudinal faults break the basin into long, narrow fault blocks 0.8 to 1.6 kilometers (0.5 to 1 miles) wide, which, in turn, are broken by a complex of very numerous, commonly transverse faults. In addition to faults with large to small displacement, there are shear zones with various cataclastic effects, but relatively small displacement. The longitudinal faults are mostly very steeply dipping and many are shown to be reverse in nature, but normal faults appear more common. The longitudinal faults generally are of two types: north-dipping reverse or thrust faults showing relative movement from the north and near vertical normal faults in the south that are related to the formation of the basin (LaForge, 1932) and later movements. Slickensides on fault surfaces show a strong strike-slip component of movement on many of the transverse faults and the right-lateral offset may be substantial.

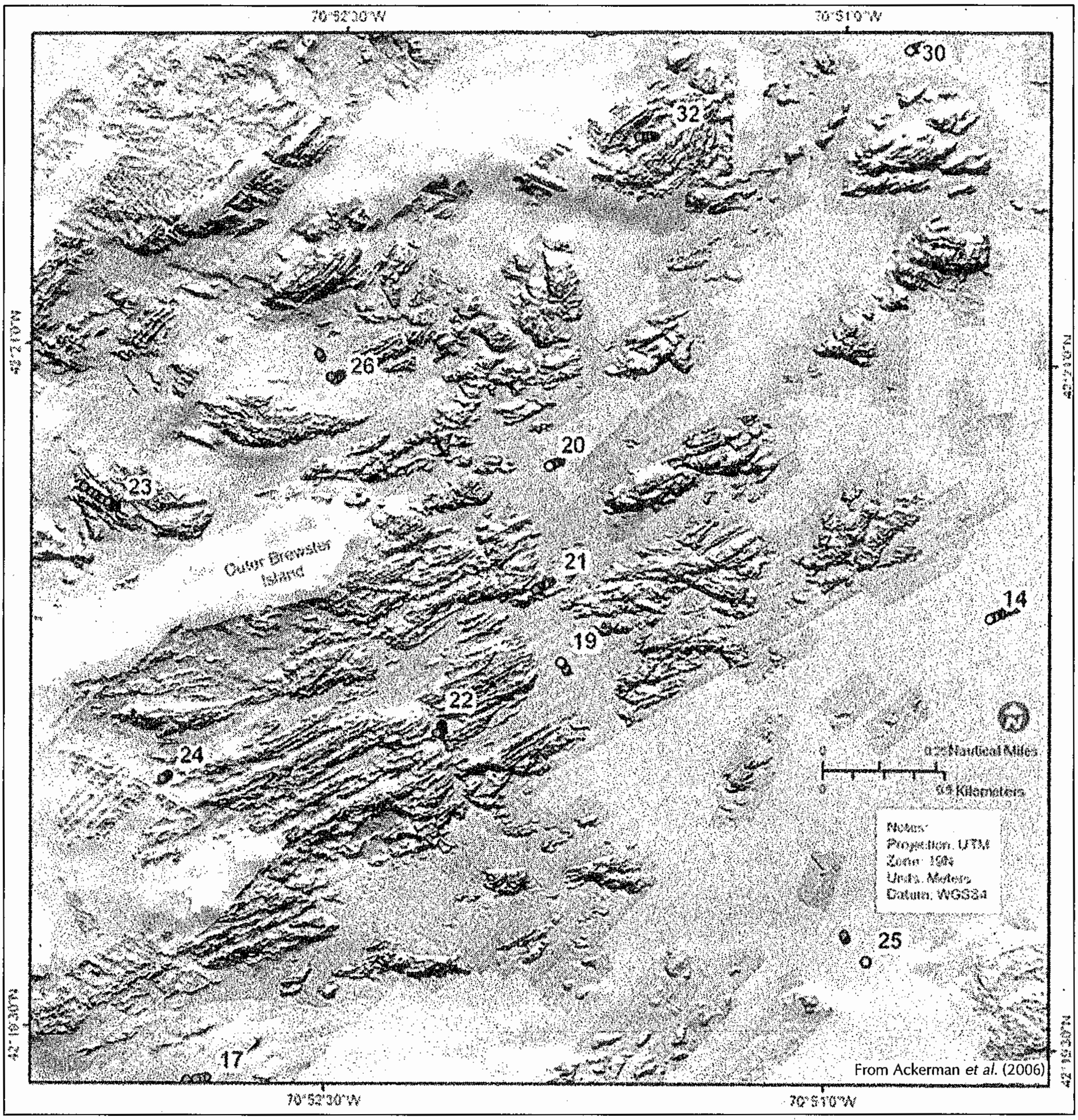


FIGURE 3-52. Submerged ledges east of the Brewster Islands.

There is surprisingly little unconsolidated fault breccia or gouge lining the basin faults. However, some faults have silicified cataclastic material, which is difficult to characterize. At present, the average lateral-spacing throughout the area for the larger faults is indicated to be about 150 meters (490 feet), measured in any direction, although the density of faults varies from place to place and many more small ones exist, as can be seen in all areas of good exposure (Crosby, 1893 & 1894; Bell, 1975a; Wolf, 1976; Ross & Bailey, 2001; Ross 2001; Metcalf & Eddy, 1990b) and in tunnels (Clarke, 1888; Kaye, 1980a; Barosh & Woodhouse, 1990; Davidson, 2003). Detailed mapping in the Wellesley Extension Interceptor Tunnel in Dedham, just off the southwest side of the basin, shows closely spaced faults and very complex joint systems (see Figure 3-53). Seven joint trends, chiefly with steep dips, are recognized near the Blue Hills (Chute, 1966) and most, if not all, are throughgoing ones that reflect the fault sets present. The fault pattern varies with the amount of

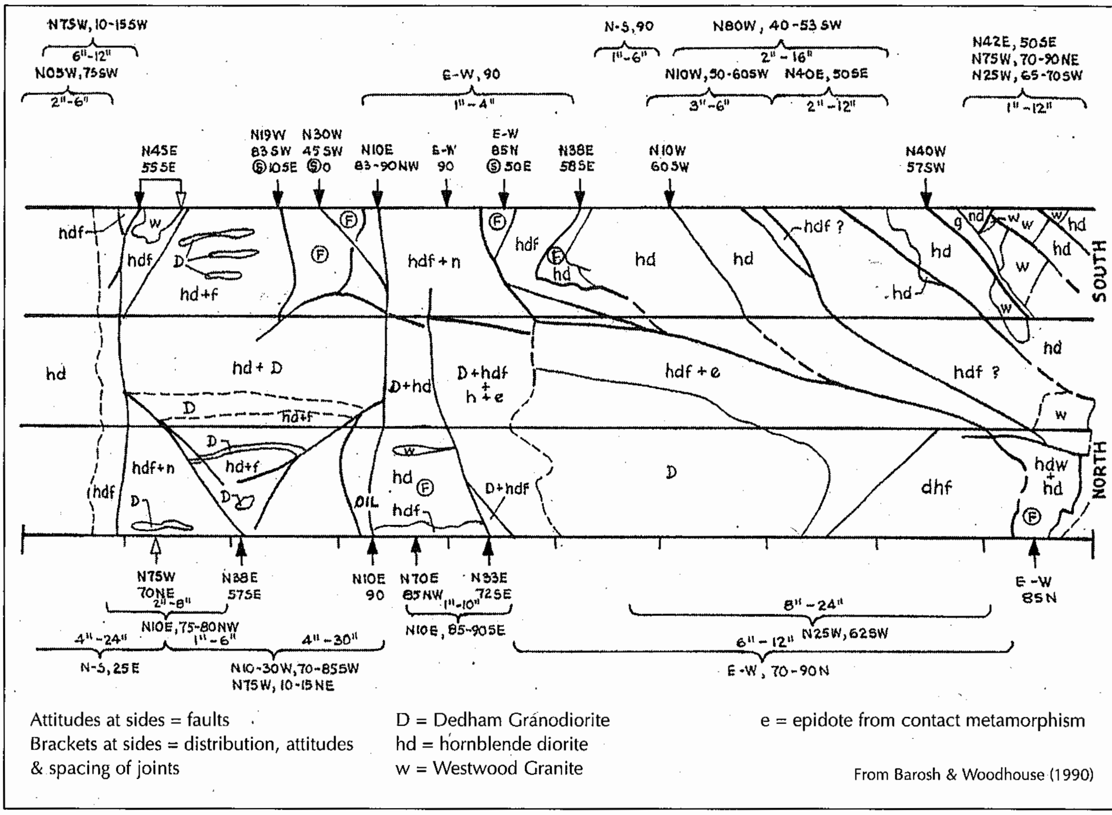


FIGURE 3-53. Geologic map of the roof and both sides of a 61 meter (200 foot) segment of the Wellesley Extension Intercept Tunnel in Dedham showing all faults and joints.

data. That pattern in central Boston appears rather simple (see Figure 3-51), but just to the south between Dorchester and Milton the surface and tunnel exposures show a complexity more representative of the basin (see Figure 3-54). In that area, the general east-northeast structural trends are cut by northeast and north faults along with a few northwest-trending ones. The late north-trending faults are prominent across the southern side of the basin and the late northwest-trending ones more common in the northeast, as is reflected in the bottom topography in Massachusetts Bay and outer islands and trend of the late dikes (see Figure 3-52).

Any folds within the longitudinal fault blocks trend parallel to the fault blocks and may plunge to the east (Crosby, 1880; LaForge, 1932; Kaye, 1980a). Various anticlines and synclines have been interpreted in the Boston Basin in the past, but the designations and placements have varied greatly between researchers depending on the data available. However, none of these proposed folds continue along strike into the older metamorphosed strata and granitic rock to the west (Nelson, 1975a & 1975b; Barosh, 1977b) nor are any seen to the north or south of the basin. The older rock to the west does show broad folds, but the fold axes trend northerly (Barosh, 1972 & 2005, Barosh & Hermes, 1981) and a nose of a broad northerly plunging fold (see Figures 2-17 & 2-18) lies just west of the Boston Basin (Nelson, 1975b). These are syntectonic folds, which formed during the intrusion of the batholithic granite in the Late Proterozoic prior to the formation of the Boston Basin (Barosh, 1972 & 2005) and no younger regional folds have been found to cross them. What folds that may be present in the Boston Basin, therefore, cannot be related to any regional folding involving the basement, but are shallow features related to various motions on the longitudinal faults and are therefore drag

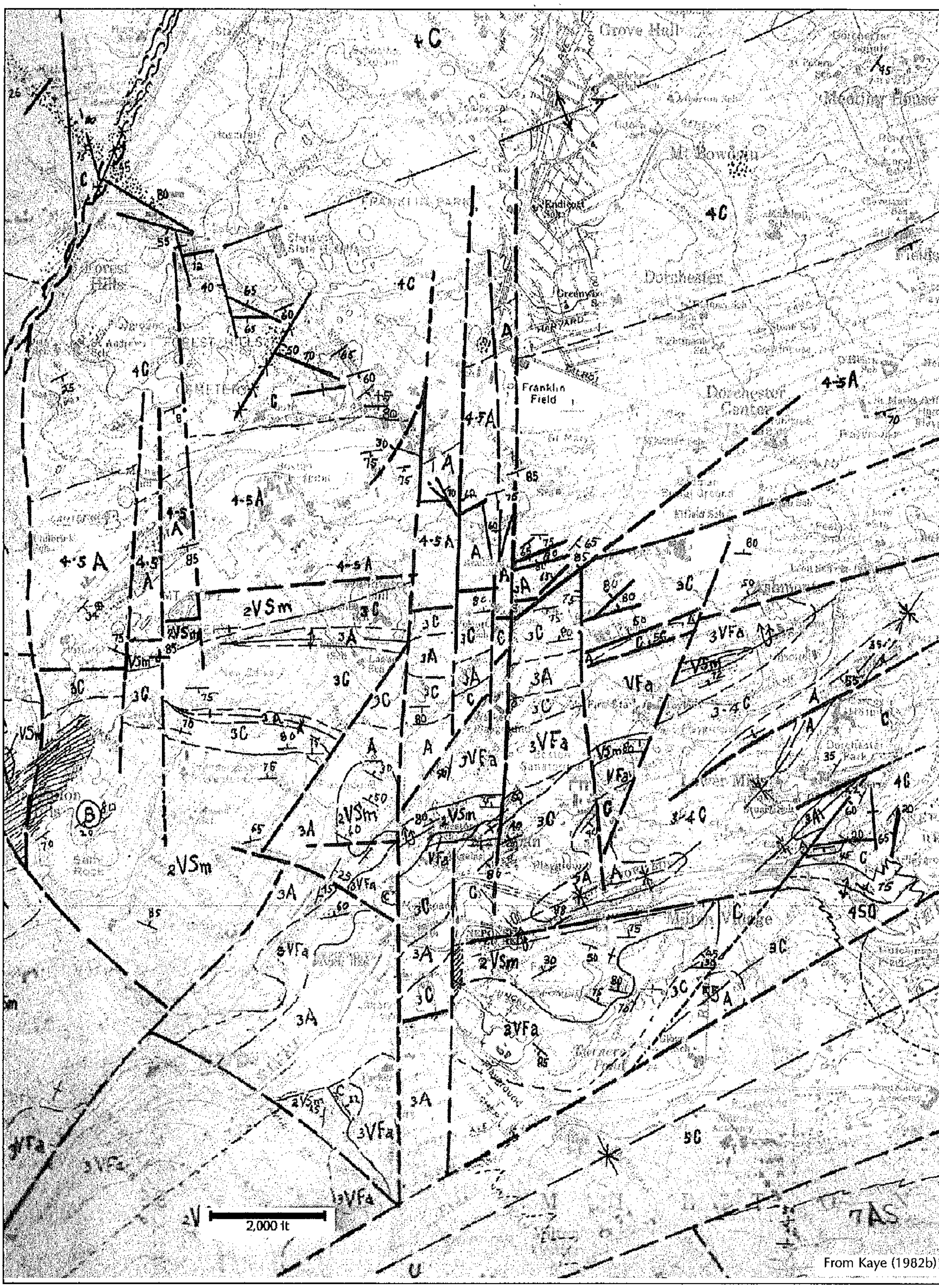


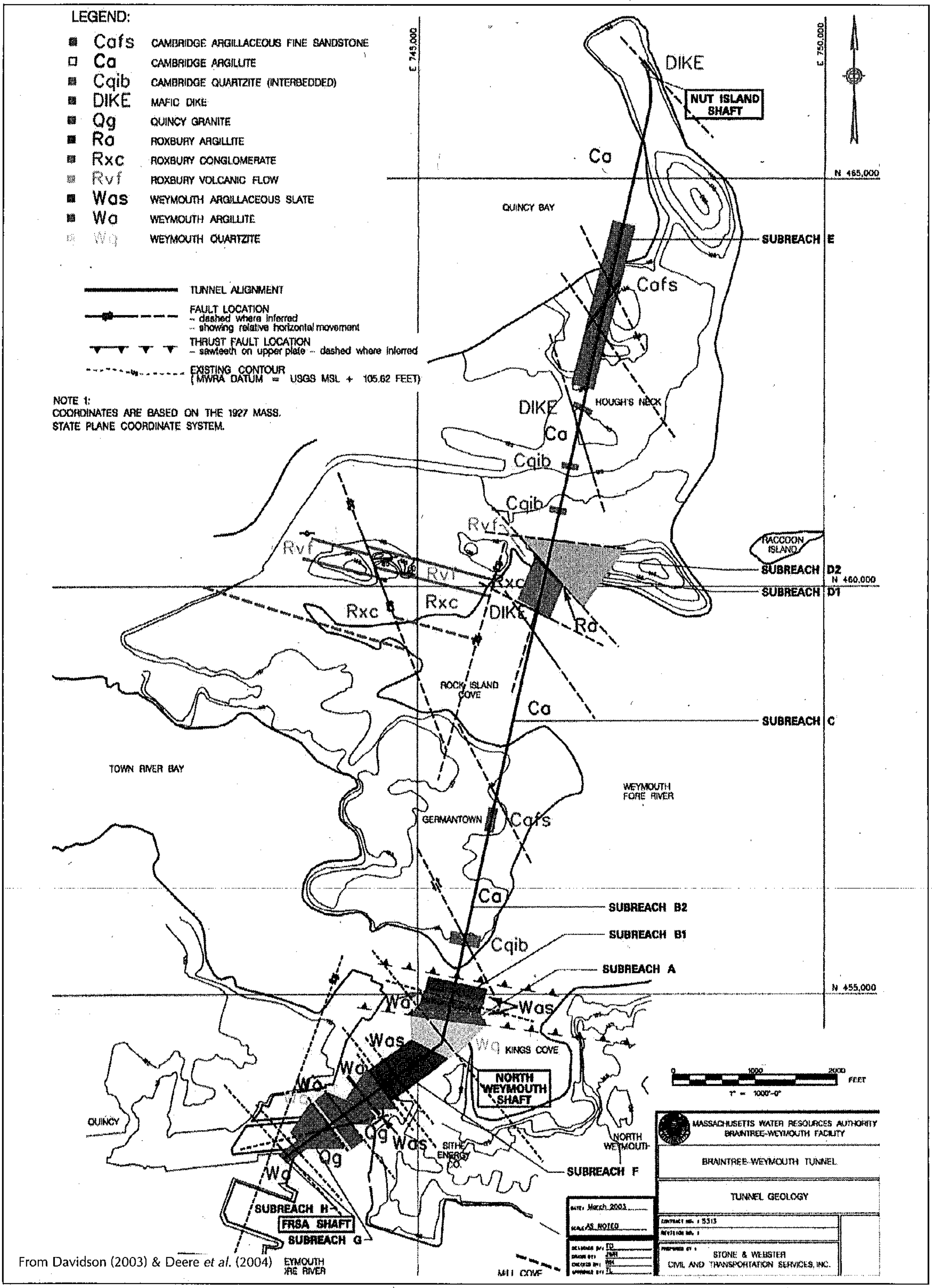
FIGURE 3-54. Bedrock geologic map of the Dorchester-Milton portion of the Boston South quadrangle.

folds. Many of the earlier interpreted folds are discovered to be tilted fault blocks by the various tunnel exposures. LaForge (1932) in effect labeled each area of older rock in the basin an anticline, although he also showed faults bounding their south sides (see Figure 1-30). Billings (1929, 1976a & 1976b) hypothesized that some of LaForge's faults could be additional folds and later enhanced the size of small folds when he summarized his student's tunnel mapping. He likely interpreted the slump, drag and small-scale folds as indicative of large-scale features (see Figure 1-33). The large-scale map of the City Tunnel Extension shows considerable faulting and apparent drag folds, but the generalized section by Billings and Tierney (1964) does not, in contrast to Kaye's (1980) faulted summary of the geology. Kaye (1984a) considered possible folds between the longitudinal faults, but his map data (1980a) show many of these are fault repetitions. Others, such as Cazier (1987), interpreted different periods of folding in the Norfolk Basin from cleavage where mapping only indicates drag folds. Just a single large fold, the Needham-Savin anticline, appears supported by the dips of the strata at present in the basin, but its axis lies to the south of where LaForge placed it (see Figure 1-30).

Reinterpretations of LaForge's data as folds by Billings have not been supported by additional mapping. Billings (1982a) renamed the faults and folds shown by LaForge (1932) and reinterpreted a slice of Roxbury Conglomerate in LaForge's Rock Island Fault on Hough's Neck on the southeast side of the basin as the core of a Hough's Neck Anticline (see Figures 1-30 & 1-33). Borings and mapping of the Braintree-Weymouth Tunnel in Hingham, which crosses this area, shows that not only is the Rock Island Fault present (see Figure 3-55), but many smaller faults are as well (Davidson, 2003). Another example is the Northern or Charles River syncline, which was shown with an axis along the Charles River (see Figure 1-33). The contrasting lithology across the axial zone was interpreted as due to facies change, but the change is so abrupt it demonstrates instead the presence of a fault (see Figure 3-56). The reversal of dips at the river marks a fault zone and the south-dipping strata to the north of it are in a rotated block between this fault and the Northern Boundary Fault. However, some smaller folds are present along the northern edge of the basin. These folds appear to be from drag associated with the reverse faults of the Northern Boundary Fault Zone. Billings (1929) removed faults between three of LaForge's anticlines to form a single large Central anticline (see Figures 1-30, 1-32 & 1-33), but recent data show that these faults are present (Kaye, 1982b). The Needham-Savin Anticline lies along the south side of this "Central Anticline."

The original rift basin was a half-graben, dropping the rock down to form a basin to the north. It had extended much farther to the north, but this portion was later cut off and its original width is unknown. The basin (see Figure 3-10) may have faced a narrow arm of the sea or a gulf to the north and had a similar tectonic and structural setting as the contemporary rift at Saint Johns, New Brunswick (Barosh, 1995), and both basins apparently formed as part of a broader basin-and-range topography (Kaye, 1984a). The position of the Mattapan Volcanic Complex centered in Needham apparently was controlled by the initial faults. The Blue Hills igneous complex, which was a volcanic center in the Late Ordovician, was controlled apparently by the border faults as well. The complex interfingering of the volcanic rock, conglomerate and argillite (along with the slumps, mass movement and graded beds) indicates a rapidly rising upland to the south consistent with longitudinal normal faults being very active during deposition (Dott, 1961).

The normal movement along the southern border faults would have rotated some strata to dip into the faults and may have created local drag folds. Large southward directed slumps in the argillite in the Inter-Island Tunnel near the south border suggest movement toward a fault, which caused rotation shortly after deposition of the strata. The basin strata dip into the steeply north-dipping Squantum Head fault that forms the southern boundary of the basin near Dedham. This fault passes along the north shore of Squantum Head (see Figure 3-57), which is considered to be a rotated fault



From Davidson (2003) & Deere *et al.* (2004)

(see color version on page 460)

FIGURE 3-55. Geologic map of the Braintree-Weymouth Tunnel from Hough's Neck to Nut Island, Hingham.

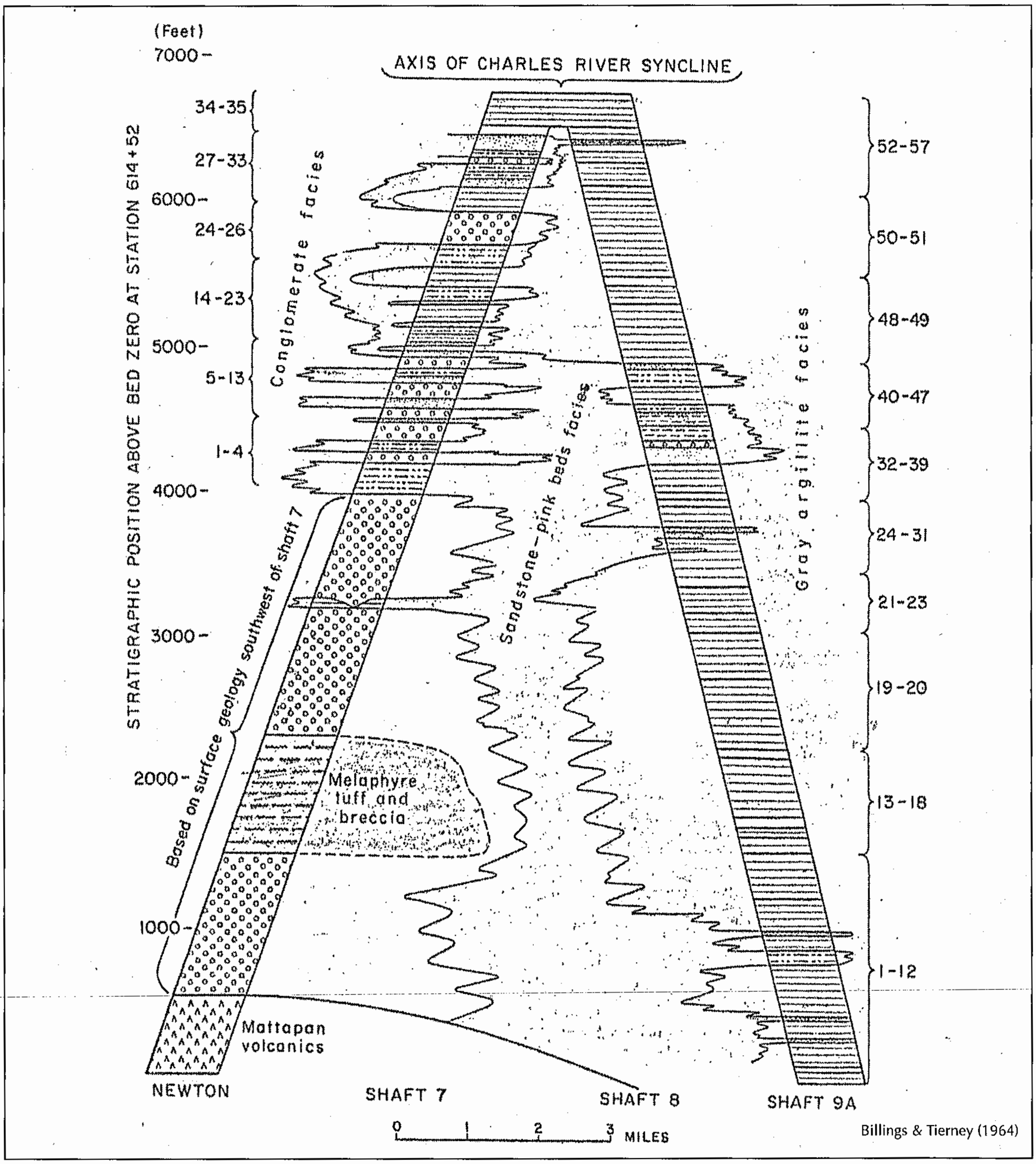


FIGURE 3-56. Strong lithologic contrast across the axis of the "Charles River syncline" in the City Tunnel Extension described as facies changes by Billings and Tierney (1964), but the abruptness could only indicate the presence of a fault. Numbered brackets on the sides indicate the stratigraphic units mapped in the tunnel.

block by Wolfe (1976), and projects toward a fault zone found south of Deer Island. The border to the east is now displaced farther south, but such rotation against the steeply north-dipping east-west trending normal faults is present there as well. The Rock Island fault dips 75 degrees to the north and adjacent smaller normal faults also dip to the north (Crosby, 1893 & 1894; Bell, 1975a; Davidson, 2003) and apparently represent some of the early basin faults (see Figures 1-31, 3-58, 3-59 & 3-60). Some of the adjacent

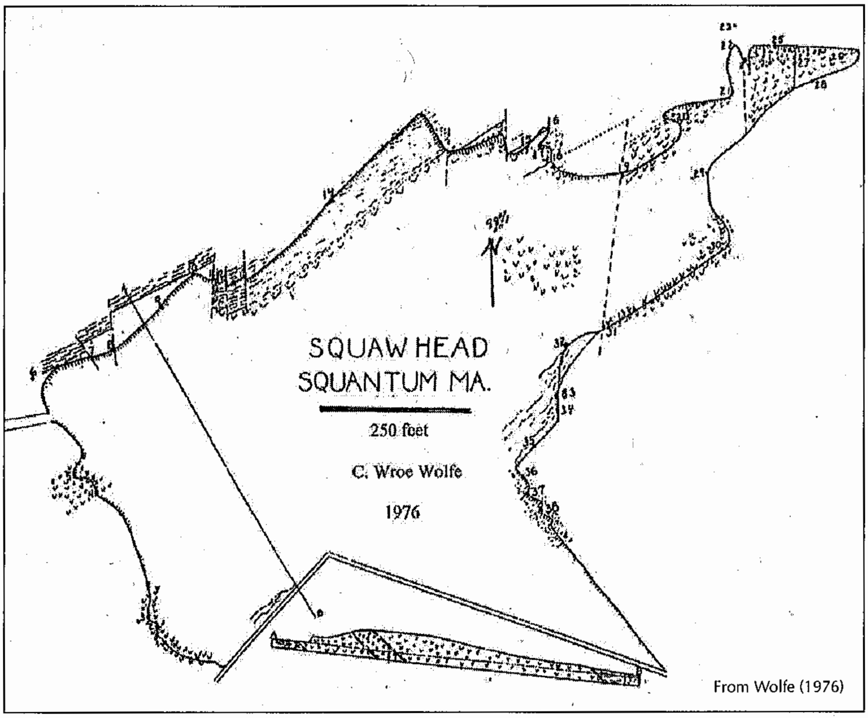


FIGURE 3-57. Geologic map of Squaw Head, Squantum, Quincy, showing closely spaced north-trending faults. The area is underlain by pebbly mudstone to conglomeratic slump deposit lenses in the Cambridge Argillite, with normal argillite along the northwest shore.

small faults show a minor left-lateral component as well. Such rotational movement elsewhere in the basin could account for tilted blocks and explain some of the misinterpreted folds. The primary longitudinal faults can be difficult to pick out in places because of the later reactivation and offset.

The nearby Southern Boundary Fault in Quincy was changed to a south-dipping thrust that moved the Quincy Granite relatively northward over the basin strata (Billings, 1976a). The Braintree-Weymouth Tunnel not only does not show evidence for the south-dipping thrust (see Figure 3-55), but the Cambridge Argillite is, at least locally, thrust in the opposite direction southward above the Weymouth Formation and Quincy Granite (Hager, 1995). This movement would have been later than the normal faults in the area.

The reverse and thrust faults are more predominant to the northwest and are associated with movement along the Bloody Bluff Fault and the closing of the collision zone to the northwest at the end of the Ordovician (Kaye, 1984a). These faults are related to the thrusting in the Nashoba Thrust Belt farther to the northwest and not part of the original basin structure as suggested by Kaye (1984a). The predominant movement on such reverse faults is northwest over southeast, with a right-lateral component, as seen along the Northern Boundary Fault of the basin where the north side of the fault overrides the basin strata and makes a sharp boundary (Nelson, 1975a; Volckmann, 1977; Bell, 1977; Kaye, 1980a). A couple of curved thrust faults in Newton, and one to the east, apparently dip northwest about 35 degrees, but the others are generally much steeper. Much of the north and west sides of the basin was lost during this faulting and the lateral movement telescoped and shortened the basin. The Northern Boundary Fault, which curves to the southwest and cuts off the west end of the basin fill, dips moderately to the north or northwest (see Figure 3-61). Local silica-filled fractures along it suggest that it underwent later extensional movement, perhaps in the Mesozoic, whereas some reverse faults in the central Boston Basin might have developed as reactivations of earlier normal faults.

A right-lateral component of movement along some of the longitudinal reverse faults can more easily account for the fault repetition of strata in the basin than vertical movement alone. This lateral movement appears to have resulted in an overlap of the sedimentary sequence in the basin between fault slices. The various sequences of interbedded conglomerate and volcanic rock that grade upward into argillite in the basin all appear to top to the north, as seen at the South Shore, Newton Upper Falls and Brighton (Crosby, 1893 & 1894; Bell, 1975a; Kaye, 1980a). The sequence at Mattapan is highly faulted but is chiefly to the north (Kaye, 1980a), which is the obvious direction of deposition from the south when the basin formed. Broad folding is incompatible with the attitudes and topping of these strata. Vertical offset along faults, especially if accompanied by the rotation of fault blocks, can account for some of the pattern. However, if the sequences also are assumed to be offset right laterally by the faults, the distribution pattern of the units cannot only be satisfied, but can also account for the partial bends in the units as drag folds. The Brighton and Roxbury anticlines in the northern part of the basin (see Figure 1-30) are found to be uplifted blocks over reverse faults rather than folds when reviewed in light of the present map data (Kaye, 1980a) and their partial fold noses drag features.

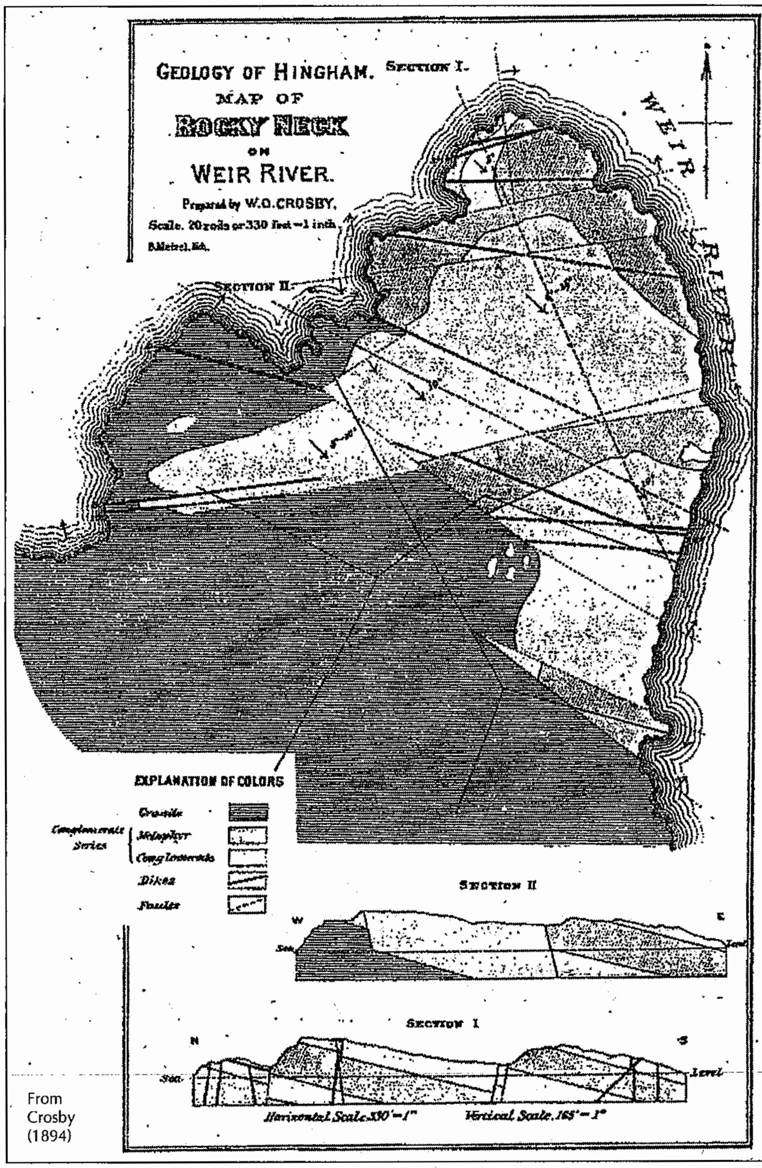


FIGURE 3-58. Map and cross section of Rocky Neck in Hingham.

If the stratigraphic units in the fault blocks are moved back into a possible original alignment across the major fault zones that separate them, the units are aligned along the side of basin nearly twice the present length of the Boston Basin. Only the argillite at the south side of the Needham-Savin Hill Anticline, where this transitional sequence is missing, is left as an inlier. This argillite could be explained by block rotation to the south. The amount of structural overlap due to the reverse and right-lateral movement on the northern faults is unknown, but the basement block north of the Northern Boundary Fault would have been off to the west-northwest originally. Such a reconstruction produces a plausible rift within a coastal range shedding talus into an offshore basin to the north.

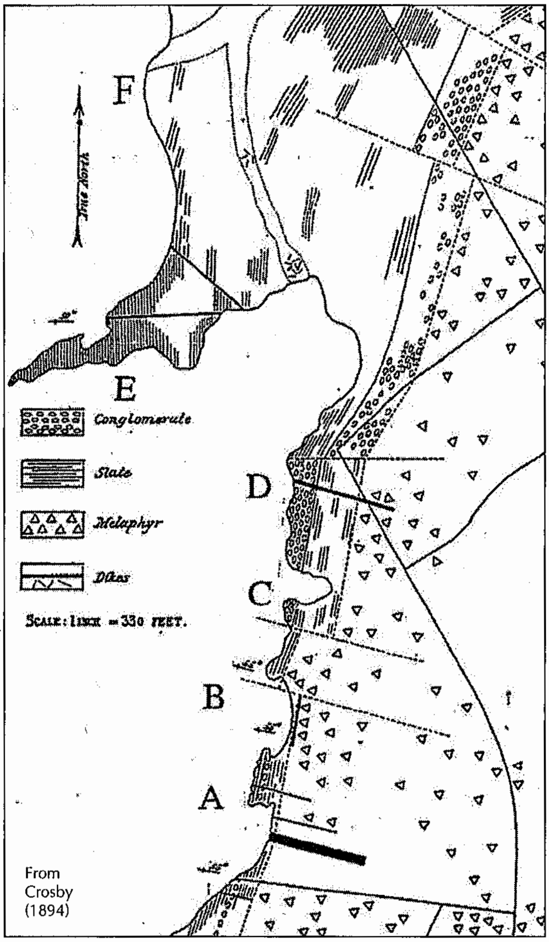


FIGURE 3-59. Geologic map of Huit's Cove.

Northeast-trending normal faults, which formed later, dominate the south border of the basin, with several of them possibly representing reactivated early faults (Barosh, 1995). These faults are obliquely offset from the east-west to east-northeast-trending faults along the border. Some faults moved during the Early Pennsylvanian and other movements probably occurred during the period of Late Triassic-Early Jurassic normal faulting across the region. The Blue Hills and adjacent Norfolk Basin formed a single structural block that has been rotated progressively toward a normal fault, the Straits Pond Fault, on the south side of the Norfolk Basin (Crosby, 1900; Loughlin, 1911; Chute, 1969; Cazier, 1987; Barosh, 1995). The Quincy and Blue Hills granites to the north form the core of the Blue Hills and contain remnants of vertical to steeply south-dipping Cambrian strata and Upper Ordovician rhyolite, which is overlain by the moderately south dipping Lower Pennsylvanian strata of the Norfolk Basin. The block continued rotating to the south, while the Pennsylvanian Norfolk Basin formed (Chute, 1969), and rotated at least 30 degrees more after the strata were deposited. The Pennsylvanian beds are folded into a narrow syncline against the fault from drag. Crosby (1900) recognized that the block was rotated, but considered the fault to be a south-dipping thrust. Chute (1969) followed this interpretation, although he reported a zone of vertical to steeply north-dipping faults and fractures cutting the adjacent strata. This border fault of the Norfolk Basin (see Figures 3-29 & 3-50) projects to the northeast-trending Straits Pond Fault and other associated faults exposed along the coast to the northeast in North Cohasset (Bell, 1975a & 1975b) where they cut the east-west-trending normal faults of the earlier Boston Basin border (see Figure 3-60). The north boundary of this structural block is the Southern Boundary Fault that must have moved again at that time to accommodate the rotation.

The latest northeast-trending faults offset the Norfolk Basin and the southern Boston Basin. These faults parallel the Late Triassic-Early Jurassic faults in the region and are probably of the same age. A late northeast-trending fault cuts off the northwest border of the Norfolk Basin and continues into the harbor south of Squantum Head (see Figure 3-29 & 3-50). This fault, portions of which are mapped in the southwest by Chute (1966) and to the northeast by Kaye (1982b), is herein named the Neponset River Fault, since it is locally followed by the river. This fault offsets the Southern Boundary Fault (see Figure 3-50) that displaced and helped rotate the Quincy Granite to the south and forms the border of the Quincy Granite and associated rock to the west (Crosby, 1900; LaForge, 1932). The partially parallel Squantum Head Fault to the northwest probably reactivated at this time to cut the Cambridge Argillite in the harbor. The adjacent blocks of Proterozoic granite and volcanic rock that are referred to as the Dedham and Readville anticlines by LaForge (1932) (see Figure 1-30) are extremely

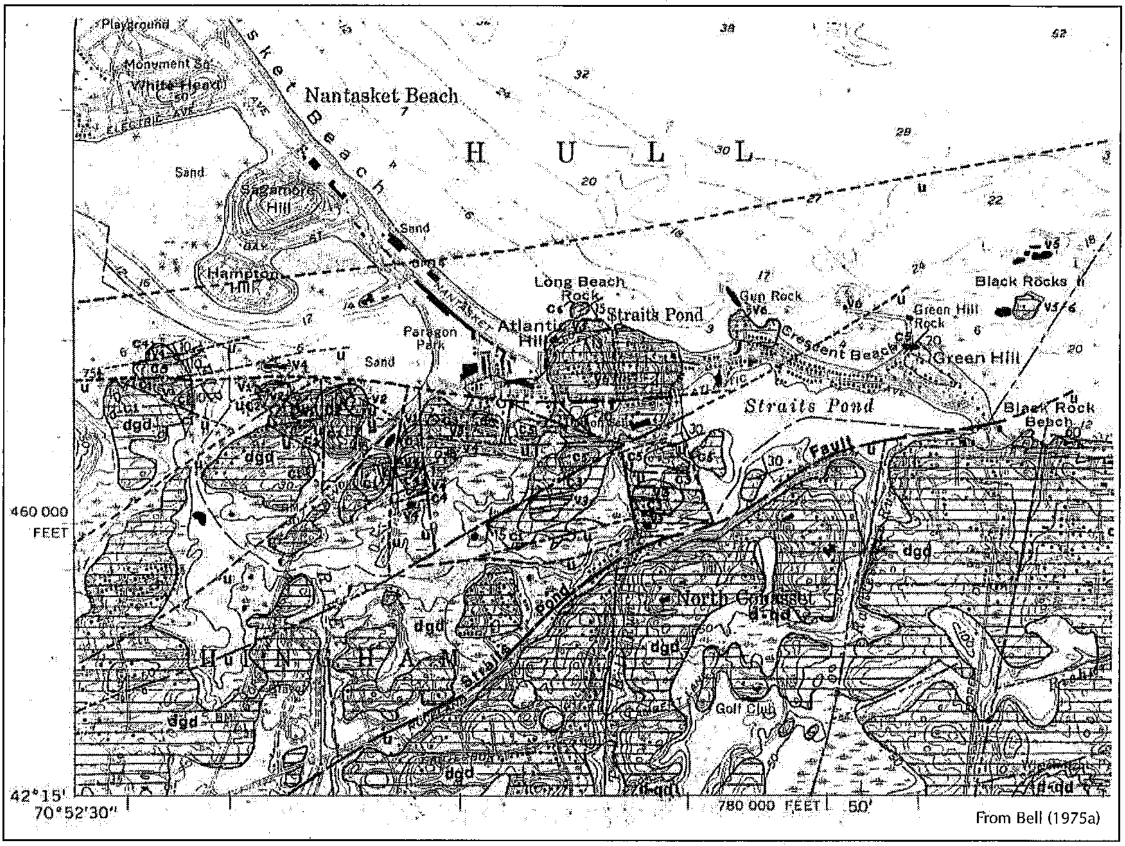


FIGURE 3-60. Geologic map of the southwest corner of the Hull quadrangle.

faulted and have highly variable attitudes in both surface and tunnel exposures (Kaye, 1980a). They are obviously broken by faults of many ages. The Neponset River and Squantum Head faults nearly merge to the northeast and would connect somehow with a broad fault zone, which extends northeastward from the southern end of Deer Island, found in geophysical exploration for the outfall tunnel. Other such late northeast-trending normal faults in central Boston may have formed about the same time (see Figure 3-51).

A great many steeply dipping transverse faults, which represent several periods of extensional movement, cut the basin rock and longitudinal faults. Most of these faults have normal offset and many are invaded by dikes and quartz veins, which in turn, are offset or sheared (see Figure 3-62). The great variety and age spread of the dikes in the basin are an indication of the chiefly extensional movement during the history of the basin. Many are shown to be pre-Late Ordovician by the age of the dikes. The east-west dikes in the basin are controlled by early faults, but some of these have reactivated and have offset transverse dikes. The principal sets of the later faults appear to be Mesozoic or younger and match the relatively recent faults sets found across all of southern New England. These sets are northeast, north-south and northwest faults in order of their age (Barosh, 1990a, 2005 & 2006c), along with some east-west ones. In addition to the northeast-trending faults at the southeastern side of the Boston Basin, there are smaller ones, which are followed by diabase dikes, both in and west and northwest of the basin. North- and northwest-trending faults, which are the latest fault sets found in New England, cross the basin. The northwest-trending dike-filled faults predominate in the northeastern part of the basin and the north-trending ones predominate in the southern part. A broad area of northwest-trending faults that is indicated by

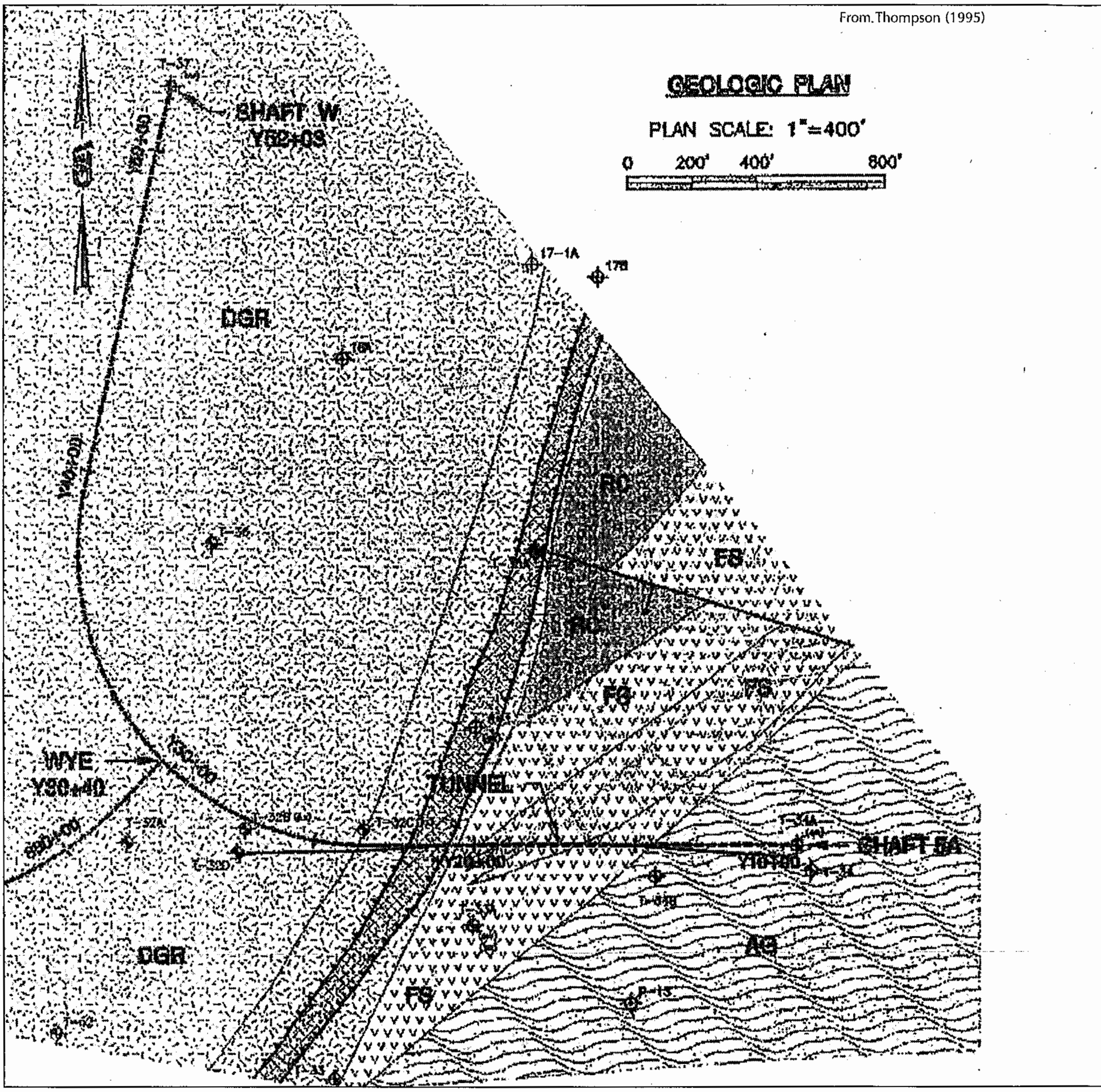
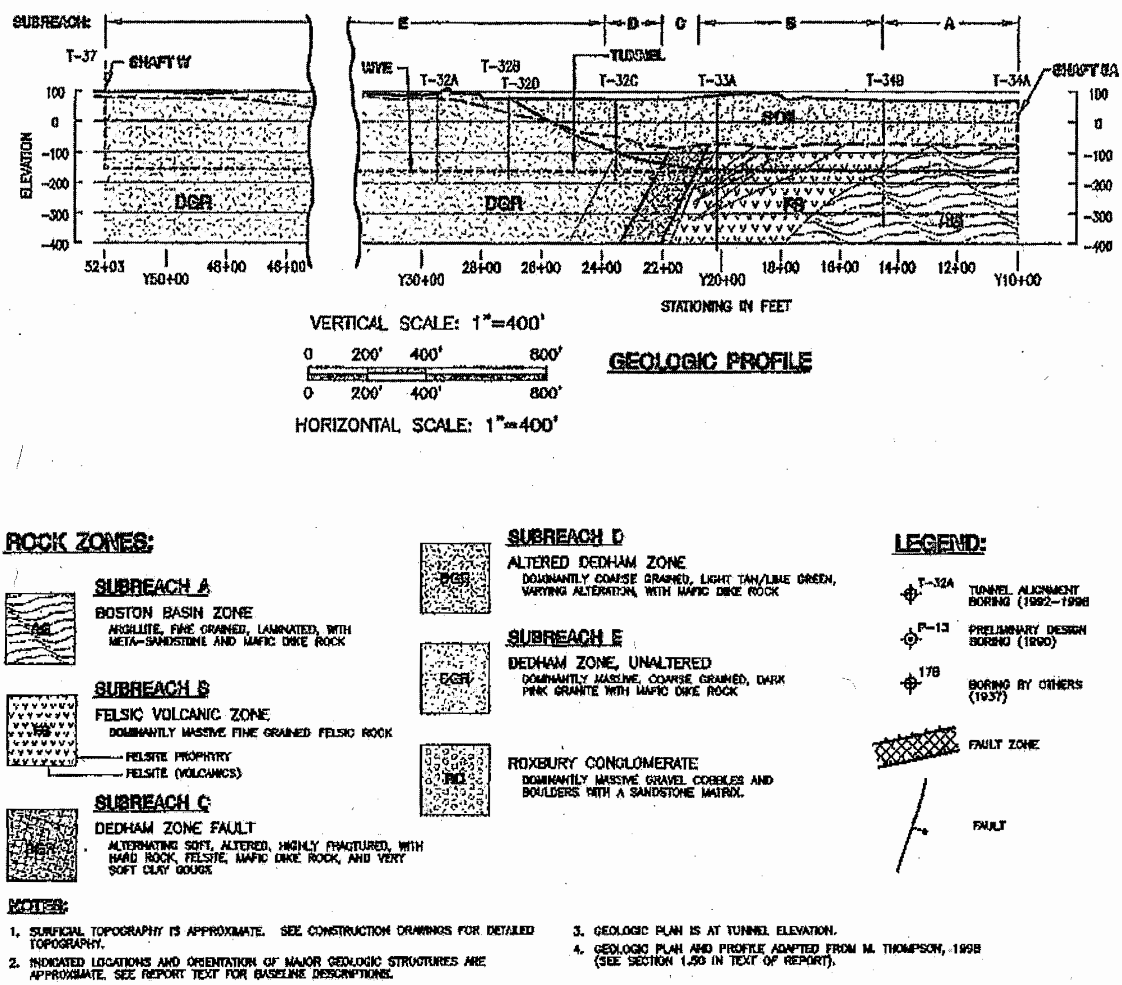


FIGURE 3-61. Geologic map and section of the east end of the MetroWest Water Supply Tunnel in Weston and Newton showing the boundary fault of the Boston Basin.

topographic and geophysical lineaments and mapping encompasses Nahant, crosses the outer harbor and locally extends to the south shore (see Figure 3-52). These faults in part belong to the earlier fracture system followed by the great number of dikes across Nahant to Medford (see Figure 3-43) and may be a reactivation of it. Geographically, at least, it is an outlier of the great zone of northwest-trending apparent faults that crosses the New Hampshire coast.

Numerous north-trending faults (see Figures 3-55, 3-57 & 3-60) cut the northern border of the Narragansett Basin and the Norfolk Basin (Chute, 1966 & 1969) and extend across the Boston Basin (Bell, 1975a & 1975b). Large Mesozoic diabase dikes lie along them south of the basin and one — the



Medford Dike (see Figures 3-43, 3-45 & 3-46) — extends across the basin (Kaye, 1976a & 1980a). Other smaller diabase dikes follow such faults as well and many show indications of later movement after dike emplacement (LaForge, 1932; Wolfe, 1976; Kaye, 1983a, 1984a & 1984b; Barosh & Woodhouse, 1990). The north-trending faults are more important to the south where they show greater extensional movement and form the Narragansett Bay and other grabens. Faults of this trend appear to be slightly younger than the northwest-trending ones in the western part of Boston Basin, but in the Narragansett Bay Graben and most other areas they are the elder of the pair. Some of the north-trending faults form a possible older set, which has relatively down to the east displacements compared to the west side. These faults include: the Mother Brook Fault, the fault bounding the east end of the Quincy Granite, and that bounding the East Point area of Nahant. Kaye (1983a & 1984a) found no drag folds associated with the later

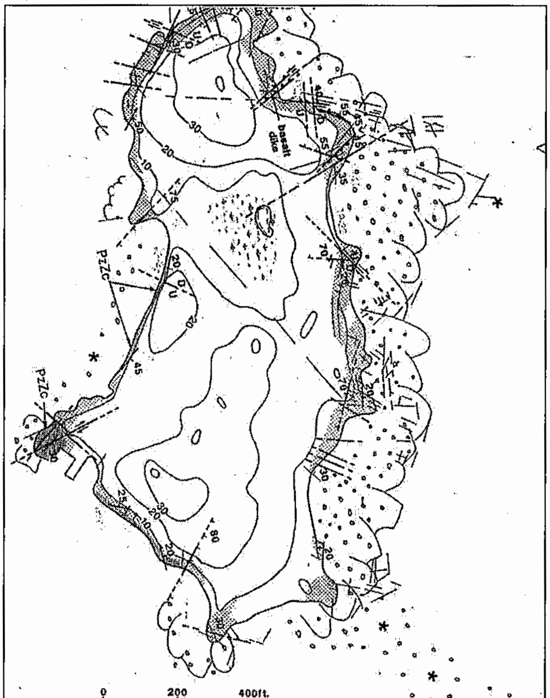


FIGURE 3-62. Geologic map of Calf Island showing faults and a diabase dike cutting igneous intrusive and Cambridge Argillite.

Mesozoic normal and strike-slip faults in the basin.

Bedrock Topography

The topography of the buried bedrock surface is a result of a combination of erosion by Mesozoic and Tertiary stream action, pre-Wisconsin Pleistocene ice movement and stream carving in interglacial times (Judson, 1949). A seaward sloping surface developed during the latter half of the Mesozoic as the effects of the earlier Mesozoic extensional faulting was smoothed and overlapped on the east by Coastal Plain deposits (see Figures 2-34 & 2-35). The shoreline would have shifted back and forth across Boston during the Mesozoic and Tertiary, but by the end of that period a river drainage system converged into the lowland of the Boston Basin and stripped away most of the overlapping coastal plain deposits, remnants of which are found just south of the basin. The surface was further modified by rivers and ice in the Pleistocene prior to the Sangamon interglacial stage (125,000 to 75,000 years ago), when a rising sea left the Boston Basin covered by the marine clay of tidal flats. This early marine clay was overridden, scraped up and incorporated into the till of the first preserved deposits of the following Wisconsin glacial advance. The glacial event would have smoothed the rock surface further and deepened it locally, but the effects of subsequent glaciations would have been negligible. The essential features of the bedrock surface and its river channels formed before the Sangamon interglacial stage.

The bedrock topography both was controlled and was modified by the Pleistocene glaciers. The lower part of the ice followed the topographic lows as it scooped up the loose material and smoothed the surface. The volume of regolith (loose surface material) and rock removed from the area during the Pleistocene probably far exceeded the volume of glacial debris presently found (Kaye, 1976a). The bedrock surface topography below Boston is quite irregular, with the rock surface generally at a depth of 23 to 53 meters (75 to 175 feet) below the surface (see Figure 3-63). The relief ranges from the deep bedrock valley, which extends to known depths of almost 90 meters (295 feet) bordering the west side of Back Bay to rock that just crops out to the northwest of Beacon Hill in the area of the Charles River Park development (Kaye, 1982b). Thinly covered conglomerate rock also rises to the south of the peninsula at Savin Hill in Dorchester, Dorchester Heights and the intersection of Gallivan and Morrisey boulevards in Dorchester to about elevation 30 meters (100 feet) MSL and is seen on many outer harbor islands such as such as Outer Brewster and Calf islands, and exposed beneath drumlins. The bedrock surface within the Boston Basin reflects the relative hardness of the local rock. The deeper section under the Charles River and Back Bay is underlain by softer argillite, siltstone and sandstone, and the high-standing area along the southern margin marks the outcrop of massive conglomerate. In detail, the bedrock surface is

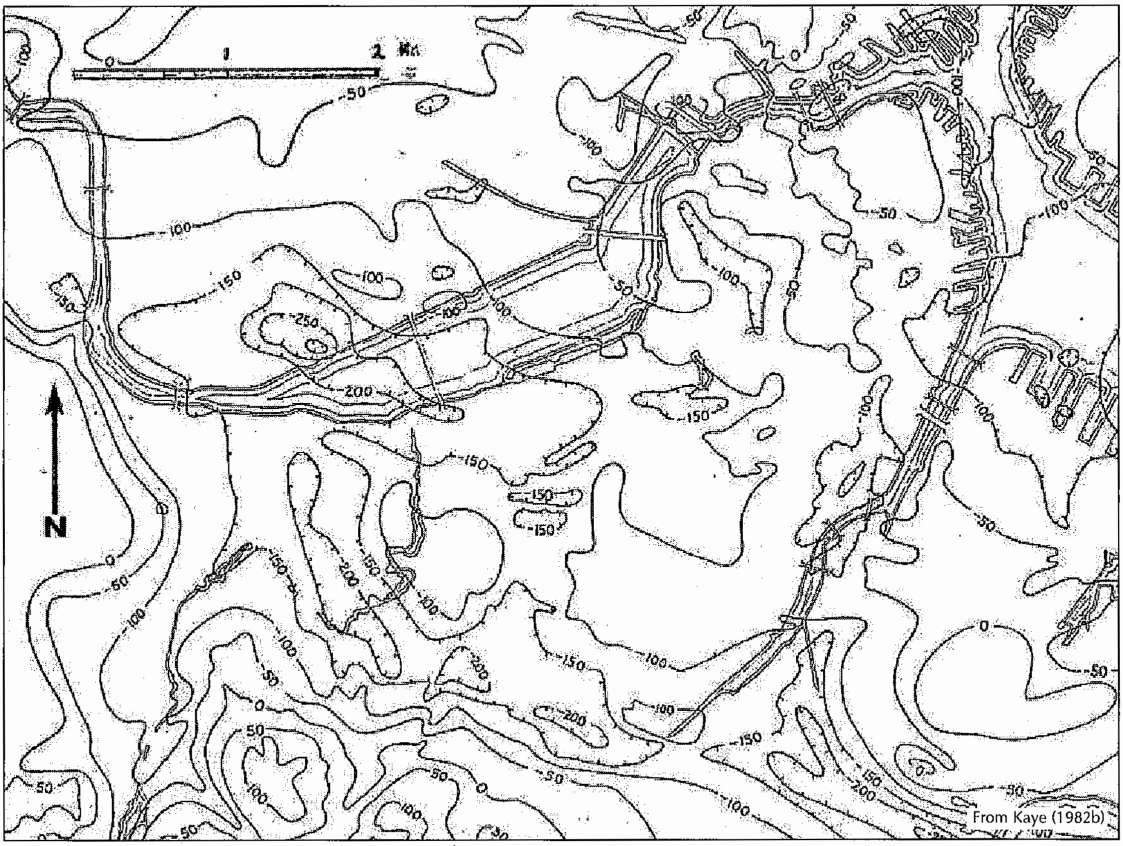


FIGURE 3-63. Simplified bedrock surface beneath Boston. The contour interval is 15 meters (50 feet) measured from MSL.

highly irregular. Dikes stand up as knobs and ridges, faults are deeply grooved and closed depressions abound. These irregularities have been revealed by the great number of borings in the city (see Figures 3-64 & 3-65) cataloged by the Boston Society of Civil Engineers (1961, 1969, 1970 & 1971; Kaye, 1970) and by the immense amount of new data from the Central Artery/Tunnel Project (see Figure 3-65) that has not yet been entirely catalogued.

The principal features found are four major buried valleys that extend into the Boston Basin and converge to flow into Boston Harbor (see Figure 3-66), along with local enclosed basins produced by glacial erosion (Upson & Spencer, 1964). The valleys (see Figure 3-1) correspond in part to present drainage courses for which they are named (Kaye, 1982b). The most striking feature on the bedrock topography near Boston is the deep, somewhat interrupted and irregular trough (see Figures 3-63, 3-66, 3-67 & 3-68) that cuts diagonally south and southeastward from the Aberjona-Fresh Pond Buried Valley to Carson Beach on Dorchester Bay (Crosby, W.O., 1899b & 1900; LaForge, 1932; Crosby, I.B., 1937 & 1939; Chute, 1959; Upson & Spencer, 1964). The south-trending Aberjona-Fresh Pond Valley veers to the southeast around a bedrock ridge beneath Mount Auburn Cemetery and joins the Charles buried valley in Allston at about the Massachusetts Turnpike Allston-Brighton interchange. From there, the Charles Valley bends and continues to the sea south of the city rather than along its present course to the northeast (Clapp, 1901). The Charles Valley traverses the Fenway and is found beneath Ruggles Street, crossing the MBTA Orange Line at Ruggles Station. The Aberjona-Fresh Pond channel was first thought to be the former course of the Merrimack River (Crosby, 1899a), but no connection was found northward of the Aberjona River in Woburn to link to the Merrimac (Crosby, 1937;

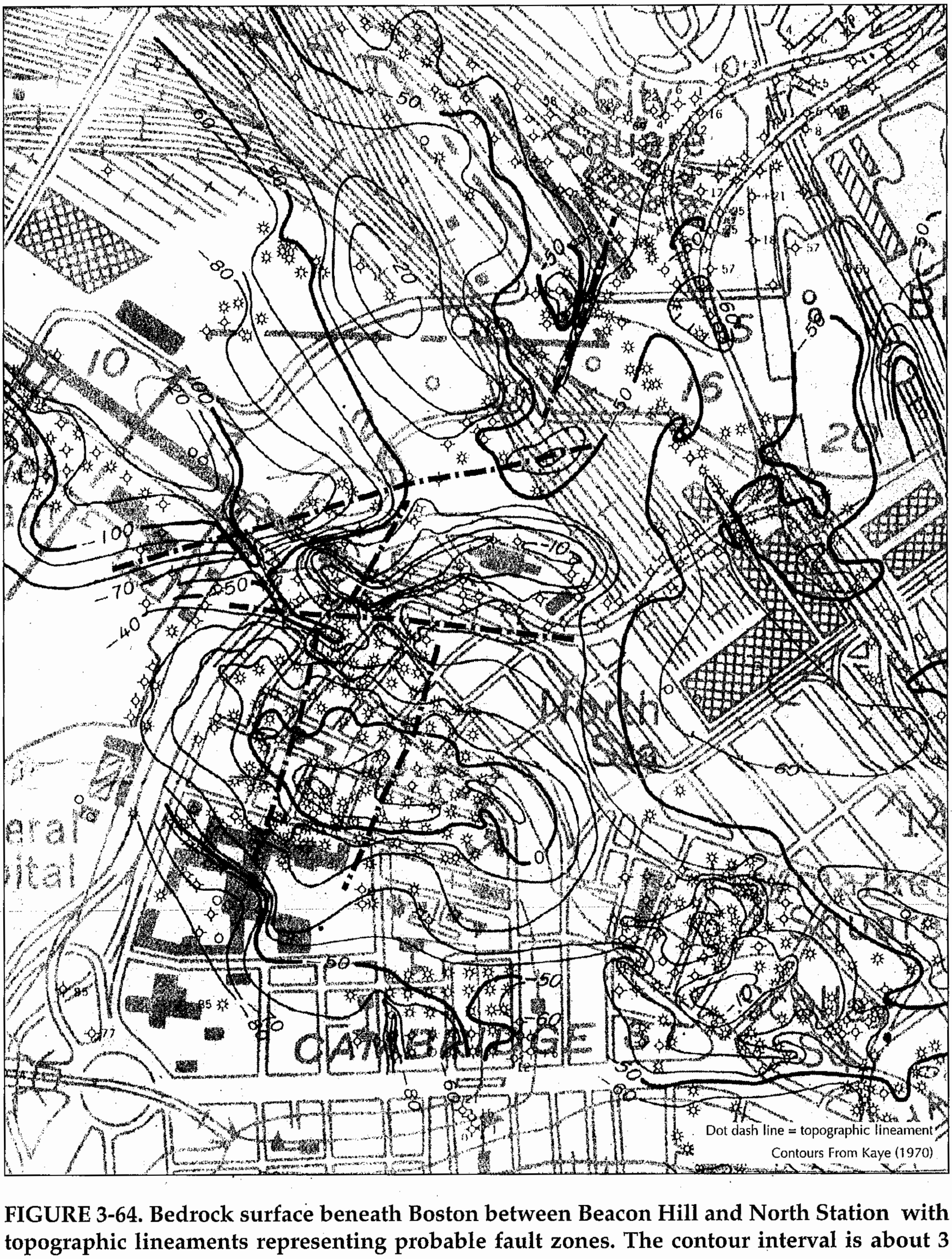


FIGURE 3-64. Bedrock surface beneath Boston between Beacon Hill and North Station with topographic lineaments representing probable fault zones. The contour interval is about 3 meters (10 feet) MSL.

LaForge, 1932; Chute, 1959; Upson & Spencer, 1964). Kaye (1970) noted tributaries to the lower Charles Valley: northeast flowing ones, which apparently followed fault zones, across Dorchester Heights, and a southwest flowing one below Fort Point Channel. The buried valley

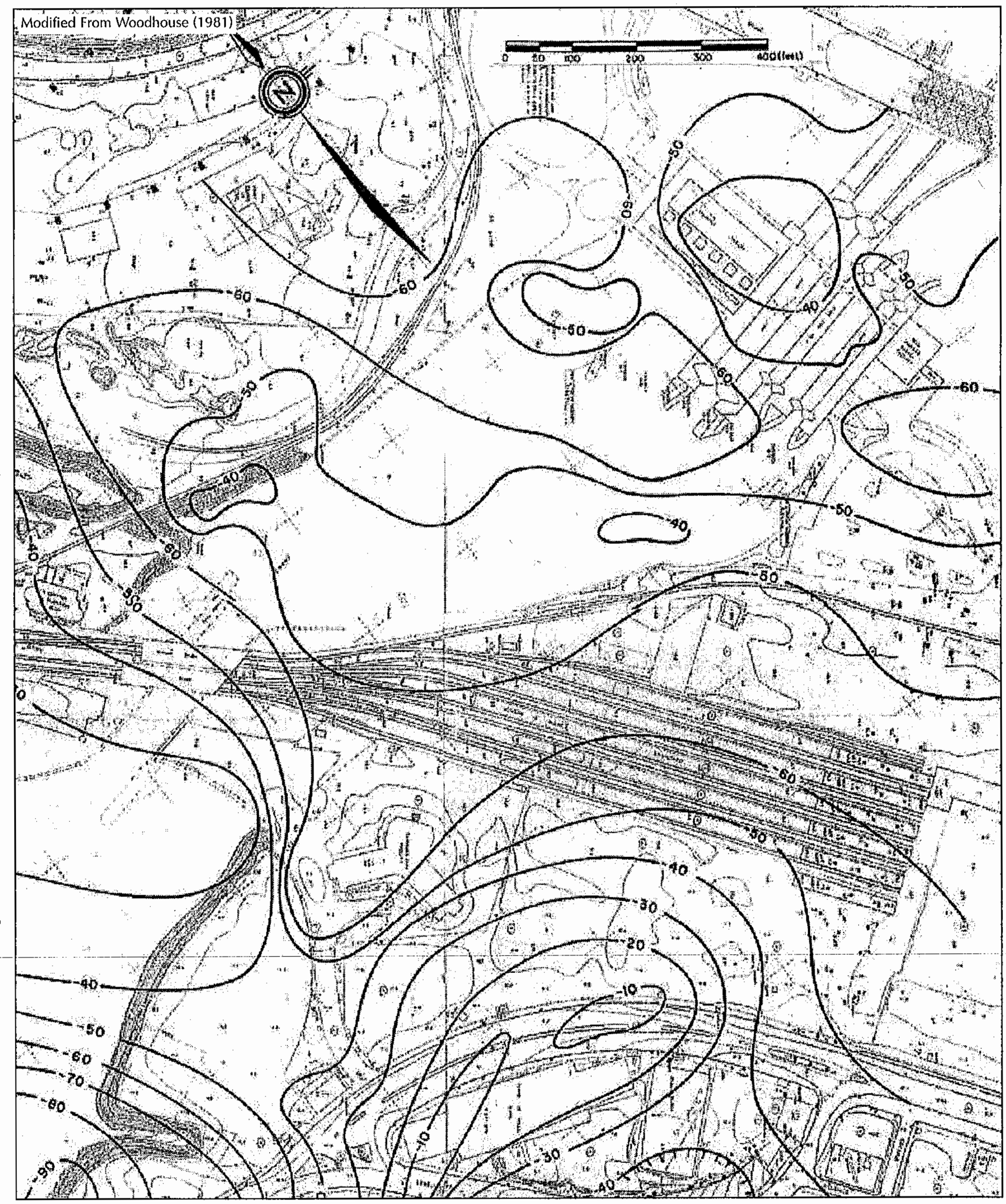


FIGURE 3-65. Bedrock surface in the North Station area, Boston — a detail of northeast corner of Figure 3-64. The contour interval is about 3 meters (10 feet) MSL.

of the Charles is joined by the buried Neponset Valley from the south and turns northward to join the buried Malden Valley and curve seaward off Deer Island (Crosby, 1937; Halberg & Pree, 1950; Upson & Spencer, 1964).

These are deep channels and the full understanding of the ancient Charles River system is hampered by the lack of elevation control of the channel as it leaves the harbor. The Charles buried valley enters Dorchester Bay

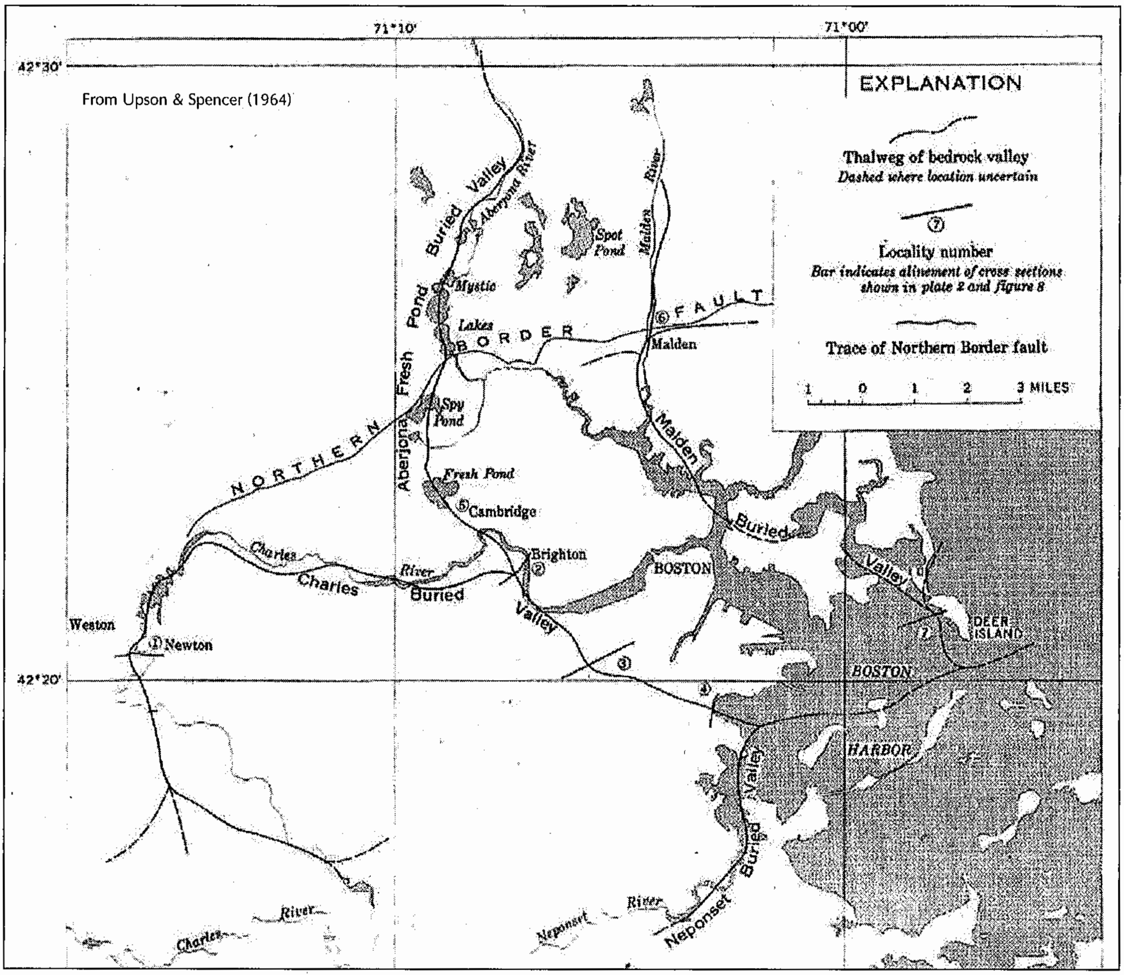


FIGURE 3-66. Map of the environs of Boston Basin showing the four major buried river channels carved into the bedrock.

(see Figures 3-66 & 3-68) at about elevation –73 meters (–240 feet) MSL and the Malden buried valley (see Figure 3-69) is at about elevation –65 meters (–212 feet) MSL or less near Deer Island (Upson & Spencer, 1964). Seismic refraction and sub-bottom seismic profiling under Dorchester Bay, along the trend of the depression to the east and southeast, and work on the Inter-Island Tunnel failed to reveal any direct seaward continuation for the Charles (Kaye, 1982b; Sverdrup, 1990b) and its channel must swing northward to join the Malden and, thence, perhaps pass south of Deer Island before continuing seaward along the channel of President Roads as shown by Upson and Spencer (1964). The lowest known bedrock surface off northern Deer Island is elevation –65 meters (–212 feet) MSL, but off southern Deer Island it is only –50 meters (–163 feet) MSL. However, the borings just south of the island are 427 meters (1,400 feet) apart and the channel can easily be deeper. However, the channel must be above the underlying tunnel roof that is about elevation –76 meters (–250 feet) MSL (Sverdrup, 1990b). The channel depth over the tunnel apparently would be between elevation –65 meters (–212 feet) and a perilous elevation –70 meters (–230 feet) MSL estimated by Upson and Spicer (1964) that leaves only 6 meters (20 feet) of rock cover. However, a lower channel may continue northeastward beneath northern Deer Island to connect with an east-northeast trending trough found by Rendigs and Oldale

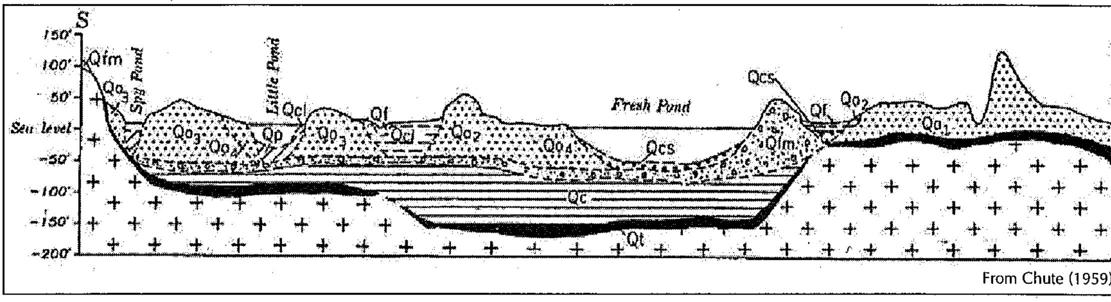


FIGURE 3-67. Section through the ancestral Aberjona river channel in bedrock beneath the Pleistocene deposits north of Fresh Pond showing an incised inner channel.

(1990). This channel would cross above the North Metropolitan Drainage Tunnel, the crown of which is about elevation –89 meters (–291 feet) MSL, before turning seaward.

Kaye (1982b) felt that the lower Charles River buried valley follows the strike of soft tuffaceous siltstone of the Cambridge Argillite, which was eroded by glacial action rather than by a river with a regular gradient. Gray-white shale and some sandstone intersected in the channel beneath Dorchester may be soft kaolinized rock, although it was considered by Pearsall (1937) to be possibly Cretaceous or Tertiary sediment. This channel may be a partial control, but it appears too much like a curving river valley sloping to the southeast to be simply an unrelated glacial feature. It is recognized, however, that there may have been some glacial deepening similar to that which apparently formed local enclosed surface lows found elsewhere. Perhaps the base level for the river system is near elevation –70 meters (–230 feet) MSL and any lower sections can be attributed to glacial erosion of soft rock.

The Aberjona-Fresh Pond buried valley (see Figure 3-67) is shown to be a broad valley with an inner gorge formed by a period of increased headward erosion during their formation either by uplift of the land or a drop in sea level (Crosby, 1937 & 1939; Chute, 1959). An inner channel also is present where the valley enters Dorchester Bay (see Figure 3-68). The bedrock topography under Boston also indicates later headward erosion that caused a

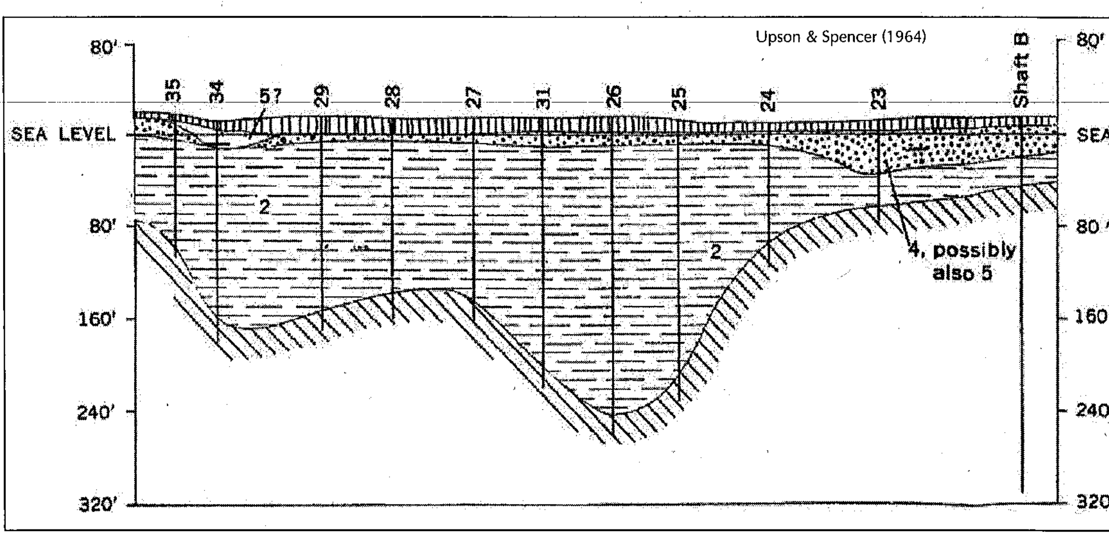


FIGURE 3-68. Section along the shore of Dorchester Bay showing the bedrock surface across the Charles buried valley at Columbus Park; view west-northwest. Data from Main Drainage Tunnel boreholes.

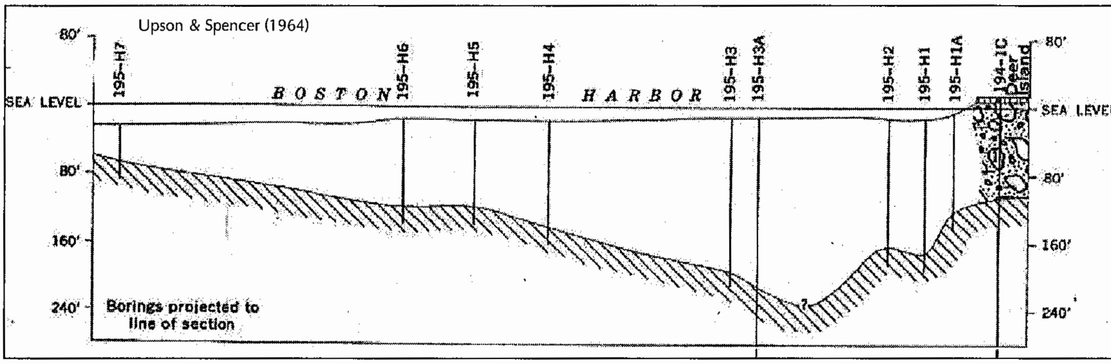


FIGURE 3-69. Section southwest of northern Deer Island showing the bedrock surface across the Malden buried valley; view north-northwest. Data from Main Drainage Tunnel boreholes.

shifting of the Charles River Valley by pirating during a period of probable rapid down-cutting. The lower Charles appears to have first flowed east toward South Station at an elevation of –27 meters (–90 feet) MSL and was likely joined by a tributary that passed beneath Beacon Hill (see Figure 3-70). The lower, eastern end was first diverted below elevation –30 meters (–100 feet) MSL by a stream from a lower level that worked its way upward above Fort Point Channel from Carson Beach. Further erosion of this "Carson" stream extended

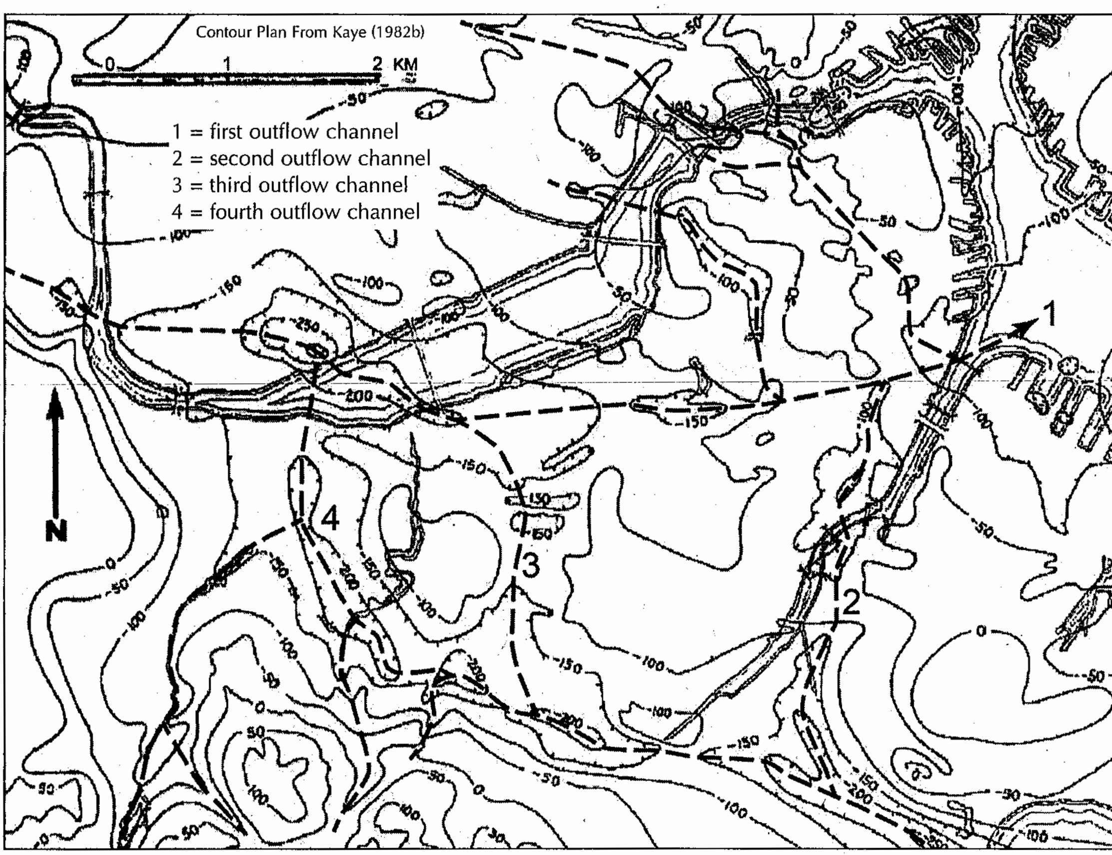


FIGURE 3-70. Bedrock surface beneath Boston showing paleo-river system and sequence of pirating of the ancestral Charles River.

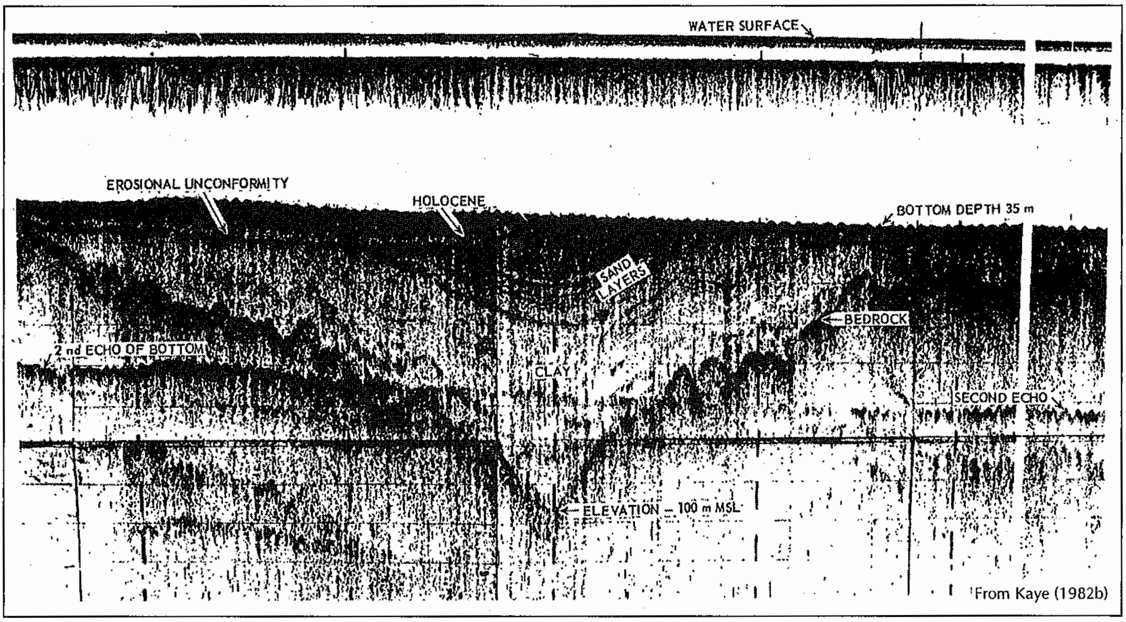


FIGURE 3-71. Sub-bottom seismic profile in western Massachusetts Bay, off Boston, showing V-shaped trough in bedrock filled with marine clay and, in upper part, interbedded sand (upper outwash). Note conformable bedding, erosional unconformity and overlying post-glacial sand. The bottom of trough is at about –95 meters (–312 feet) MSL.

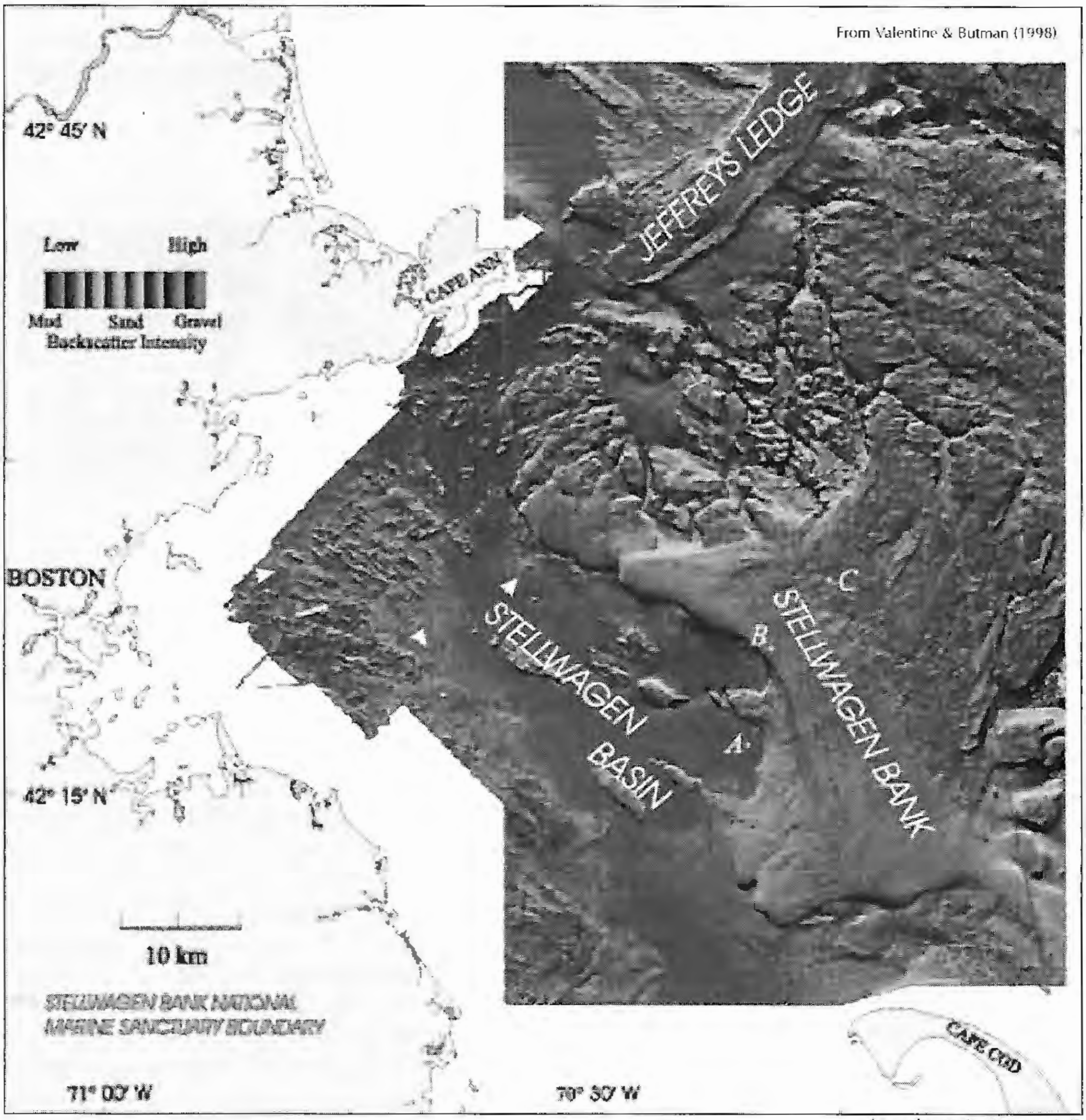
west and thence north, along a fault, into southern Back Bay near the Prudential Center at an elevation of about –45 meters (–150 feet) MSL to capture more of the eastern part of the ancestral Charles. Finally the headwaters of the "Carson" river extended farther northwestward to divert the rest of the early Charles River channel at the west side of the basin at an elevation of –60 meters (–200 feet) MSL and perhaps tapped a lake depression below the Charles River Basin.

The original Malden buried valley may have connected with the Charles near Beacon Hill before being diverted to the southeast. A separate river channel is seen at the north end of the Shawmut Peninsula in the detailed topography of the buried surface around North Station (see Figure 3-65). Here, a sharp channel (related to the Malden system) almost certainly follows a weak zone along a basin fault. It trends eastward toward the harbor and is flanked on the south by a paralleling ridge. The four main river channels form the principal late Tertiary or interglacial river system in the Boston Basin when the sea level was below elevation –61 meters (–200 feet) MSL. This drainage pattern gradually evolved into the present one as it was blocked by glacial debris and locally re-excavation, which occurred in the upper Charles River Valley (Clapp, 1901).

A V-shaped channel in bedrock filled with marine clay (see Figure 3-71) was located farther offshore from Boston Harbor in western Massachusetts Bay by Kaye (1982b) at a depth of 95 meters (312 feet), which would appear to fit in depth with those found beneath Boston (if a connecting channel could be found). Seaward in Massachusetts Bay, the bedrock topography shows a change to a series of north- to northwest-trending enclosed basins and highs (see Figure 3-72) with aligned east-northeast-trending irregularities (Oldale & Bick, 1987; Valentine & Butman, 1998). These features indicate a chiefly structural control with only modification by glacial ice and without any clear river channels, which suggests that some of the enclosed basins closer to shore have more of a structural control than heretofore considered.

Surficial Geology

Overview of Pleistocene Deposits. Glaciers during



(see color version on page 461)

FIGURE 3-72. Sea floor topography from Massachusetts Bay to Stellwagen Bank.

the Pleistocene epoch, which spanned about 2 million to 10,000 years ago, further eroded the Tertiary valley that formed along the relatively soft rock of the Boston Basin. These glaciers reworked the soil and weathered rock and then deposited a wide and complex mixture of sediment that is topped by Holocene deposits and the debris of nearly 400 years of building and filling in the city. More than 95 percent of the surface of bedrock of the central Boston area lies buried beneath these deposits. The glacial deposits are especially complex since they involve a mixture of terrestrial and marine debris from several glacial episodes during the last glacial episode (the Wisconsin). These deposits, along with extensive younger ones, blanket the Shawmut Peninsula in a confused fashion that leaves each site different in Boston. The description and understanding of these deposits was gradually revealed in excavations and from the logging and analysis of innumerable samples by geotechnical firms, the USGS and early work by personnel of universities in the Boston area. The references cited are historical ones and recognize the work of early workers as well as more current ones. Much of the deposition, thickness and characteristics of the earlier deposits, which influenced the later ones, are controlled by the bedrock topography.

The thick glacial deposits of the Boston Basin are probably the most complex in the country (see Figure 3-73). There had been a long period of weathering in the region to provide soft and loose material for glaciers to move and remove. Now only rare remnants of pre-glacial weathered rock (saprolite) are uncovered in valley bottoms, usually after floods. Glacial deposits cover bedrock almost everywhere in the central Boston area and attain a maximum thickness of 90 meters (295 feet) in a few places under the Charles River Basin. These deposits are related to ice that locally vary by about 90 degrees in basal flow direction and include multiple layers of till, sand, gravel, silt and clay of both terrestrial and marine origin. The depositional environments and facies relations of the glacial debris were complicated by the dynamic nature of the glacial ice in a coastal environment that was repeatedly flooded by marine waters. Variation in ice thickness, eustatic sea level and isostatic crustal levels were all interrelated factors affecting erosion and deposition. The result is an often bewildering array of strata that may change abruptly over short distances (see Figures 3-74 & 3-75). The late glacial Wisconsin deposits dominate the region, and no pre-Wisconsin drift from the long course of earlier glaciation has been definitely identified, although some is suspected. Wisconsin deposits of at least two major advances and one lesser glaciation remain, along with remnants of a possible earlier one. The first two moved across the entire city and harbor, but the following lesser one extended only to its northern and western sides.

The origin of glacial deposits was a mystery to early geologists and one geologist even considered them debris from a comet impact (Donnelly, 1883). (Note: a version of the comet theory has been resurrected by West *et al.* [2006] and several colleagues who believe a comet or asteroid exploded over central Canada 12,900 years ago to trigger the last, Younger-Dryas, glacial event, which is known in Boston as the Lexington Substage; others place the impact in Chesapeake Bay or Georgia.) However, great strides in describing the glacial deposits in eastern Massachusetts (and unraveling the events that produced them) were made quickly after the mid-nineteenth century. This unraveling occurred after Louis Agassiz arrived from Europe in 1846 with his knowledge of Swiss glacial deposits and theories on continental glaciation. The deposits around the edge of the basin and on harbor islands were studied to reveal that the drumlins consist of two tills, with the lower one containing an extensive shelly fauna (Crosby & Ballard, 1894). However, much in Boston remained little known because of the urban and water cover until borings and deep excavations began to reveal their character. By 1949, Judson recognized an early extensive glaciation in Boston that he referred to as the Boston Substage, lumping together the two tills mentioned above, and a last minor one, called the Lexington Substage. He also recognized evidence for an earlier event in two inclusions in the till. Kaye, of the USGS, noted three different layers of drift at the southern edge of Beacon Hill and the two divisions of the till on the harbor islands began again to be acknowledged (Kaye, 1961). When excavations at Beacon Hill, which originally had been thought to consist entirely of till, revealed a core of thrusted outwash and till deposits, up to five glaciations were interpreted by Kaye (1967b & 1976c). This disturbed section was interpreted in various ways that are difficult to correlate with one another (Kaye, 1961, 1967b, 1976b & 1982b) because various repeated layers were considered to represent separate events when he wrestled with unraveling the thrusted layers.

Establishing the age of the units was an equally slow process. The scheme of four major glaciations, which were based on relations and ages found in the Midwest by the USGS, and that covered the entire Pleistocene epoch, was applied to the Boston area (Kaye, 1961). But evidence for such a long period of multiple glaciations based on observations in and around Beacon Hill has not been found in Boston in spite of extensive studies by many workers, including Woodhouse. The glacial deposits of Boston, which are much more

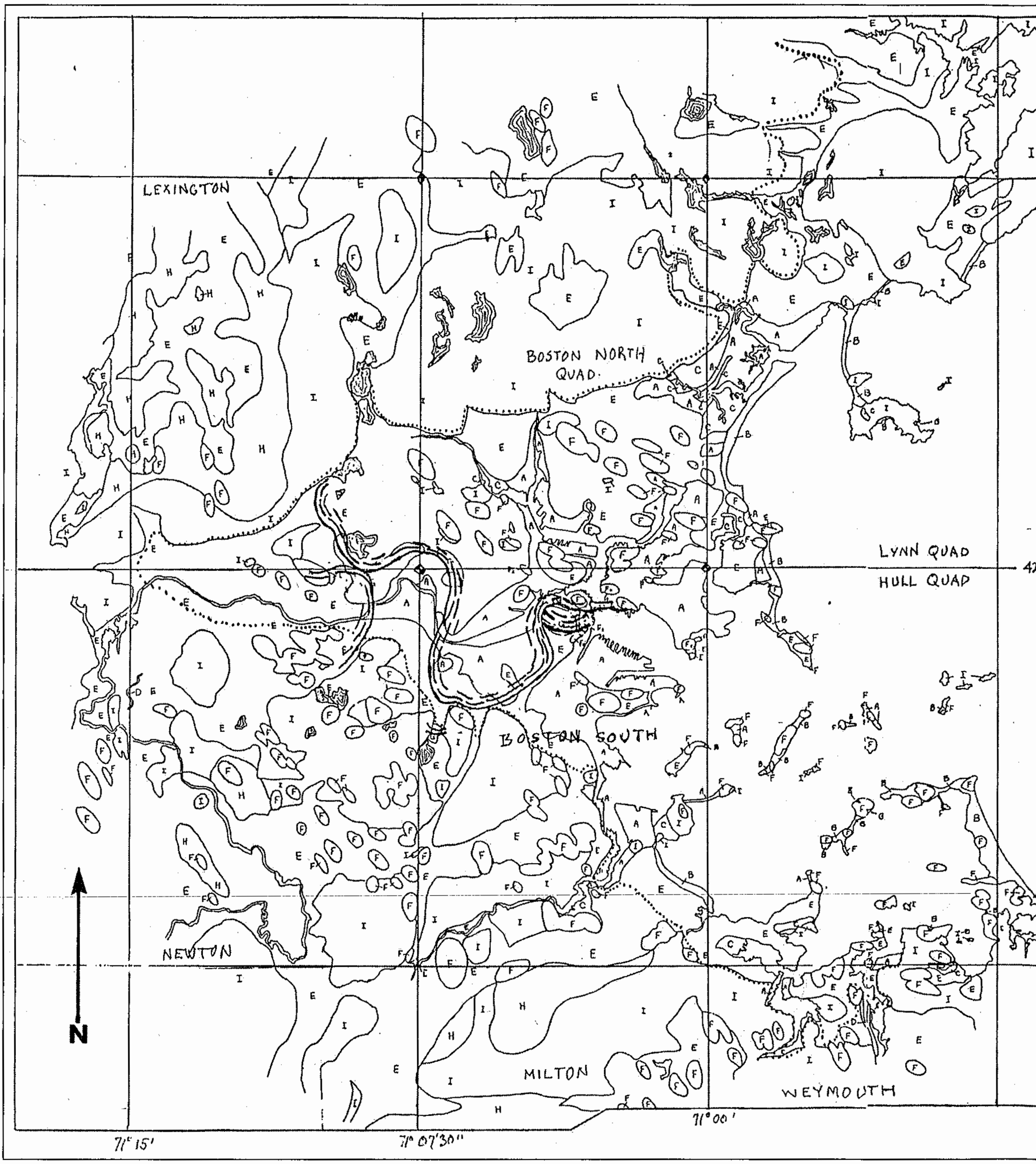
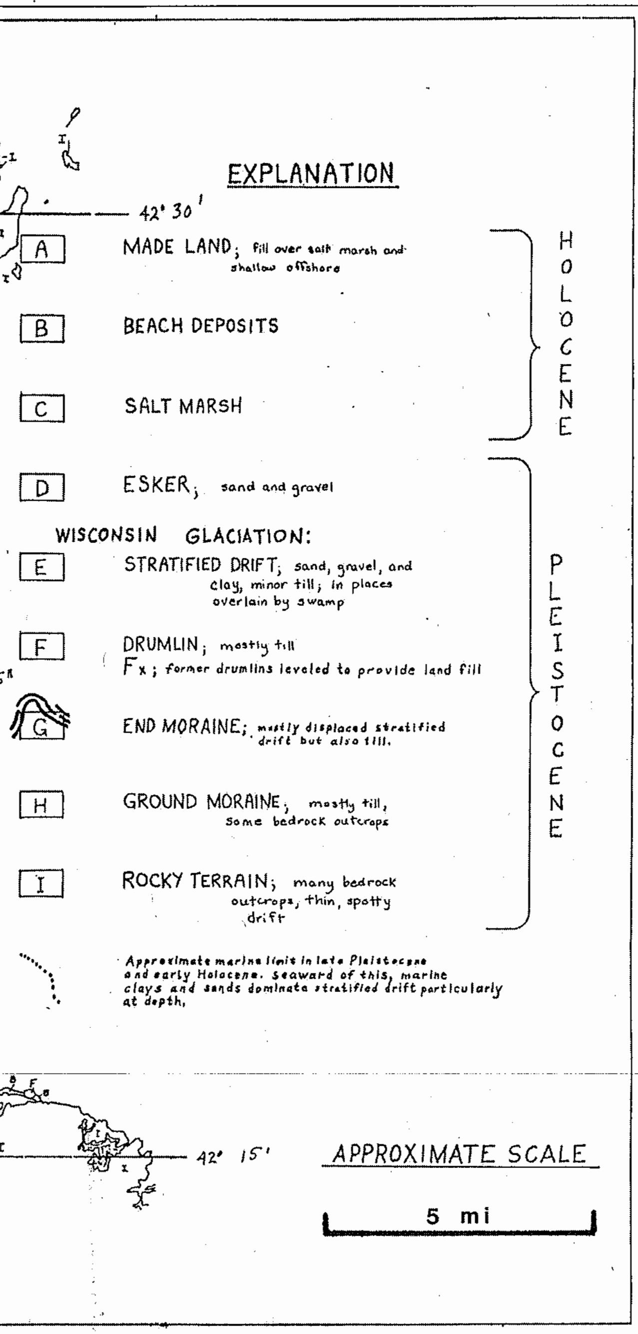


FIGURE 3-73. Surficial geologic map of Boston and vicinity.

complex than in the Midwest, are found to only relate to the youngest, Wisconsin Stage of the Pleistocene (Kaye, 1982b).

Kaye's conclusions concerning multiple glaciations were made during the period beginning in 1959, when Boston's construction boom began with the building of the Prudential Center, until his passing in 1985. They were based primarily on interpretations of glacially deformed thrust deposits exposed in excava-



From Kaye (1978)

tions in the Beacon Hill area. These excavations included those for the Boston Company Building on Court Street, the parking garage under the Boston Common on Charles Street, and the Holiday Inn and Garage on Cambridge Street. Since 1985, excavations for the Post Office Square Garage and Millennium Place on Tremont Street, and many test borings, have provided additional information for the interpretation of these overthrusted deposits. These data and those from the Central Artery/Tunnel Project and harbor tunnels have brought a flood of new information, which has greatly clarified and expanded the knowledge of the entire Pleistocene section. These data revealed the relations of the units noted by Kaye, eliminated repetitions of units and added newly discovered ones. The southern limit of the deformed deposits was found to be at about Stuart and Kneeland Streets (Woodhouse observations) based on explorations and excavations for the Wang Center on Tremont Street, the Park Plaza Hotel tower in Park Square, the proposed hotel at Charles and Boylston streets, the Transportation Building on Stuart Street and a housing development in the South End. Deformation to the north of Beacon Hill ends on Cambridge Street west of the Holiday Inn (deformed sediments) and near the entrance to the Massachusetts General Hospital on Grove Street (Woodhouse observations). In that location, test borings and an excavation for the relocation of a historical building found organic sediment overlying marine clay.

A highly complex but consistent picture of the glacial deposits and histories now has emerged. The surficial deposits around Boston were formed by two major Late Wisconsin glaciations and one that only reached the outskirts of the city, plus scattered minor remnants that may represent an earlier one. The last two events correspond to Judson's (1949) local provisional terms of Boston and Lexington substages. These substages are useful in grouping the till and retreat sequences associated with a glaciation. The preceding one is herein referred to as the Beacon Hill Substage. The existing record shows marine clay had spread widely across the area in the last major interglacial period (the Sangamon Stage) under warmer conditions than today. This period was followed in the Wisconsin by the Beacon Hill Substage. The Boston Substage was the last advance that covered all of Boston, shaped Beacon Hill and formed the drumlins of the harbor islands. The last major Late Wisconsin glacial ice started about 18,000 years

QUATERNARY STRATIGRAPHY OF BOSTON

AGE	GLACIATION	SYMBOL	STRATIGRAPHIC UNIT
HOLOCENE		F	Fill
		^^^	
		SS	Shore Sediment
		^^^	
		OS	Organic Sediment
		^^^	
PLEISTOCENE UPPER	___	RMC	Reworked Marine Clay
		^^^	
		LC	Lake Clay & Capping Outwash
	L		
		UO	Upper Outwash
	___	MD	Moraine Deposit/
		^^^	
		MC	Marine Clay

	B	LO	Lower Outwash
		^^^	
		GM	Glaciomarine Sediment

	___	UT	Upper Till
		^^^	
LOWER	BH	DSS	Deformed Stratified Sediment

	___	LT	Lower Till
		^^^	
	?	P-T	Pre-Till Sand and Gravel

BH = Beacon Hill Substage
B = Boston Substage
L = Lexington Substage

FIGURE 3-74. Columnar section of Quaternary deposits of Boston and vicinity, consisting of Wisconsin and Holocene deposits.

ago, but the retreat was not uniform and fluctuations of the ice front resulted in local re-advances (Kaye, 1982b). A terminal readvance, the Lexington Substage (Judson, 1949), only extended into valleys north and west of Boston. This substage appears to coincide with a short, abrupt cooling and glacial re-advance about 12,900 to 11,500 years ago named the Younger Dryas in Europe. It interrupted the general warming at the very end of the Pleistocene (Muscheler *et al.*, 2008). Small shelly fauna indicate that conditions were warmer than the present both preceding and following the Boston and Lexington substage glacial events (Dodge, 1894). Additional northern species demonstrate how the climate cooled before the onset of the Boston Substage. The latter warm period is evidence of a weak post-glacial climate optimum existing in the early Holocene, after which the waters cooled and then began to warm again.

Additional earlier glacial events such as those recorded on Martha's

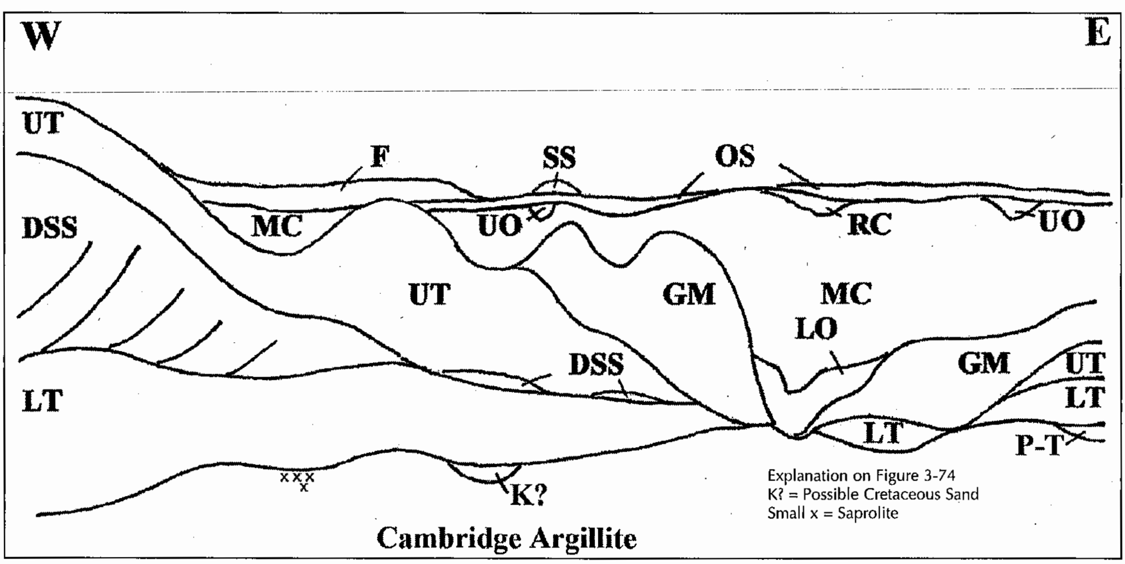


FIGURE 3-75. Diagrammatic sketch showing relations of Quaternary deposits of Boston and vicinity.

Vineyard (Kaye, 1964b), the glacier that was in retreat at 50,000 years ago in lower Manhattan (Moss & Merguerian, 2009) when the sea was lowered at least to elevation –28 meters (–93 feet) MSL, and others offshore to the east (Uchupi & Bolmer, 2008) would have affected Boston, but their record has been erased here. The reported continuous depositional sequence starting at 19,000 years ago found to the east on Stellwagen Bank (Tucholke & Hollister, 1973; Silva & Hollister, 1973; Kaye, 1975) shows a corresponding Late Wisconsin section, lacking the earlier Pleistocene stages.

The glacial events at Boston, during which ice formed and melted, are reflected in the changing relative sea level of the latest Wisconsin, as recognized early from deposits and a range in shoreline terraces (Shaler, 1874; Wolfe, 1976). However, the change affecting the shoreline is not a simple process related only to the rise of water, but it is acted in combination with the isostatic rebound of the crust from glacial melting and various tectonic movements (Barosh, 1986c). Both the rebound and a major tectonic movement involve the tilting of the East Coast, which cause differences in the relative rise of sea level and recorded shorelines at different latitudes; therefore, the data used must be kept fairly local. The early record around Boston can be inferred from the depositional history and the later record from dated horizons.

The depositional sequence in and around Boston reflects the above factors during glacial advances and retreats during the Wisconsin, plus later, more recent Holocene erosion and deposition (see Figures 3-74 & 3-75). Rare scattered remnants of sand and gravel below the first till over the argillite may record an earlier glacial event. The Beacon Hill Substage forms the first definite sequence with till (lower till) from the glacial advance and then overlying retreat deposits of deltaic sand and gravel and clay (deformed stratified sediment). Erosion by the second advance (the Boston Substage) removed most of the retreat deposits except those it deformed and piled high beneath Beacon Hill. The till (upper till) of that second advance is widespread and forms at least the cap, if not the whole, of the numerous drumlins in the basin. Its retreating glacier front discharged material into marine waters to form poorly-sorted glaciomarine sediment (glaciomarine sediment), which emerged and was incised by channels that partially filled with outwash sand and gravel (lower outwash) as the glacial front receded inland. The course of the ancestral Charles River would have shortened, lengthened and shifted since being first buried in the Pleistocene, but its present swing northward and around the northern end of Boston appears established by this channeling. Further erosion removed some of the outwash as the ice retreated northward and the area was again inundated by the sea. Marine clay, derived from the more distant glacial front, subsequently blanketed the submerged areas that would have been to a higher elevation than today in the Boston area and smoothed out the relief. The clay emerged during isostatic rebound when the relative sea level fell and the ancestral Charles River and its tributaries, plus a river along Fort Point Channel, were once more incised. Another glacial ice re-advance extended from the north and invaded just into the western and northern edges of the city during the Lexington Substage, where it pushed up two moraines (moraine deposit) near Fresh Pond, and sent tongues of sand and gravel, and clay outwash (upper outwash) down river systems and onto low areas of the marine clay. Lake clay, in part reworked marine clay (lake clay deposit), filled in behind the moraine during the retreat along with outwash sand farther north.

The patterns of deposition, erosion, interfingering and relief often left a bewildering assortment of sediments at any particular location (see Figure 3-75). Similarities in the description of the glaciomarine deposits and till only added to the confusion. Any unit may locally rest on any older unit beneath it due to erosion and relief, which commonly causes abrupt lateral changes with one unit replacing another. Each type of material may have been deposited and re-deposited at different times and be in complex stratigraphic relations. The following description presents a detailed depiction of the formation of the numerous

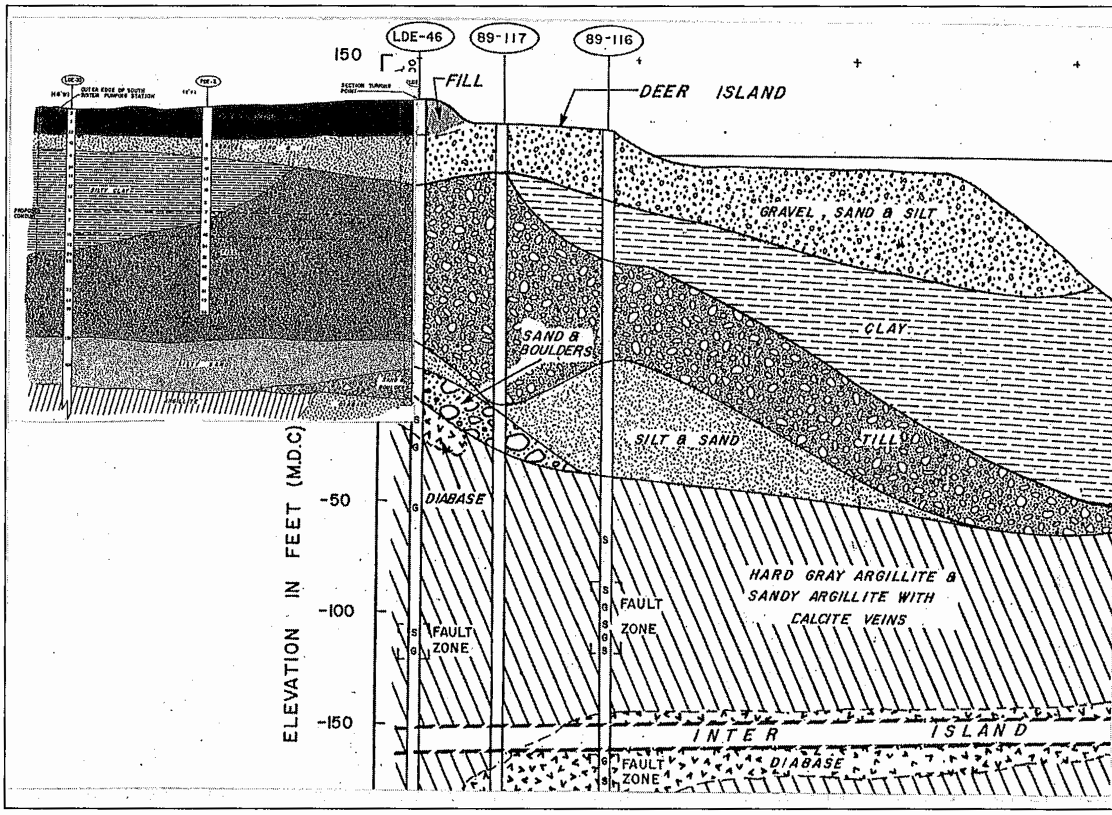


FIGURE 3-76. Sand and gravel deposit beneath the lowest till deposit at the southern end of Deer Island and the Inter-Island Tunnel, view east.

site-specific glacial deposits and landforms in Boston and the surrounding areas. It draws upon the work of many geologists, in particular that of Clifford Kaye, S.S. Judson and John Humphrey. This depiction includes the results of many, often extensive site sub-surface investigations by geotechnical firms and the USGS. The Central Artery/Tunnel Project sub-surface profiles especially provide great insight into the geology along the waterfront areas of Interstates 93 and 90. The establishment of uniform terminology and correlation of units across the basin has demonstrated their stratigraphic relations well.

The descriptions below are arranged chronologically, starting with the oldest. These relations are described briefly below. Grain size analyses for many of the deposits are given by Judson (1949).

Pre-Till Sand & Gravel. The first preserved evidence of Pleistocene glaciation may be the scattered small deposits of sand and gravel found beneath the lower till. Stratified sand up to 1.8 meters (6 feet) thick underlie the till in a few places, such as in Tech Square in Cambridge across the Charles River from Boston between Kendall and Central squares, in Davis Square in nearby Somerville and under the original John Hancock and New England Mutual buildings in Copley Square. These deposits have been interpreted as undermelt deposits (Woodhouse, 1981), but could conceivably be remnants of an earlier retreat deposit. Future exploration may clarify this classification, particularly if till is found beneath any deposit. Judson (1949) also reports similar thin deposits of sand, gravel or clay that may have either origin. A thicker sand lens is present between the till and argillite near South Station and a greater layer of sand and gravel is found in the same stratigraphic position under Deer Island.

A very dense layer of brown to gray-orange-brown, fine to coarse sand with some silt and gravel, shell fragments and few cobbles and boulders underlies the till across the southern end of Deer Island (Sverdrup, 1990b; Metcalf & Eddy, 1990b). The deposit (see Figure 3-76) is 6.1 meters (20 feet) thick north of the shore, thins greatly southward over a bouldery lens and thickens again to 18.3 meters (60 feet) farther south at the shoreline, with a north-south extent of over 670 meters (2,200 feet). Beneath it and over the argillite is a narrower lens of sand and boulders reaching 6.1 meters (20 feet) in thickness that was encountered in two boreholes 150 meters (490 feet) apart. It consists of boulders, fragments and some cobbles of argillite, quartzite and igneous rock with some sand and gravel. The deposit drapes over a shoulder formed of a diabase dike that drops off to the south. If the boulder deposit is an esker, it is unusually wide and the overlying sand is hard to explain. The boulder deposit might also be a residual talus or till deposit covered by outwash sand. The overlying till likely consists of both lower and upper till as it does on nearby Long Island and fills a channel cut through the sand a short distance to the south. Such sand and boulder deposits beneath the till are not described elsewhere along the Inter-Island Tunnel alignment to the south. The shell fragments suggest the deposit is post-Sangamon and Wisconsin in age.

Lower Till. Sometime following the marine incursion of the area during the Sangamon interglacial time, ice of the Beacon Hill Substage advanced across the Boston Basin, leaving the widespread lower till deposit that was laid down on a surface that was not submerged at that time. Some of this deposit was torn up and redeposited with other material as an overlying upper till by the next glaciation of the Boston Substage as it passed over the region. These two tills are commonly in contact, and the recognition and separation of these two tills has evolved slowly. The till was recognized as consisting of two separate till units by 1894 (Crosby & Ballard, 1894), but these were later lumped into a single unit in Boston (Judson, 1949). They are now again divided into upper and lower tills representing separate glaciations, the upper one being laid down as capping on the numerous drumlins formed in the basin. It was recognized early that the presence of numerous shells and a slightly different color in the lower part made for a twofold division. Upham (1889) recognized that the shells were swept up into the till by an advancing ice sheet following an explanation of similar features in England. Crosby first felt that it was a single till in which the shells in the upper till had been dissolved, but then found that there were two tills separated by a retreat and readvance (Crosby & Ballard, 1894). Exposures on the islands east of the city reveal that the two tills are generally juxtaposed without significant intervening stratified deposits, although Fuller (1914) and MacClintock and Richards (1936) had noticed some on Long Island. However, borings, excavations and sea cliffs now have shown that many drumlins consist of two tills with a zone of very compact thinly stratified clay and silt in between (Kaye, 1984b). Lenses of stratified material found at depth within the till along the east side of Boston form a separating unit, which apparently thickens to the west to form a thick wedge of deformed material. This material lies beneath the upper till in Beacon Hill. The lack of intervening retreat deposits on the islands has spurred extensive research to understand and divide the tills, which are generally not distinguished in boring logs. The lower till is the beginning of a glacial sequence (herein called the Beacon Hill Substage) whose retreat deposits were mostly eroded or buried.

Both the lower and upper till are typically a dense, heterogeneous unsorted and generally non-stratified mixture of all particle sizes composed of a clay and silt matrix, with coarser fractions up to cobble and boulder size (see Figure 3-77). The rock fragments are often broken pieces of the underlying bedrock material. Where the underlying bedrock is argillite, the composition of the till is more silty and clayey with many argillite clasts. The unoxidized color is gray to olive gray, and changes to buff to brown where oxidized. Locally, the till has a low plasticity that has caused foundation problems. Foundation engineers learned lessons about this material on earlier projects when piles driven into what was classified till

(see color version on page 462)

FIGURE 3-77. Typical till at Great Brewster Island.

or till-like often did not take up as planned and instead became friction piles. This behavior, for example, was experienced during the construction of the Little Mystic housing project in Charlestown, in the Fenway area of Boston and in Haymarket Square. In places, weathered till has a blocky texture or cubic jointing, which extends to a depth of nearly 15 meters (50 feet) that is characteristic of previously frozen ground (Judson, 1949). The lower till at the west side of the Boston Common is a thin, very dense, pebbly and silty sand that has few cobbles and boulders and is somewhat variegated in color (Kaye, 1961). This thin dense till is found in deep borings in the Boston Basin but has not been recognized on the surface (Kaye, 1961), except on some islands.

The differences in composition, weathering, mineralogy, structure, magnetic properties and degree of soil development of the two tills on the islands have been studied extensively by many and have been the subject of countless harbor field trips since the late nineneeth century (Upham, 1879; Grabau & Woodman, 1898; Newman *et al.*, 1990; Colgan & Rosen, 2001). The focus has been on distinguishing whether or not these deposits represent the overridden (lodgement) till, till from material in the ice that has settled (ablation) or tills of different glaciations — along with determining their ages. On Long Island, for example, the lower till is extremely compact, olive-gray, has a more clayey matrix and contains marine shells; whereas the upper till is compact, olive in color, has a more sandy matrix and is more bouldery (Newman *et al.*, 1990). The difference is also found in the till outside of the Boston Basin where it is ascribed by many to ablation and lodgement till of the same age. On Great Brewster (see Figure 3-78), Long and Peddocks islands, the analysis of weathering depth profiles, the sequence of clay mineral alteration products and the presence of soil formation features in the upper part of the lower till indicated to Newman *et al.* (1990) that a long period of weathering occurred between the tills and that they are, therefore, from different glaciations (Newman, 1988; Newman *et al.*, 1990). In Boston, the presence of till of different glaciations is clear at Beacon Hill, which has a core containing a lower till and a cap of an upper till separated by stratified sand, gravel and clay. Shells in the lower till on the islands were derived from eroded pre-existing marine sediments and the lack of shells in the upper till probably reflects a lack of significant marine sediment in the time between the tills. The lack of drumlin structure in the lower till, corresponding to that of the upper till on the islands, also shows a difference in age. However, the upper and lower tills cannot be separated in samples from the extensive boreholes on Deer Island and the many exploratory holes over the 14.5 kilometer (9 mile) outfall tunnel to the east (Metcalf & Eddy, 1990; Parsons Brinckerhoff, 1990).

Originally, the lower till would have formed local drumlins, but water and ice erosion have modified these drumlins beyond recognition. The till is about 9 meters (30 feet) thick under the Boston Common and thin elsewhere beneath the city (Kaye, 1961). It is locally absent, as in the North Station area

(Woodhouse, 1981), owing to erosion prior to the deposition of the marine clay and around the Airport subway station where the erosion was prior to the glaciomarine deposition. In the Back Bay, the till is relatively thin, varying from 1 meter (3 feet) to almost 9 meters (30 feet) in thickness. Elsewhere, as at Charlestown, it is combined with the thicker upper till. The till along the proposed Phase III Silver Line Tunnel alignment from South Station along Essex Street and ending at Tremont and Boylston streets ranges from 2 to 15 meters (6 to 50 feet) thick. Elsewhere, as below 111 Federal Street, gravelly silty till with a thickness of 1.5 to 6.25 meters (0.5 to 20.5 feet) was encountered at elevations –9 to –15 meters (–30 to –50 feet) MSL, but the till is absent beneath 33 Arch Street just one block away.

(see color version on page 462)

FIGURE 3-78. Great Brewster Island showing rougher and gullied lower till overlain by smoother upper till.

Seashells were first noted in drumlins during the American Revolution in Telegraph Hill in Hull by General Benjamin Lincoln (*Geographical Gazetteer*, 1785). The abundant shell fragments were swept up and incorporated into the lower till as the glacial ice moved across the basin. Abundant foraminifera (primitive one-celled plankton with calcium carbonate shells) and ostracodes (a tiny crustacean also called seed shrimp) that came from sediments accumulating in shallow marine and estuarine environments also were picked up (Orton & Colgan, 2001). The shells were studied early by Niles (1869), Dodge (1888), Upham (1879 & 1889) and Crosby and Ballard (1894) who described fifty-five species from twenty-four locations. Where these species are presently found indicate that waters warmer than present, which then cooled at the onset of the Beacon Hill re-advance. The species found in the till at different locations are summarized by Upham (1890) and Crosby and Ballard (1894), who found the greatest number (thirty-four) at Great Head in Winthrop (see Figure 3-79). The sites are in cliff exposures of drumlins and hand-dug wells scattered across the basin west to Jamaica Plain and spilling over to the south a short distance. Dodge (1888 & 1894) noted that the shelly species are all still living and Newman (1988) was able to date over one hundred shells in the lower till as Sangamon in age (circa 100,000 years ago). Abundant shell fragments also occur in the basal till of the upper Narragansett Bay, and they, along with those near Boston, suggest that there was an earlier widespread Sangamon deposit, reflecting a high interglacial sea level. Some of the fossils correlate with beds at Sankaty Head, Nantucket, which are also dated as Sangamon (Crosby, 1909; Oldale *et al.*, 1982). Sediments found at Scituate were correlated by Kaye (1983b) with the Sangamon Gardiner's Clay of Long Island. The interpretation of the paleotemperatures indicates that the fauna in the lower Sankaty beds lived in water tempera-

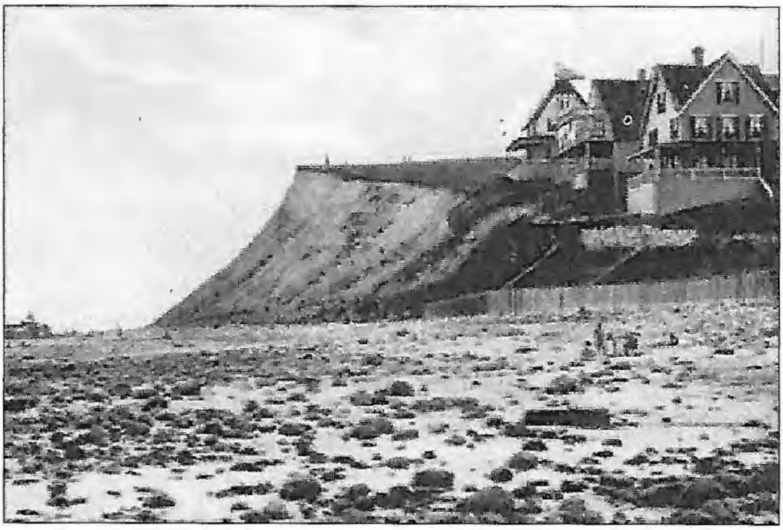


FIGURE 3-79. At Great Head in Winthrop in 1908, showing an eroding drumlin consisting mainly of lower till, in which were found thirty-four species of Sangamon fossils. Residual boulders from eroded till litter Rocky Beach in the foreground.

tures now found south of Nantucket and those found in the upper beds are now found to the north of Boston; thus the unit appears to transcend the Sangamon-Wisconsin time boundary (Gustavson, 1972 & 1976; Oldale *et al.*, 1982). Various attempts to further date the fossils using an amino acid analysis were reviewed by Colgan and Rosen (2001), along with their analyses of Mercenaria shells, and they concluded that the shells grew in the Sangamon. *Mercenaria mercenaria* (taxonomic name of a clam species) from the islands gave carbon 14 (C14) dates of more than 37,000 years ago (the actual date is limited by the accuracy of the radiocarbon method) and suggest a temperate and, therefore, interglacial climate (Kaye, 1976a). The fossils date the two tills as Wisconsin, but there has been endless debate as to whether these tills are Early, Middle or Late Wisconsin. The weathered zone on the lower till suggests it could be of Early Wisconsin age (Koteff & Pessl, 1985; Newman, 1990; Newman & Mickelson, 1994), but most (including herein) interpret the overlying upper till as Late Wisconsin (Newman *et al.*, 1990). This interpretation is certainly the case since the upper till is part of the last major glaciation that began its retreat shortly after 20,000 years ago. How the lower till relates to the retreat underway in lower Manhattan at 50,000 years ago, however, is not known.

Any older Illinoian, pre-Sangamon deposits would have been overridden by Wisconsin ice and would not be expected to survive in such a dynamic environment. Evidence in Boston, Martha's Vineyard, Nantucket, Cape Cod and Long Island demonstrates that the ice margin was very active. The fluctuations at the edge of the ice, and resulting erosion and deformation, would be expected to have eroded pre-Wisconsin deposits. Any remaining deposits should have been revealed by the very extensive drilling for numerous construction projects around Boston.

There also is more uncertainty regarding the ages of the two widespread tills found outside of the complexities of the Boston Basin (Currier, 1941; Chute, 1940; Moss, 1943; White, 1947; Schafer & Hartshorn, 1965; Koteff & Pessl, 1985). These tills are rarely found to be separated by stratified sand and gravel, as is seen in the test pits for the Lahey Clinic in Burlington. The parent rock for the till governs the nature of the deposits. The upper till is oxidized, more granular and pervious because any silt and clay fines were either a small percentage originally or have been removed, and because it overlies a dense, less pervious till containing a larger percentage of the finer fraction. Workers have interpreted these two tills to be of Wisconsin age, representing a super (meaning above or upper) till (also known as ablation till) overlying a basal or lodgement till. Thin Late Wisconsin tills have been dated in various places across New England (Stone & Borns, 1986; Borns & Stone, 1986). Evidence for these two till types extends southward to at least the Plymouth area (Newman, 1988). They appear to represent till laid down during a single glacier advance (lodgement) and subsequent meltback (ablation), and not tills of different ages as

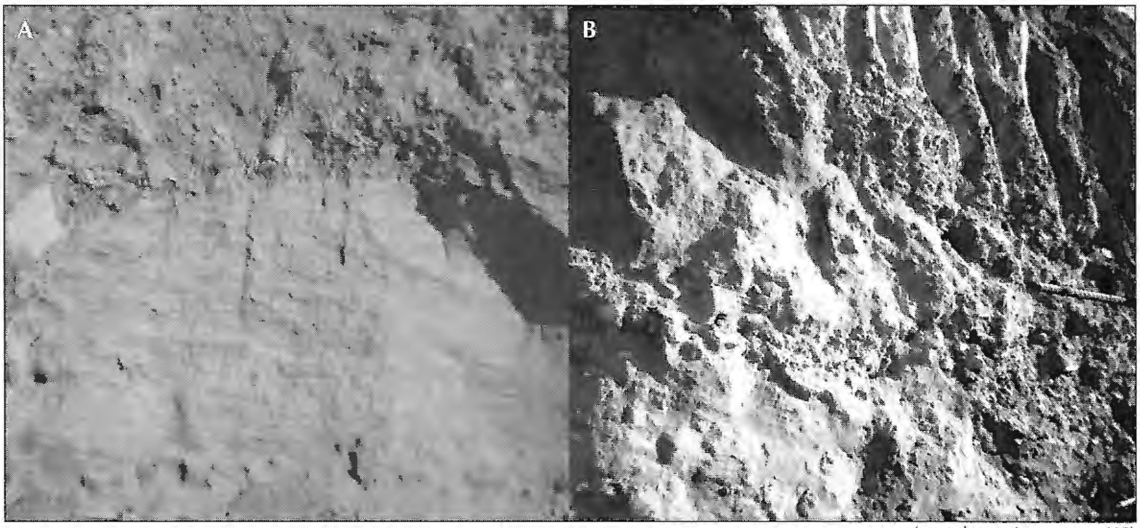


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FIGURE 3-80. Photos of deltaic sand and gravel north of Beacon Hill, looking south at the face against Cambridge Street during the excavation for the Holiday Inn showing: (A) partly faulted stratified sand and gravel, and (B) tilted stratified sand and gravel, unconformably overlain by till.

seen in the Boston Harbor (although till of more than one age could be present as well).

Deltaic Sand, Gravel & Clay. Sand, gravel, silt and clay that were discharged from the retreating ice of the Beacon Hill Substage formed a variable blanket across the lower till around Boston. A delta probably formed north of Beacon Hill, and silt and clay lake deposits, and then marine clay, probably were laid down across the city. Only remnants exist now as local deformed material beneath the upper till in central Shawmut Peninsula and as lenses between the two tills elsewhere in isolated areas (see Figure 3-80). Much of the material was moved and reshaped during the formation of the later Beacon Hill drumlin. The interior of the drumlin is made up of a complex of ice-thrusted and folded deltaic sand, gravel, clay and till lying over an undeformed core consisting of till and deltaic foreset beds of coarse gravel (Kaye, 1961 & 1982b), known from exposures and borings (see Figure 3-81). These overridden sediments thin southward across Boston Common and continue thinning into Back Bay. They also thin to the north and to the east (see Figure 3-81), such as under the Boston Company Building (Johnson, 1973). Farther east, clay and sand lenses found within the till along the Central Artery separate the two tills and seem to represent attenuated deposits of the same interval (see Figure 3-82). Rare thin lenses of sand and clay also are exposed between the two tills on some islands. On Long Island a 2-meter (6.6-foot) layer of sand is incorporated into the base of the upper till, which has a sandy silt matrix (Newman *et al.*, 1990). Such sand deposits could have been pinched or squeezed out when overridden by the upper till as the ice crossed the higher parts of the lower till, as can now be seen on the islands. These sand deposits also are observed to thin eastward. None were found in the extensive borings on Deer Island nor were any seen in the exploratory boreholes in the harbor south to Nut Island and seaward to the east (Sverdrup, 1990b; Parsons Brinckerhoff, 1990).

Relatively undisturbed sand and gravel with basal and capping clay layers occur (see Figure 3-83) on the south side of Beacon Hill to the west side of Boston Common between the lower and upper tills (Kaye, 1961). The basal clay lens, 0 to 7.6 meters (0 to 25 feet) thick, is compact olive-gray unoxidized clay, sandy clay and very fine sand similar to known marine clay elsewhere in coastal New England. It is in sharp conformable contact with an overlying thick unit formed of charac-

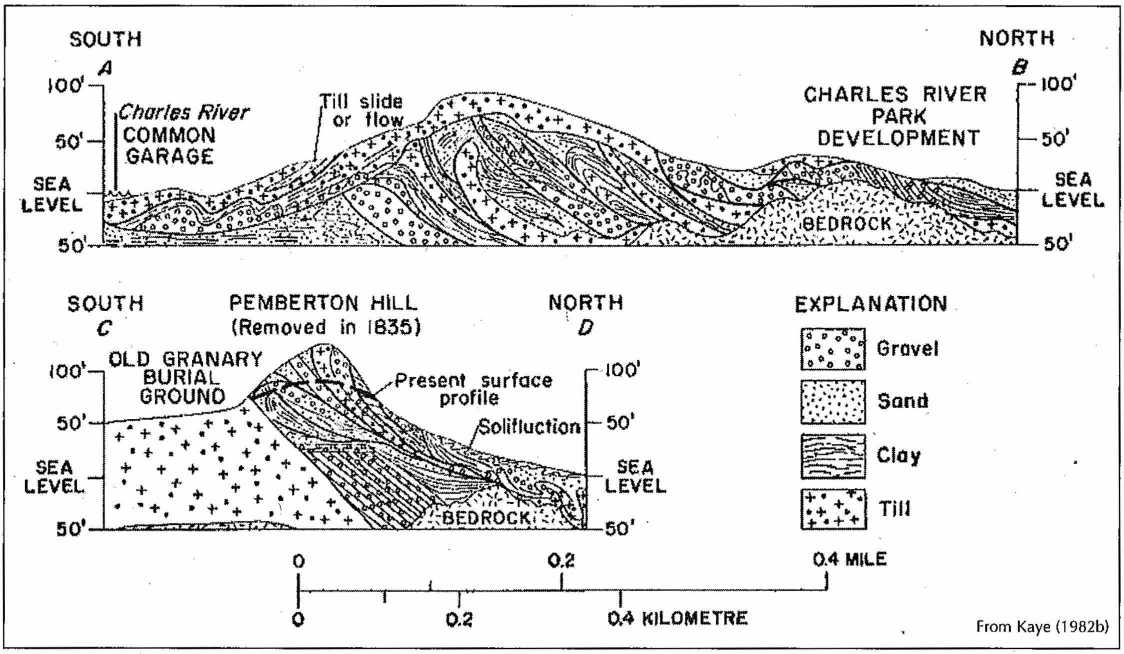

FIGURE 3-81. Sections across Beacon Hill, top, and Pemberton Hill, bottom, showing the disturbed beds revealed in deep excavations for foundations beneath the upper till.

teristically brown, well oxidized coarse gravel interbedded with lesser amounts of fine gravel and sand, and sparse layers of compact yellow silt. This unit has a maximum thickness of 20 meters (65 feet) here and contains pebbles of schist and argillite that show varying degrees of decomposition. It also contains pebbles of granitic rock and feldspar that generally appear fresh. The capping clay is an unoxidized bluish to slightly greenish gray, except close to the present surface. Stratification in the clay is well marked in some zones by alternating lighter and darker laminae. The lower contact of the clay may be either sharp and apparently undisturbed or disturbed, and the contact may exhibit waviness from loading.

Similar sediments are found in Beacon Hill, along with peat that was encountered at a depth of 30 meters (100 feet) in colonial wells dug in the hill. Pervious layers of sand up to 6 meters (20 feet) thick are present and served as the source of water for the early settlers. The continuity of such layers was demonstrated (Aldrich & Lambrechts, 1986) during extensive dewatering on Harrison Avenue that caused water in observation wells located 1.6 kilometers (1 mile) away to drop 9 meters (30 feet) and that caused piezometers across the Charles River to drop up to 0.6 meters (2 feet). The excavation for the Boston Common Garage ran into an unanticipated water problem when the expected deep till turned out to be thick gravel whose large groundwater flow necessitated costly dewatering and drainage installations and a delay of many months (Kaye, 1961 & 1976a).

These sediments at Beacon Hill were deformed during the last passage of glacial ice over Boston and smoothed over by the upper till during the Boston Substage. The sand, gravel and clay deposits are highly thrusted and broken beneath Beacon Hill, and slices of the lower till also are carried upward and interlayered with the deposit. This deformation has been seen at many sites around Beacon Hill by Woodhouse. It extends southward (see Figure 3-84) along the east side of the Boston Common to at least Millennium Place on Tremont and Boylston streets, but not beyond Stuart and Kneeland streets (Woodhouse, 1981; Miller, 2000). On the south side, in the Common, the sand and gravel outwash is found to be deformed into folds by the ice load, with some

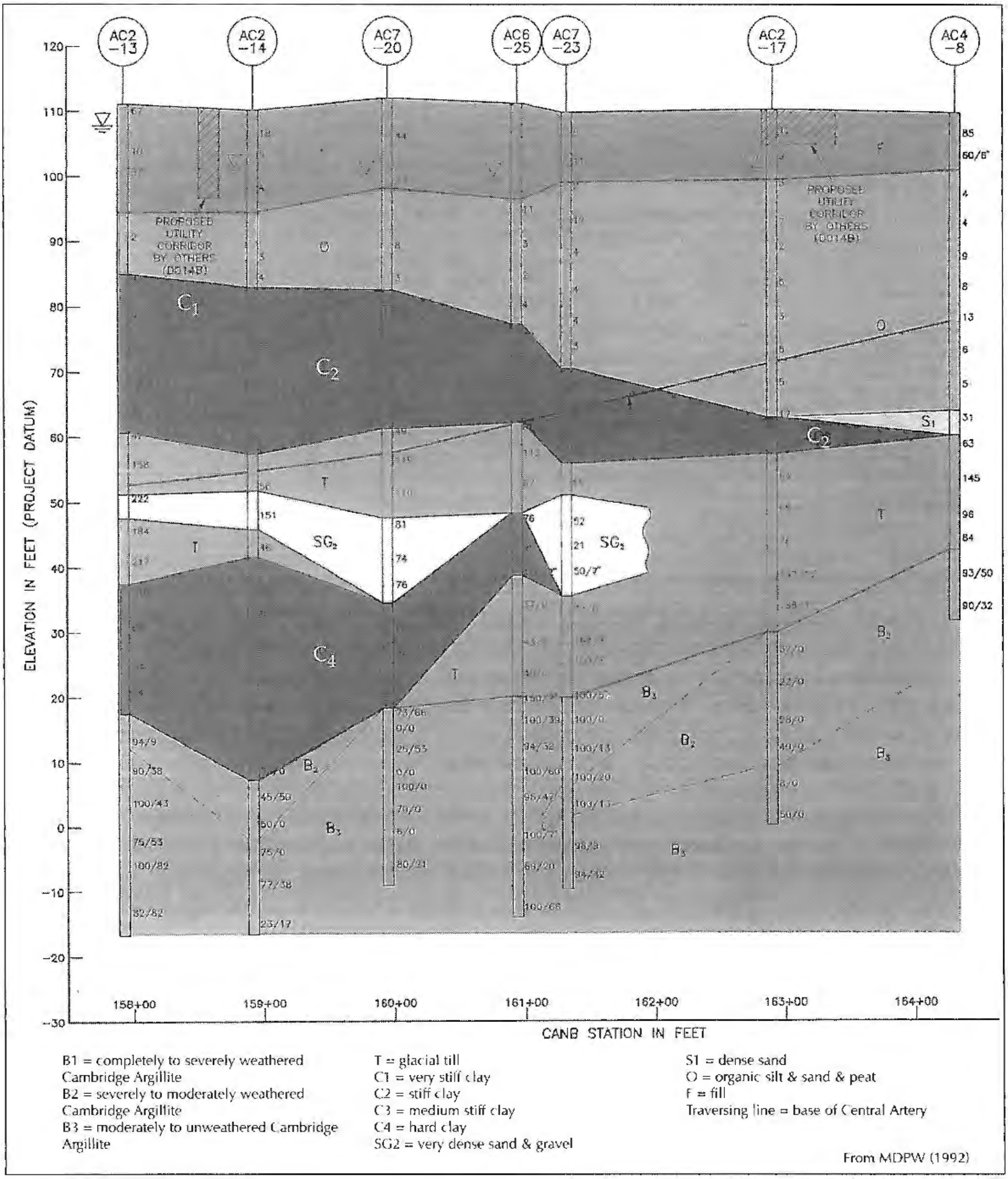

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FIGURE 3-82. Geologic cross-section (from the southwest) along the Central Artery Tunnel between Valenti Way and Causeway Street (east slurry wall, stations 158+00 to 164+00) showing an apparent clay and sand filling of a channel cut through the lower till and later covered by upper till and partially thrusted between the upper and lower tills, which here are undifferentiated.

faults that cross into the upper clay. Folding and faulting of glacial deposits can occur while they are frozen as the ice mass pushes frozen slabs of soils ahead of itself or drags soil slabs below the advancing ice. Relic fractures in the clay are seen as evidence of the previous freez-

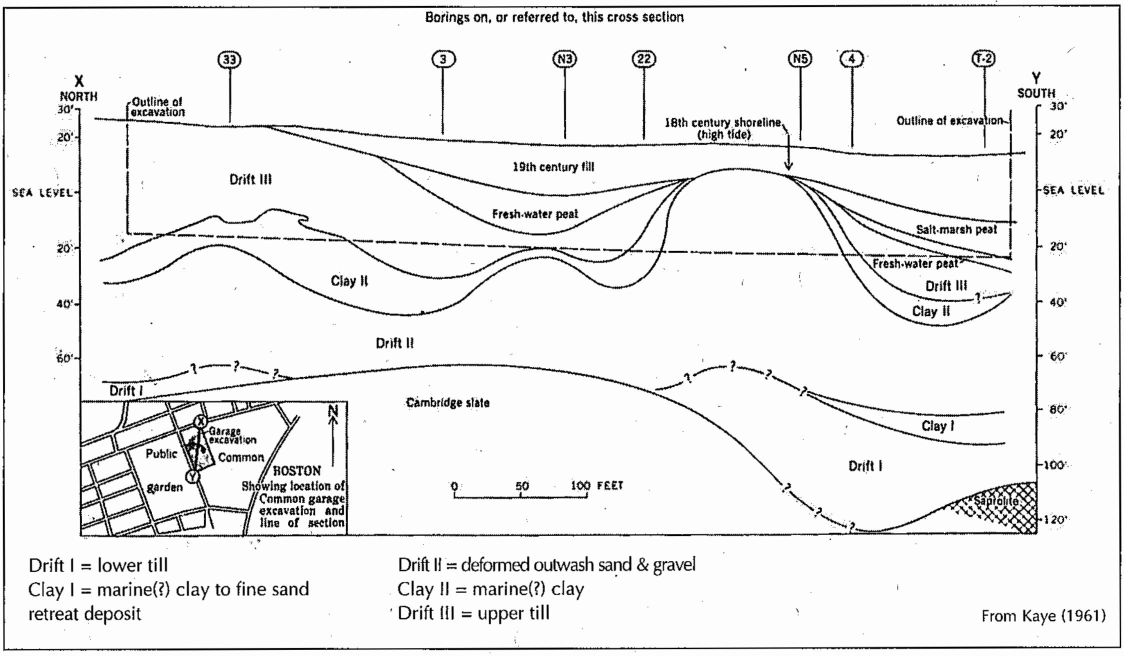


FIGURE 3-83. Geologic section through folded and faulted sand and clay deposits at the underground Boston Common Garage site at the southern edge of Beacon Hill in northwestern Boston Common. The upper till is capped by organic deposit and fill. The minor marine clay, which overlies the upper till in the northeast corner of the excavation at about 4.6 to 7.6 meters (15 to 25 feet) altitude, is not shown. Drift II and Clay I and II are part of the deformed outwash unit.

ing. The deformation tapers off from this area. On the west side of the Common at the garage, the sequence only was folded and moderately faulted prior to or as the upper till was laid down and the disturbance appears to end west of Charles Street (see Figure 3-83). The thick, deformed sand and clay thin abruptly to the north of Beacon Hill where the bedrock rises and stratified sand was penetrated in borings at Strong Place on Cambridge Street, and silty sand and gravel were encountered in borings at the Saltonstall Building on Ashburton Place and One Beacon Street. The stratified sand and gravel observed at the Holiday Inn and Garage site on Cambridge Street are moderately faulted, but the deformation appears to end just to the west. The similar deposits found in the Boston Company Building excavation on Court Street (east of Beacon Hill) are not highly deformed, but are sheared by a large normal fault in the clay and sand layers. In addition to this displacement, large festoons of tight, overturned folds in clay and sand, which may have been formed by later downslope solifluction, occur in places on the lower flanks of the Beacon Hill (Kaye, 1976a).

A very thin deltaic deposit, which is present to the south beneath the Back Bay, is described as 1.2 meters (4 feet) of coarse sand and several centimeters (a few inches) of overlying clay beneath a thin upper till (Judson, 1949). It overlies the Cambridge Argillite, which lies at a depth of between elevation –34 and –43 meters (–112 and –142 feet) MSL below the John Hancock site. The thin blue clay appeared to grade into the till, which is bluish with a high clay content. This deposit appears to be a thinned remnant of the deltaic sand and clay smeared by the overriding till.

The relatively limited area of the thick portion of the deposit, plus the recognition of deltaic foreset and bottomset beds (Kaye, 1976a), indicate that the sand and gravel, clay, and peat were part of a delta complex before being overridden and pushed up into Beacon Hill. The present distribution of the sediment

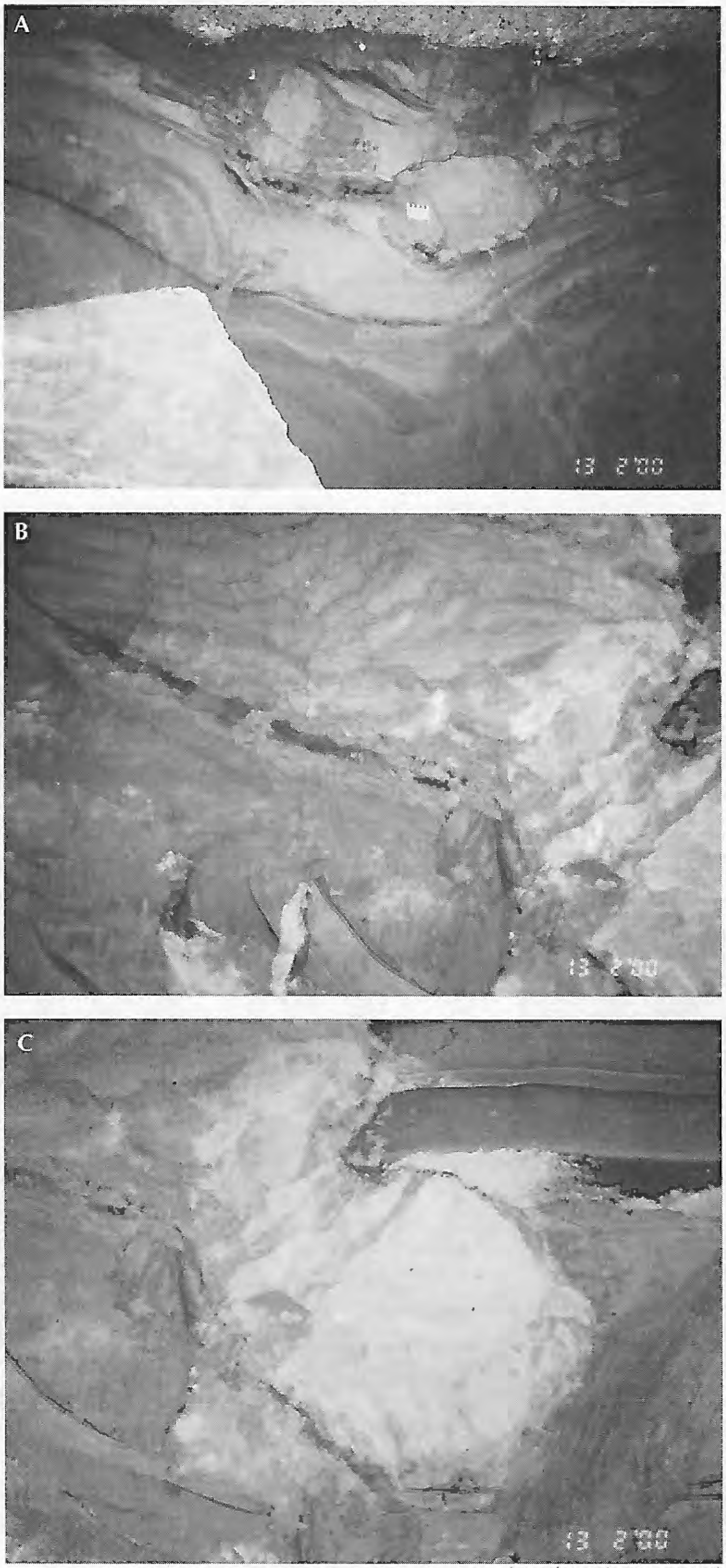


FIGURE 3-84. Excavation for garage at Millennium Place, Tremont and Boylston streets, on the southeast corner of Boston Common in 2000, showing (A) banded blue clay on lower left complexly faulted against blocks of stratified sand, (B) graded-bedded fine-grained sand on upper right thrust over sand with clay seams along small thrusts on lower left (which also shows teeth marks of the backhoe in the lower part of the photo), and (C) banded orange and buff stratified sand with brecciated blue clay above.

(see color version on page 464)

suggests that a large delta was centered in the Charles River Basin and adjacent Cambridge and that this delta was fed from the north by a subglacial river along the ancient Mystic River Valley, which followed the Aberjona-Fresh Pond Buried Valley (west of the present Mystic Valley) and then the Malden Buried Valley (east of the present Mystic River). It may have been similar to the many subsequent well-preserved deltas along coastal Maine that built out into the marine clay equivalent of the "Boston Blue Clay" and the large one on the northeast side of the center of Concord (Koteff, 1964b). Kaye (1961) also felt that the clay beneath the edge of Beacon Hill was marine, but at least some clay seen by Woodhouse appears to

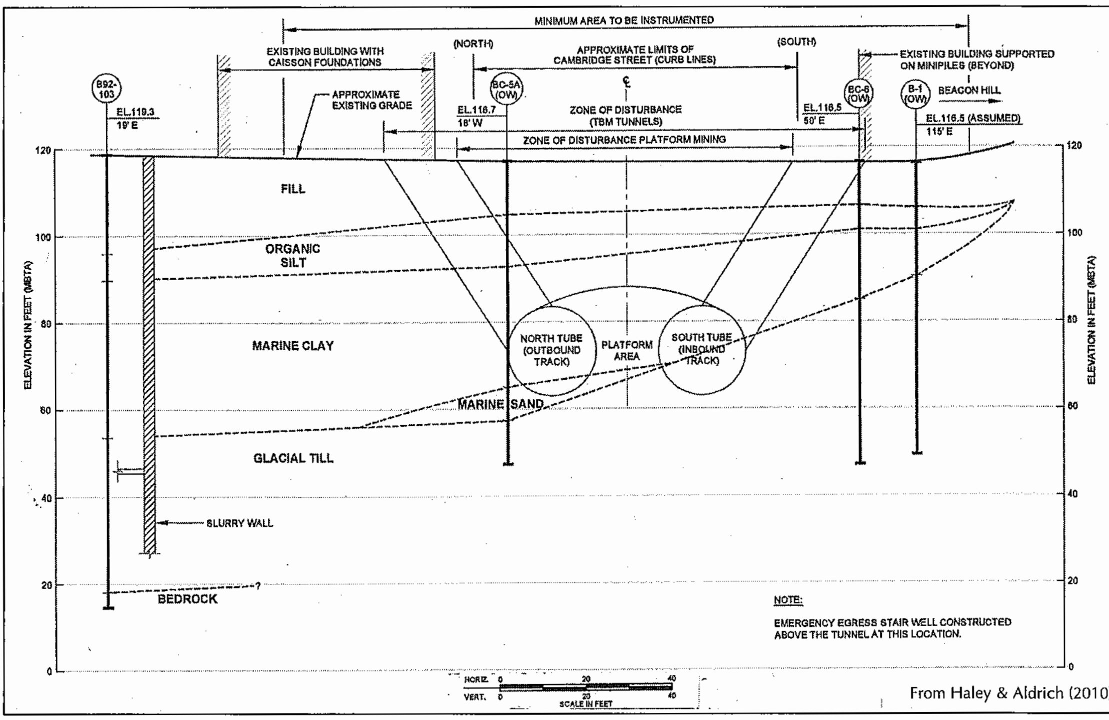


FIGURE 3-85. North-south section (view east) showing the northward thinning base of the Beacon Hill drumlin and overlap of later deposits beneath Cambridge Street at the west side of Lindall Place (Station 11+00) across the line of the proposed Red Line/Blue Line connector at the Cambridge Station.

be a layered bottomset or lake deposit. Perhaps after the toe of a delta built southeastward onto the Shawmut Peninsula it was overlapped by clay as marine waters flooded the still depressed crust while the ice retreated farther north. The next ice readvance of the Boston Substage tore into the delta and pushed it up to form Trimountain, of which Beacon Hill forms a remnant, and the overriding glacier left a capping of till. The deposit is probably Early Wisconsin, but its exact age is yet to be determined.

Upper Till. The new glacial advance of the Boston Substage across the region laid down a blanket of till over the earlier material and shaped it into the ubiquitous drumlins of the Boston Basin (see Figure 3-73). This upper till forms the initial deposit of a sequence referred to as the Boston Substage by Judson (1949). The upper till had been recognized and studied separately in the Beacon Hill area and in the context of the two tills found on the harbor islands, but the great amount of new data from recent projects now permits a more comprehensive view of the unit. The upper till is gray to olive gray, and changes to buff to brown where oxidized and is similar in general to the lower till. However, it is usually less dense and contains larger clasts (pieces of rock). Kaye (1961) describes it at Beacon Hill and the Common as very uniform with sparse boulders up to 3 meters (10 feet) in diameter that were collected in early colonial times for building material. The pebbles and cobbles are predominately Cambridge Argillite. The drumlins on the harbor islands consist mainly of well-compacted and well-graded till, typically containing about 15 percent clay-size by weight (Newman *et al.*, 1993). Boulders are sparse, and large boulders, up to 1 meter (3 feet), are generally found on the surface or in the upper 3 to 4 meters (10 to 13 feet). The orientation of the clasts shows some preferred alignment with the long axis of the drumlins (Rominger, 1947), which is about S70°E at Beacon Hill. Varved clay and silt representing local ponding also have been found incorporated within the till under the Beth Israel Hospital west of the downtown area and along the Central Artery. The upper till is oxidized to a depth of 7.6 meters (25 feet) at the Common and up to 20 meters (65 feet) in borings on Beacon Hill. The upper till is less indurated than the lower (see Figures 3-78 & 3-81) and tends to erode with near vertical faces above the more sloping face of the lower till (Crosby & Ballard, 1894). The upper till is more than 9 meters (30 feet) thick at the Common and thicker on Beacon Hill, but thins or is missing north of Beacon Hill (see Figure 3-85), around North Station and north of Airport Station. The Beacon Hill drumlin was originally much more impressive before 30 meters (100 feet) was cut off its top and later deposits buried its base (see Figures 3-81 & 3-85). Borings and seismic profiling indicate bedrock depths in excess of 30 meters (100 feet) beneath the crest of some drumlins in the harbor (Sverdrup, 1990b). The exposed till thickness in the bluff on Great Brewster Island is 27 meters (89 feet), with more till lying below sea level, and the composite thickness of both the lower and upper tills varies from locally absent to 79 meters (260 feet) in drumlins — most of which would be composed of upper till. In the Charlestown section of Boston, the till varies from 15 to 30 meters (50 to 100 feet) thick near the Bunker Hill drumlin. The original Fort Hill drumlin contained about 45 meters (150 feet) of till, but 15 meters (50 feet) were removed between 1866 and 1872 (Kaye, 1982b) and used for fill (see Figure 3-86). Nearby along the Central Artery, the till is 35 meters (115 feet) thick between South Station and Oliver Street in the area of Fort Hill.

The upper till was laid down and shaped into about two hundred simple or compound drumlin hills in the Boston Basin during the Boston Substage of the last Wisconsin glaciation that covered the entire basin (see Figure 3-73, 3-74 & 3-75). Many drumlins rise above the water in the harbor to form the islands (see Figures 1-14 & 3-87), but others remain submerged (see Figure 3-88) and partially or wholly buried by younger deposits (see Figure 3-89). The movement of the glacial ice scoops up the loose soil and rock and usually only moves it a short distance before overriding and shaping the material into the characteristic elongate oval-shaped drumlin hills. The concentration of drumlins around Boston is due to the available abundant weathered debris in the basin that could be reworked into till (most drumlins consist largely or entirely of till). The elongation of the drumlin shows the direction of glacial movement. The general flow direction in eastern Massachusetts ranges from S15°E to S25°E (Alden, in LaForge, 1932). However, the average trend about Boston is S55°E and some are almost east-west in trend. Some researchers consider the different trends represented different ages (Kaye, 1982a), but the till is relatively soft and any early drumlins would have been reshaped into new ones by the next glacial advance; therefore, those seen today were formed at one time. The various trends about Boston represent the degree in which the base of the ice was diverted by the topographic relief. The base of the ice was strongly influenced by the easterly trend of the Boston Basin. But once across it, the normal more southerly ice flow direction was resumed.

Beacon Hill was recognized early as a drumlin (LaForge, 1932; I.B. Crosby, 1928; Kaye, 1961). Lithographs, sketches and drawings dating back to the nineteenth century of the excavation of the top of Beacon Hill apparently show till. Depictions from the eighteenth and nineteenth centuries show the middle part of Trimountain with very steep drumlin slopes suggestive of cohesive material rather than sand that might be expected to have a gentler angle of repose (see Figure 3-90). Kaye (1976a) later thought Beacon Hill might be a moraine because of the sand, gravel and clay found within it and the concept that drumlins consist only of till. However, a drumlin is a geomorphic form and may be cored by a variety of material besides till, including bedrock. Bedded sand and gravel was observed in the Governor's Island drumlin, now part of Logan Airport. A large drumlin at the Massachusetts Correctional Facility at Walpole, south of Boston, is cored by relatively undisturbed lake or bottomset deltaic sand (Barosh, 1989; Jemsek & Barosh, 1993). Drumlins on several harbor islands have a core of argillite.

FIGURE 3-86. Excavation of upper till on the Fort Hill drumlin in 1869.

the re-advance (see Figures 3-80 & 3-81). These deposits were apparently slabs of frozen material that the overriding ice forced upward as thrusts, similar to those seen on Gay Head on Martha's Vineyard (Kaye, 1964a), while being shaped into a drumlin. The shearing seen in some of the island drumlins (Kaye, 1967b) appears due to the same kind of movement. Kaye reports some argillite fragments along the thrusts indicating they skimmed the bedrock, which rises up to the north. The variable distribution of the sand and clay suggests that a delta had stood just northwest of Beacon Hill and was left as an isolated hill during retreat of the glacial ice. Then when a new glacier advanced across the delta hill, it was pushed and reshaped into a drumlin a short distance to the southeast into a buried valley beneath Beacon Hill as the ice rode over it. When the upper till was smeared over

The origin of the Beacon Hill drumlin is highly unusual if not unique in the basin, as shown by the nature, thickness and structure of its internal material. Studies by Kaye (1976b & 1982b) show the core of the hill consists of imbricate (overlapping) thrusts of deltaic sand and clay, and the lower till that formed during

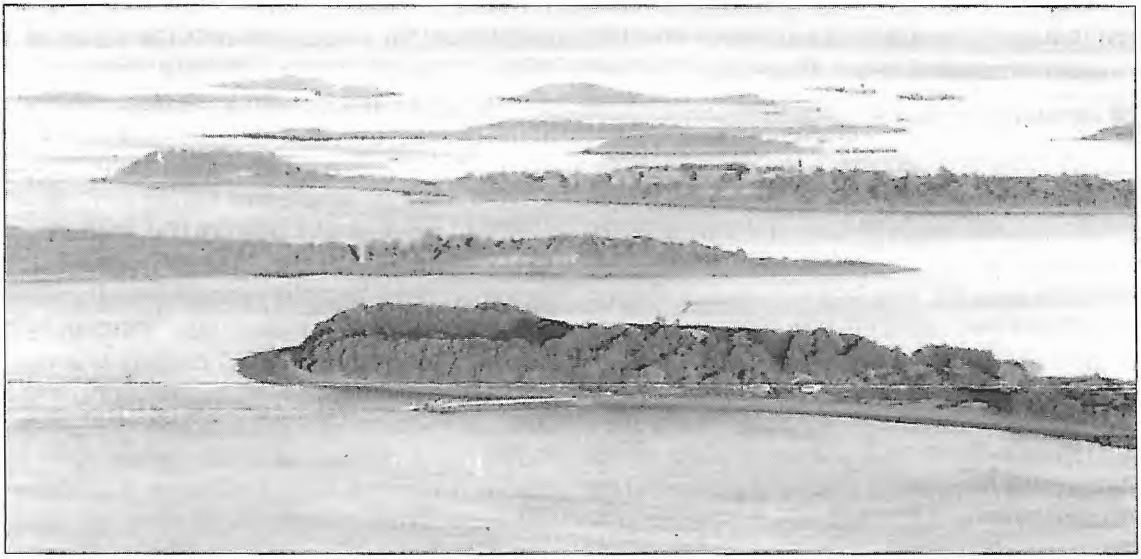


FIGURE 3-87. View northeast at Thompson Island and beyond at drumlins forming the larger Boston Harbor islands. (Courtesy of the Boston Harbor Islands National Park.)

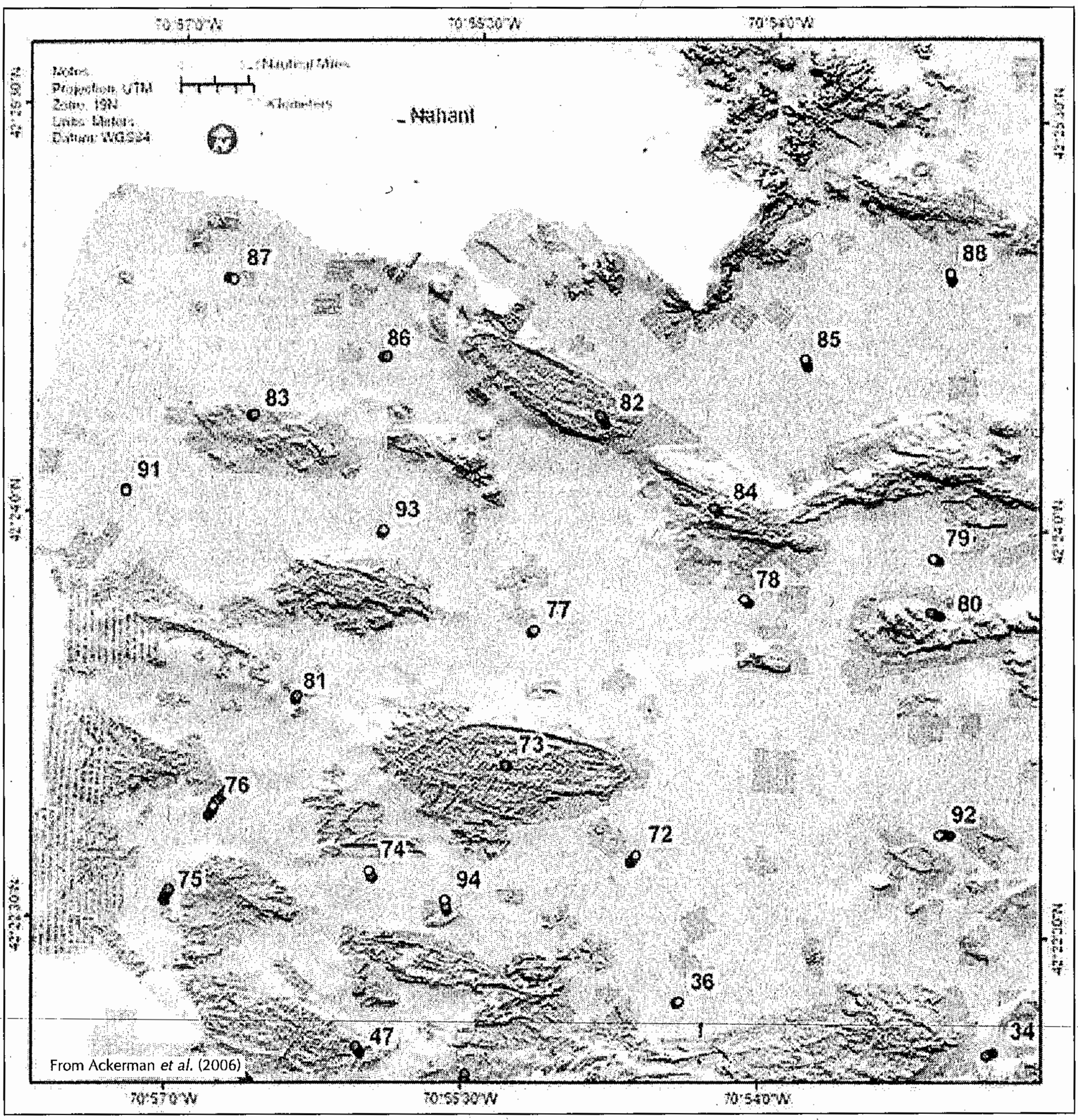
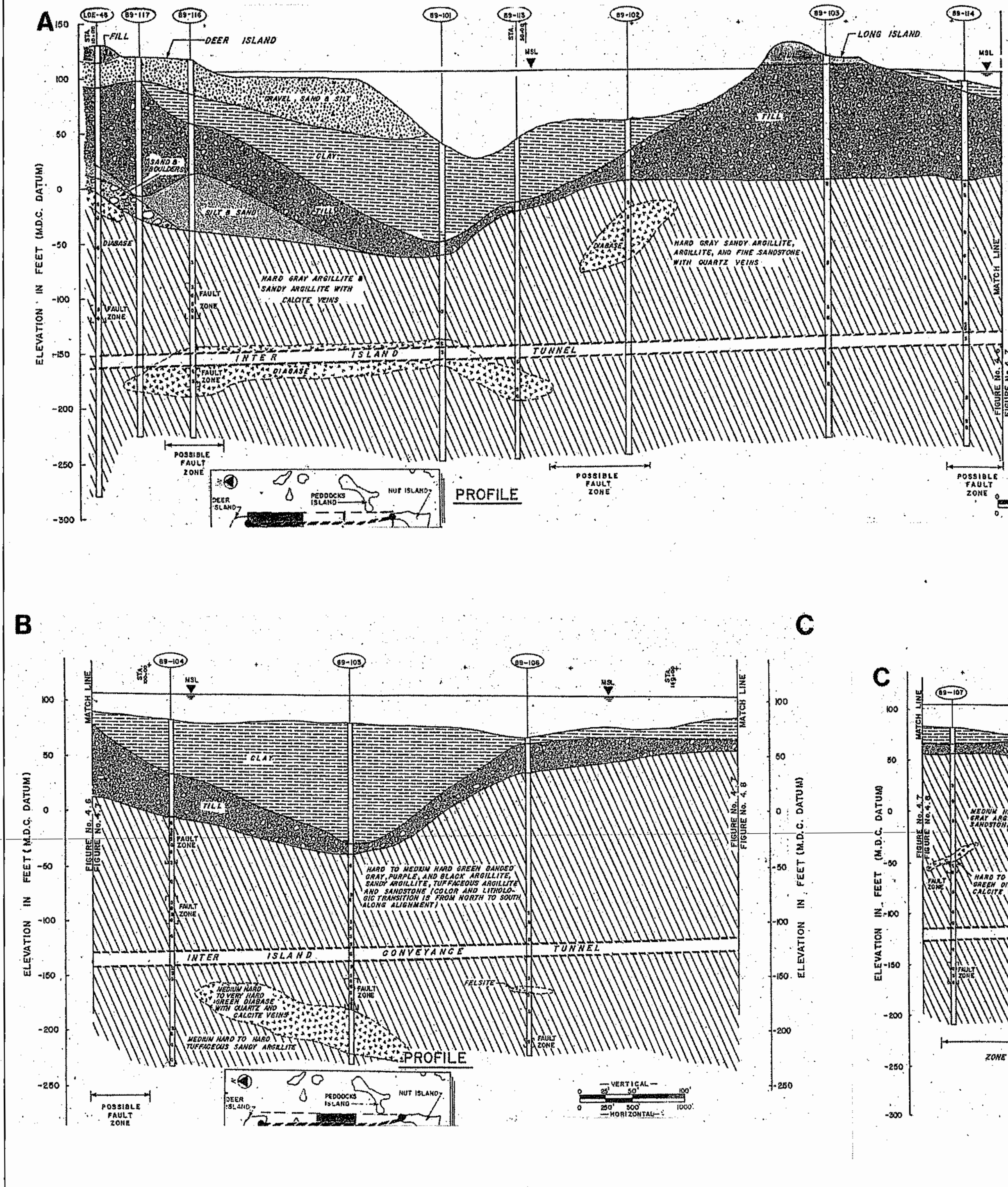


FIGURE 3-88. Shaded relief bathymetric map of approaches to Boston Harbor showing raised ovoid features representing drumlins.

the drumlin hill as a relatively thin capping, it incorporated part of the underlying material. Beacon Hill would thus owe its origin to the pre-existing delta hill in combination with the local bedrock topography. Deformed material underlying the upper till may occur elsewhere beneath the upper till, but it does not appear to form a moraine. The repeated till in the complex thrusts in Beacon Hill was thought by Kaye (1976b) to represent at least one more glacial event; however, the additional data collected since does not support this assertion.

A hill may be called a drumlin because of its glacier-formed shape, but not necessarily from its composition, once thought to be exclusively till. Some drumlins in the Boston Basin are of the classic elongate shape, rising to as much as 79 meters (260 feet) above their base in the case of Corey Hill, west of the Back Bay Fens, and 66 meters (216 feet) in the case of Parker/Mission Hill, southwest of the Back



From Sverdrup (1990b)

FIGURE 3-89. North-south geologic section along the Inter-Island Tunnel (view east).

B

GENERALIZED SOIL DESCRIPTION

FILL – LOOSE TO MEDIUM DENSE, MISCELLANEOUS FILL CONSISTING OF SANDY CLAY, PIECES OF DRY WALL, WIRE, AND OTHER CONSTRUCTION DEBRIS; OR MEDIUM DENSE TO DENSE, GRANULAR FILL CONSISTING OF GRAY, FINE TO COARSE SAND AND GRAVEL, TRACE CLAY, TRACE ORGANICS.

GRAVEL, SAND & SILT – DENSE TO VERY DENSE, BROWN-GRAY STRATUM CONSISTING OF VARYING QUANTITIES OF GRAVEL, SAND AND SILT, WITH TRACE CLAY.

CLAY – SOFT TO VERY STIFF, GRAY TO YELLOWISH-BROWN, SILTY CLAY, TRACE FINE SAND.

TILL – DENSE TO VERY DENSE, GRAY SAND AND GRAVEL WITH VARYING QUANTITIES OF COBBLES, SILT AND CLAY; OR HARD, GRAY, CLAYEY SILT, WITH VARYING QUANTITIES OF COBBLES, GRAVEL AND SAND.

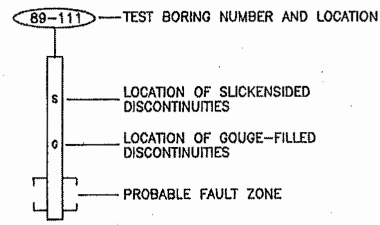
SILT & SAND – VERY DENSE, BROWN, FINE TO COARSE SAND AND SILT, TRACE SHELL FRAGMENTS.

SAND & BOULDERS – ARGILLICEOUS BOULDERS, FRAGMENTS OF ARGILLITE, QUARTZITE AND IGNEOUS ROCK, COBBLES, SOME FINE TO COARSE SAND AND GRAVEL.

ARGILLITE
DIABASE
FELSITE
ASH

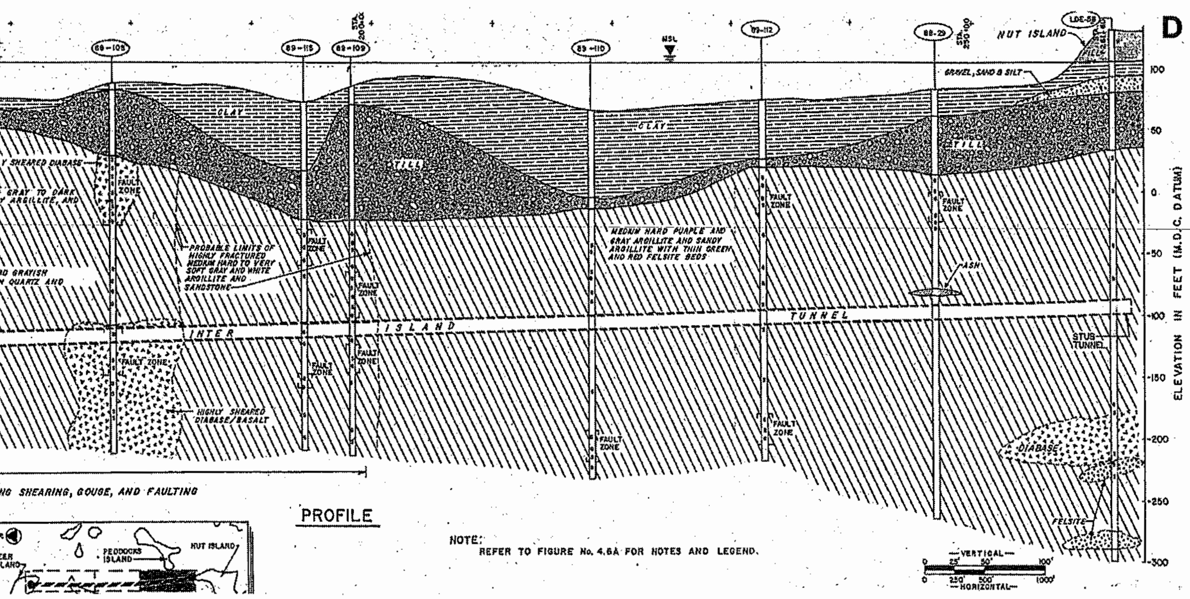
FOR DESCRIPTION OF THESE ROCKS, REFER TO PROFILE

LEGEND



THE STRATIFICATION LINES ARE BASED UPON INTERPOLATIONS BETWEEN WIDELY SPACED EXPLORATIONS AND THUS REPRESENT THE APPROXIMATE BOUNDARIES BETWEEN SOIL TYPES. ACTUAL TRANSITIONS MAY VARY FROM THOSE SHOWN.

HORIZONTAL TO VERTICAL SCALE DISTORTION FOR PURPOSES OF PRESENTATION CAUSES TRENDS IN STRATA TO APPEAR MORE PRONOUNCED THAN THOSE, WHICH ACTUALLY EXIST.



PROFILE

NOTE:
REFER TO FIGURE No. 4.6A FOR NOTES AND LEGEND.

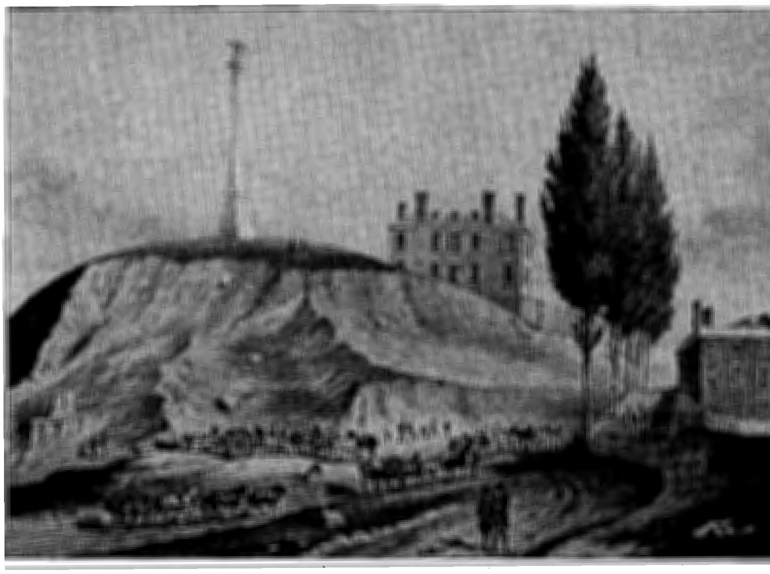


FIGURE 3-90. A view of Beacon Hill from Mt. Vernon Street near head of Hancock Street circa 1811.

Bay Fens. Others are more rounded in plan, lower in height and smaller in area. The Boston Harbor drumlins are drowned and are the primary ones in the United States that show inundation from sea-level rise. They front the harbor and are also found in the open waters in Massachusetts Bay. Much of the till is gone from these mid-harbor islands and the outer islands tend to be stripped to rock, but nearby submerged areas still have thin till over the argillite. Scattered drumlins occur where the bedrock surface is well below sea level and some of these unexposed drumlins may be buried by glaciomarine clay and other later deposits (see Figure 3-88).

The distribution of drumlins might seem random in traversing the Boston Basin, but in map view they are strongly clustered in "drumlin fields" along east-west to east-northeast trends that are parallel to the prevailing strike of the bedrock. These basin trends are in contrast with the regional, southerly trends on either side (see Figure 3-73). Most drumlins lie directly on bedrock, and their distribution and orientation, in consequence, are strongly influenced by linear irregularities on the bedrock surface. Several workers have noticed a pronounced northeast-southwest alignment of a group of drumlins that runs from Roxbury through Dorchester Heights, Castle Island and Governor's Island and terminates at Shirley Point in Winthrop. A second line runs from Neponset and includes Squantum, Moon Island and Long Island. A third line includes Savin Hill, Thompson Island and Spectacle Island. Castle Island displayed a typical shape with a cliff face toward the harbor before it was covered by fortifications (see Figure 1-15). These alignments were thought by some researchers to be associated with east-west moraines, but these alignments were also thought to reflect structural control of the bedrock islands that influenced the drumlins.

The majority of drumlins around Boston rest on bedrock highs or have a core of bedrock (W.O. Crosby, 1903; I.B. Crosby, 1934; LaForge, 1932; Judson, 1949), a relation clearly seen on several harbor islands. Geophysical evidence also indicates a rock core beneath Long Island (Colgan & Rosen, 2001). The outer islands are formed of rock, which could at one time have formed the cores of now lost drumlins. A few drumlins on land clearly overlie high points on the bedrock surface; argillite in the case of the Cobble Hill excavated in 1929 in Somerville (Haglund, 2003) and conglomerate (Puddingstone Park) at the base of Parker/Mission Hill in Roxbury. Some till-plastered bedrock knobs around Boston have been called drumlinoids because of their core. Other drumlins, however, do not have rock cores. Beacon Hill has none (see Figure 3-81) and boreholes show the bedrock surface below the Fort Hill drumlin to be flat. The relief on the bedrock surface south of Deer Island ranges between elevation –15 to –52 meters (–50 to –170 feet) MSL and appears unrelated to drumlins on nearby islands, although Deer Island itself may have a rock core (Sverdrup, 1990b). The Long Island drumlin is underlain by a broad rock core, but the smaller drumlins to the south have none and the intervening areas have thin till over the argillite, as seen above the Inter-Island Tunnel (see Figure 3-89). The surface of the lower till forming the cores of a few drumlins in the harbor also suggests a remnant drumlin shape, but this supposition is hard to verify and may be at odds with the postulated intervening long period of weathering.

Some of the drumlins that front the harbor or in the open waters of Massachusetts Bay are cut by waves and provide good cliff exposures, which display a well-defined layering and internal structure (Kaye, 1967b). This layering consists of parallel partings, which are generally marked by very thin, silty zones. The layering generally conforms to the drumlin shape, imparting an anticlinal appearance. In places, these layers are distorted and sheared, as though the entire mass had undergone intense deformation. Many drumlins have the classical simple elongated oval shapes, but others have compound shapes that may vary in orientation. The present Beacon Hill is actually the remnant of three hills, called the Trimountain, consisting of West (Mt. Vernon), Beacon (Sentry) and Pemberton hills, which are the crests of a normal, large composite drumlin now greatly modified by deep excavations. The east-trending hill (Mt. Vernon) was originally longer prior to the erosion that produced the cliff face of West Hill that is now marked by Charles Street, and higher before two centuries of excavation for fill. The top of the Trimountain had three crests that trended more to the southeast and oblique to the general trend of the mountain (see Figures 1-6 & 1-8). A change of trend between the lower and upper parts of a drumlin is fairly common in the region (Barosh, 1973 & 1986f). This change is likely due to the lower ice flow following the local bedrock topography, whereas higher up the ice is less restricted and the regional flow becomes more important. Thus, as the Trimountain drumlin grew beneath the ice flowing eastward along the Boston Basin, its top reached upward into the more southeastward regional flow. Thus, the drumlin would have been formed at the same time as the other drumlins of the harbor islands were shaped from the upper till. This change in drumlin trend, due to the bedrock control and elevation, may have been the basis for many (including: Kaye, 1976b; Newman & Mickelson, 1994; Colgan & Rosen, 2001) to ascribe drumlins of different trends to different directions of regional ice flow at different times.

The wave erosion that creates cliff exposures modifies the shape of many drumlins. The original cliff face of the round Fort Hill in Boston shows it originally had a more elongate shape, and so apparently did Castle Island (see Figures 1-12 & 1-15). The west end of Beacon Hill also had been blunted by erosion. Partially eroded drumlins along the coast tend to have shoals formed of residual boulders seaward of them that maintain the outline of their original plan, as at Great Head, Winthrop (see Figure 3-79). Boulder retreat terraces and salients (projecting areas) also are common over the drumlins in the harbor. Thompson Island contains an overlying delta and what has been described as an esker and kettle hole (Rosen, 2007), but these appear to be man-made artifacts from historical harvesting of the marsh hay (Sweetser, 1882; Snow, 1935).

The age of the upper till is Late Wisconsin and the till is the result of the last regional glacial advance that began to cover the southern New England area about 25,000 years ago (Chute, 1959; Kaye, 1961; Stone & Borns, 1986). The ice wasted away and cleared Boston about 15,000 years ago and the upper till was formed and shaped over much of this interval. Kaye (1961) reports shell fragments, mostly *Mercenaria mercenaria* in the till of Beacon Hill that is unusual for this till. They apparently have been derived from the lower till that is thrust upward and subsequently overridden in the hill and shed no further light on its age.

Glaciomarine Sediment. When the glacial ice of the Boston Substage thinned and began its retreat, rising marine waters over the still depressed crust extended beneath the end of the glacier to form a floating ice shelf. Sediment being carried through the ice, which normally would have formed the looser upper, terrestrial portion of the till now fell through water to form glaciomarine sediment. The glaciomarine sediment thus formed in a complex depositional environment where quantities of sand, silt and clay-sized particles were discharged by glacial meltwater streams directly into the sea from nearby ice with only slight sorting or dropped with no sorting. Clay, silt and sand were carried by meltwater streams and near-shore currents to form deposits nearer the shore while clay, also carried by the streams, settled out of suspension farther away with only minor amounts of granular materials. As a result, a highly complex marine deposit of alternating and interfingering layers of fine sand, silt and clay developed. The till-like granular near shore sediment may contain shell fragments, which are attributed to deposition on the ocean bottom. Hard sandy silt makes up the lower part of the glaciomarine material and clayey deposits containing shell fragments, sand and gravel form the upper part in Post Office Square (Humphrey, 1990) and Millennium Place.

This deposit overlies the upper till beneath much of Boston, Boston Harbor, Charlestown, East Boston-Logan Airport area, and Deer and Nut islands. The glaciomarine debris wedges out away from the marine waters and the deposit marks the edge of the sea beneath the ice, except where modified by later erosion.

The glaciomarine sediment was slow to be recognized because of its lithology. Lateral changes make it difficult to distinguish the unit from both normal till and overlying marine clay at places that give the appearance of local interfingering. Such deposits had been known in the literature for some time (Flint, 1971). W.O. Crosby (1903) noted a sheet of boulder clay 3 to 7.5 meters (10 to 25 feet) thick interlayered near the bottom of the marine clay in a number of the borings for the MBTA Blue Line Tunnel to East Boston on the western side of the harbor. Similar deposits were previously encountered in borings for the Charlestown Bridge and east of Beacon Hill. He considered the possibility of a re-advance, but considered them more probably the result of deposition from floating ice. I.B. Crosby (1927) also noted them. However, prior to the work of Humphrey in 1990 in the Boston area, clay containing gravel and cobbles (which at that time were thought to be dropstones) and variable amounts of sand and silty sand were classified as till-like soils or clay till. This "clay till" was frequently described by Kaye (in communications with Woodhouse) and by other workers from geotechnical firms in the 1960s and 1970s from the various building sites under investigation in Boston. Kaye, and also Woodhouse, found such deposits in the Haymarket Square and Government Center areas. They reach 21 meters (70 feet) in thickness on the west side of the JFK Building (see Figure 3-91) from where they extend westward beneath Cambridge Street, north of Beacon Hill, to pinch out at South Russell Street (Haley & Aldrich, 2010).

These complex, variable and heterogeneous deposits are described throughout the O'Neil Tunnel of the Central Artery from South Station to Charles River as:

- dense to very dense, gray to gray-brown and olive-gray, fine- to coarse-grained sand with minor silt and clay and locally containing a trace of shell fragments;
- dense to very dense, gray to olive-gray gravel with some sand and silt, a trace of clay, shell fragments, local cobbles and boulders;
- hard plastic brown and yellow-brown clay with minor silt, sand and gravel; and,
- dense to very dense gray to olive-gray silt with sand and a trace of gravel and clay.

These varieties may interfinger over short distances as the depositional environment shifted, which makes a complex deposit (see Figures 3-92 & 3-93). Locally, the deposit apparently was eroded and redeposited with little change in the marine clay to cause even more complexity (see Figure 3-92). Beneath Georges Island the glaciomarine sediment is primarily lean, low plasticity clay, with variable amounts of sand, gravel, cobbles, boulders and shell fragments and has a fabric, which could be due to a glacial surge (Miller, 2010). The clasts are slightly angular to slightly rounded. The glaciomarine sediment is overlain by the lower outwash sand and gravel or marine clay. These deposits are not as compact and dense as the basal tills (Miller, 2012). Where clay rests against eroded slopes of glaciomarine deposits, lenses described as glaciomarine deposits within the marine clay apparently represent eroded material that was quickly re-deposited. A "yellow clay" weathered cap on the glaciomarine material extends to similar depths as it does on the adjacent marine clay at Logan Airport (Bird Island Flats) and South Boston, indicating simultaneous exposure to subaerial conditions for both units (Miller, 2010).

Test borings and excavations for the new Post Office Square and Millennium Place developments encountered glaciomarine deposits (Humphrey, 1990; Miller, 2000) and discontinuous lenses of glaciomarine deposits resembling till have been described along the route of the Central Artery/Tunnel Project from Leverett Circle to South Station. Such deposits at depths of between 1.5 and 18 meters (5 and 60 feet) have a maximum thickness of 19.5 meters (64 feet) in the North Street to Causeway Street segment of the artery. The thickness is highly variable because of both its original distribution, and that erosion prior to the deposition of the lower outwash sand and gravel locally removed much, if not all, of the unit.

The Boston Substage glacier cleared Narragansett Bay before 15,500 years ago, when a lake had formed there (McMaster, 1984) and cleared Boston Harbor as the ice front retreated from the area 14,500 years ago (Oldale *et al.*, 1993), soon after the glaciomarine sediments accumulated. Following this deposition, the area rebounded above the sea and was eroded prior to the general marine encroachment, which is indicated at 14,250 years ago by radiocarbon dating of barnacles in the overlying marine clay (Kaye & Barghoorn, 1964).

Lower Outwash Sand & Gravel. While the melting ice front receded northward of Boston in the retreat phase of the Boston Substage, the rate of post-glacial bedrock rebound exceeded that of sea-level rise, and meltwater and river channels were cut and extended seaward over the exposed glaciomarine material around Boston. Outwash from the west and north was carried down the channels and spread out locally adjacent to the streams, which began the re-establishment of the river system disrupted by the glacier (and one that would eventually evolve into the present river system). The channel fills would be an eastward extension of the full and complex series of terrestrial retreat deposits that are present to the southwest and south, and which were described early (Barton, 1889; Grabau & Woodman, 1898; Clapp, 1902; Fuller, 1904). The course of the ancestral Charles River was probably established around the north end of the city at this time approximately 14,500 years ago. The lower Charles and the harbor remained above the sea for a while as some outwash accumulated and even suffered some erosion before being inundated as sea-level rise from the melting world glaciers caught up with and exceeded the rebound. Low areas were then again submerged and covered by marine clay.

The lower outwash sediment occurs locally as narrow fillings in channels cut into the top of the till, glaciomarine units and locally down into bedrock. It also occurs as thin discontinuous layers capping the eroded units (see Figures 3-75, 3-92, 3-93 & 3-94). The channels extend across the lowlands around Boston beneath the marine clay in the river valleys, and the outwash thins and pinches out eastward in the harbor. The head of the outwash to the northwest apparently forms the high sand and gravel deposit above elevation 12.2 meters (40 feet) MSL that forms the center of Mount Auburn Cemetery. Another source of outwash was apparently along a buried valley through Malden at the north side of the basin (see Figures 3-66, 3-69 & 3-70). Eroded till also may be locally redeposited with little change (see Figures 3-92 & 3-93).

The deposit is chiefly dense olive-gray fluvial sand and gravel; where silty, it is sometimes mistaken as part of the till. Thin clay lenses occur very locally and these deposits are unconformably overlain by marine clay. The channel fills may reach 17 meters (55 feet) in thickness as seen in the profiles for the Central Artery/Tunnel Project. However, the lenses outside of channels rarely exceed 3 meters (10 feet) in thickness and may be missed by standard sampling intervals in test borings. Sand in a channel in till (see Figure 3-95) north of Cambridge and Grove streets is about 9 meters (30 feet) thick (Haley &

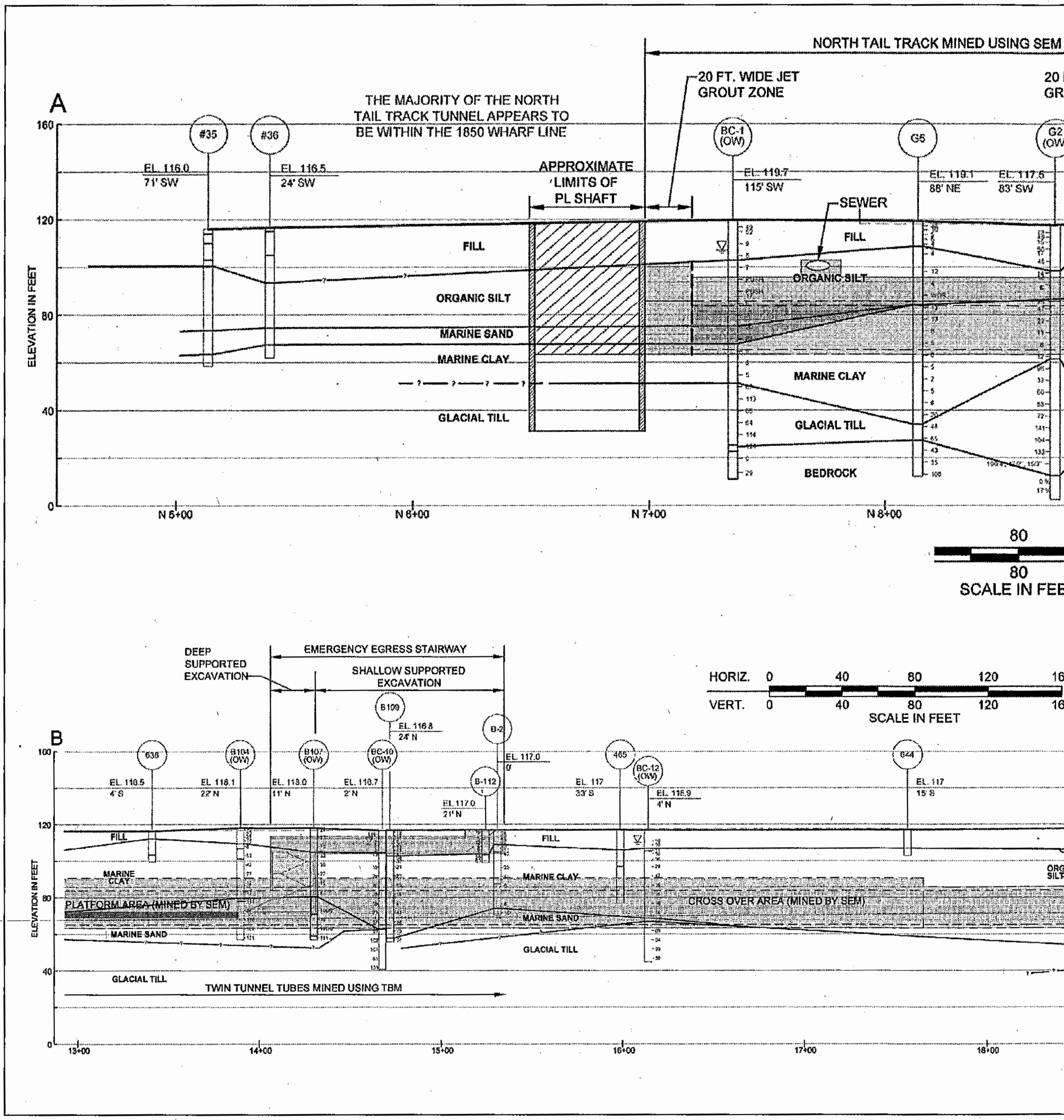
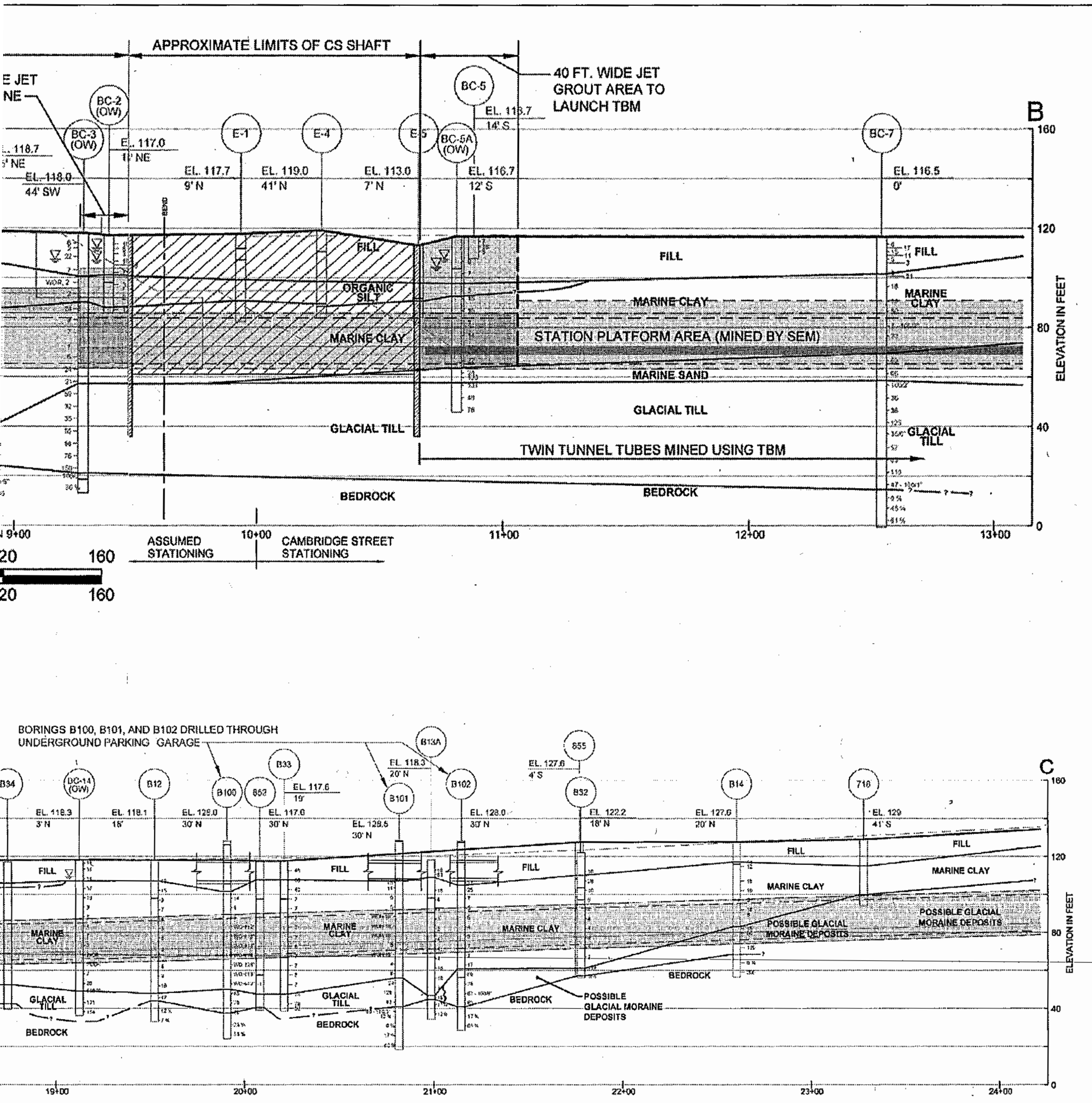


FIGURE 3-91. East-west section (view from north) beneath Cambridge Street, north of Beacon Hill, along the north tube for the proposed Red Line/Blue Line Connector. (Figure continued on pages 204-205.)

Aldrich, 2010), and extremely coarse cobbly clean gravel 9 to 12 meters (30 to 40 feet) thick fills a channel at Dewey Square by South Station (Miller, 2012). Across the Charles River in Cambridge, the outwash is thicker and increases westward to form a wedge-shaped deposit. The buried valley in Malden contains about 18.3 meters (60 feet) of outwash beneath the marine clay (Upson & Spencer, 1964).

Drilling for the Central Artery/Tunnel Project revealed one south-trending channel, which cuts through the glaciomarine deposit



From Haley & Aldrich (2010)

into the bedrock, passing just east of the MBTA Blue Line Airport Station. The relief on the west side of this buried channel reaches 42 meters (137 feet) in places (see Figure 3-93). Lenses also are found outside of the channels. A mound of the lower outwash sand grading southerly into gravel was found at Pleasure Bay south of Castle Island and a thin deposit occurs southeastward below Moon Island and Nut Island, where about 3 meters (10 feet) of dense yellowish-brown silty sand and a lower 2.3 meters (7.5 feet) of very dense, brown fine to coarse gravel are present (Clarke, 1888; Parsons Brinkerhoff, 2006a & 2006b; Sverdrup, 1990b). No lower outwash is found in the harbor north of Nut Island and across Deer Island or offshore eastward of Deer Island (Sverdrup, 1990b; Metcalf & Eddy, 1990; Goldberg-Zoino Associates, 1983; Parsons Brinckerhoff, 1990).

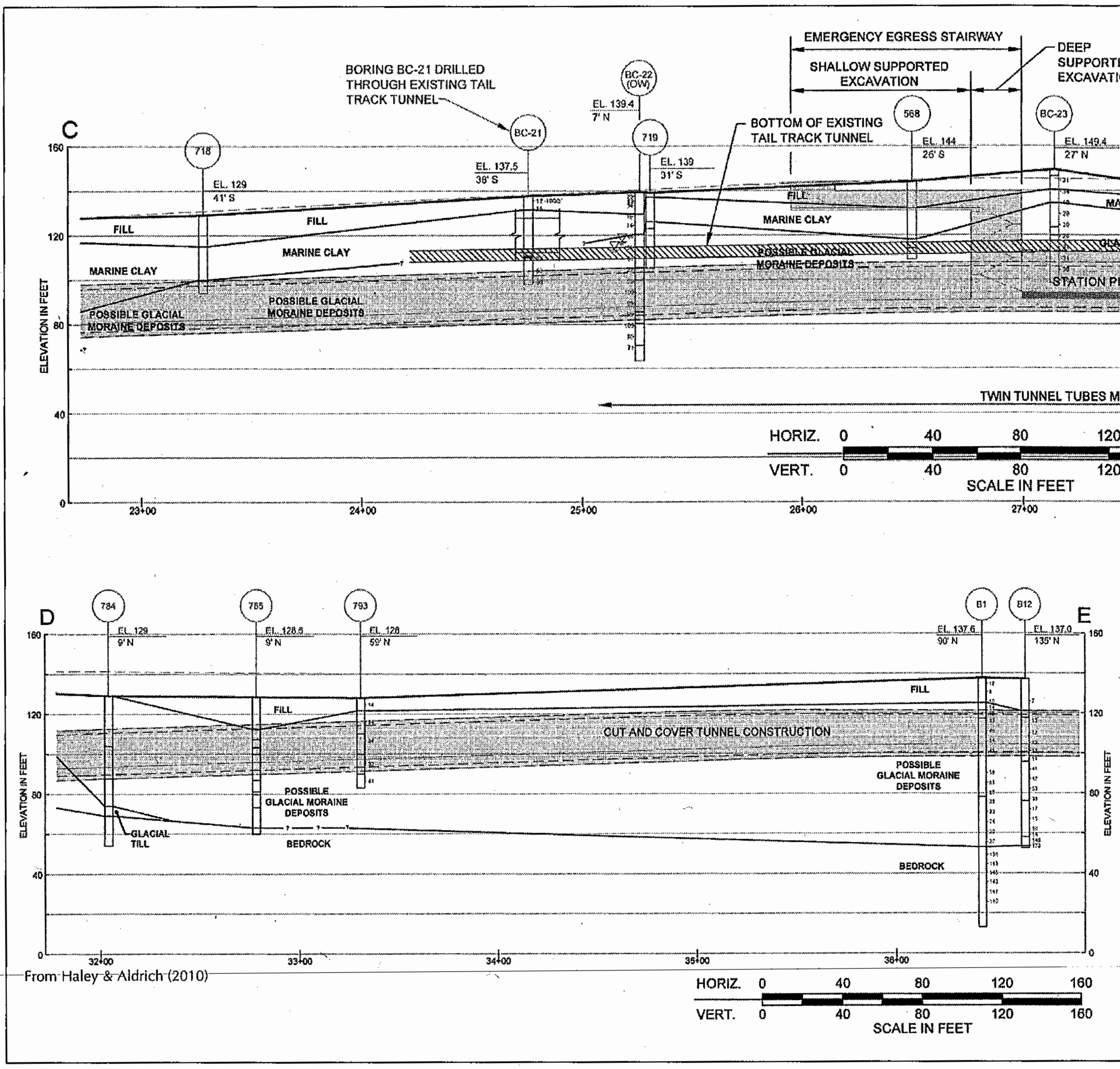
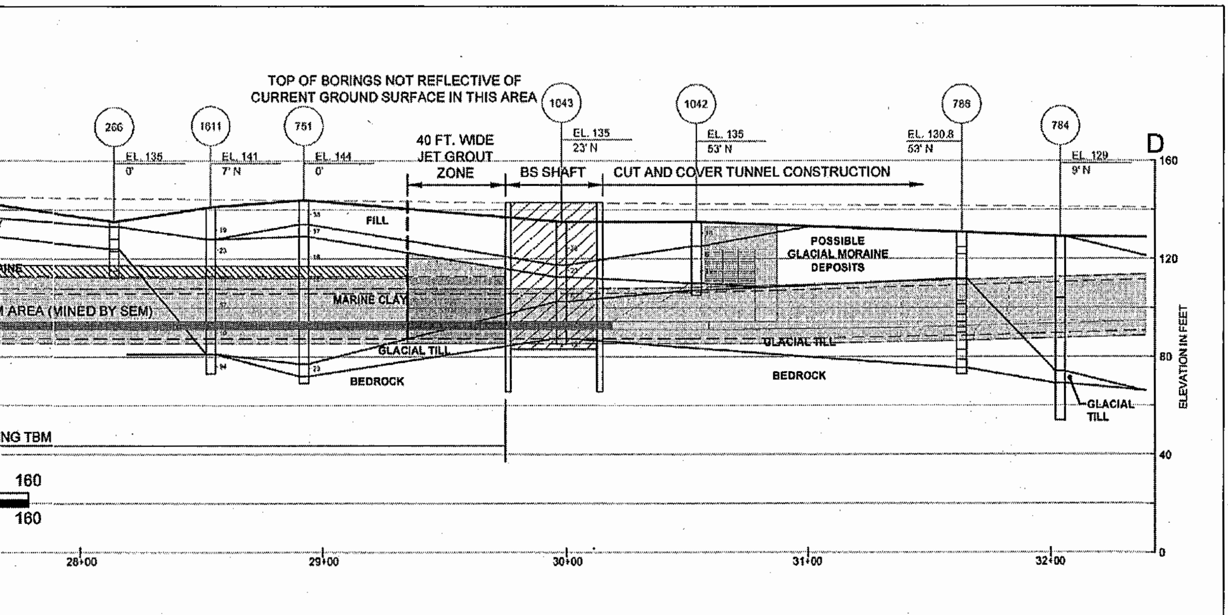


FIGURE 3-91. Continued.

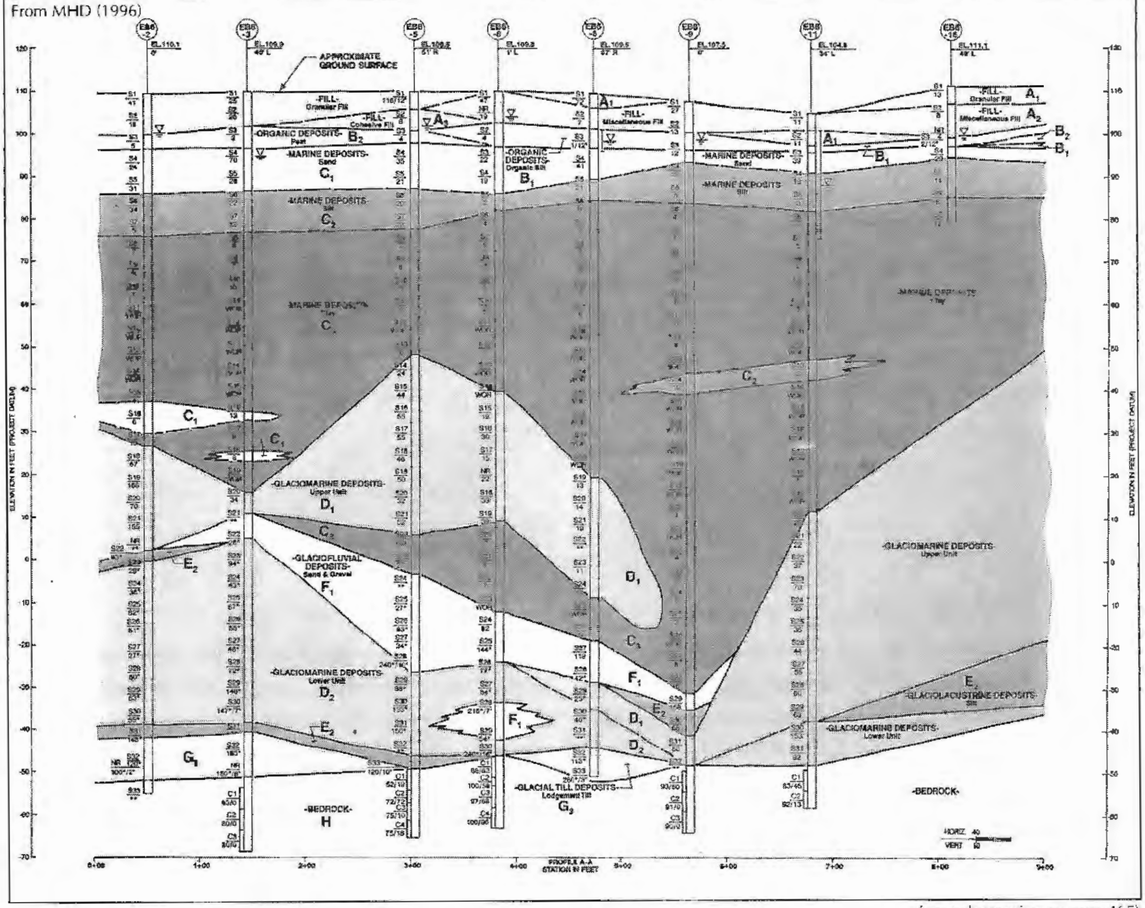
Marine Clay. Fine sediment from an increasingly more distant ice front, coupled with a rising sea level that inundated much of the low-lying areas, produced a thick blanket of marine clay that smoothed out most of the relief across the underlying units. The infilling of topographic lows and channels around islands formed by the higher drumlins is seen in many cross-sections constructed from borehole data and offshore seismic profiles (see Figure 3-71). The marine clay is found in broad channels under much of Massachusetts Bay, Boston Harbor and the rivers and surrounding lowlands that extend inland from the harbor. These areas include the old Mill Pond, Charles and Mystic rivers, the Back Bay and other former estuarine marshlands that are now filled (see Figures 1-16 & 1-17). The marine clay deposit is commonly referred to as the "Boston Blue Clay" and is found throughout the low areas of Boston (see Figure 3-89). The clay extends eastward beyond the harbor (Parsons Brinckerhoff, 1990). It was mistakenly called the Leda Clay by Sears



(1905) who observed it on the north side of the basin and northward, where shells confirmed its marine origin. The clay laps up onto the till of Beacon Hill and the drumlins of Charlestown. The outline of the Shawmut peninsular begins to emerge via the formation of a ridge of this marine clay through processes of both deposition and erosion. The Shawmut Neck was a narrow strip of land that formed the terminus of the Shawmut Peninsula. It was bordered on the west by the Roxbury Tidal Flats and on the east by South Boston Bay and was barely passable at low tide, making Boston essentially an island. The Neck ran along Orange Street (what is now Washington Street). Yellow clay, possibly glaciomarine, on the order of 3 meters (10 feet) thick was encountered during the drilling for the Wang Center on Tremont Street, which would represent the extreme western edge of the neck. Drilling on Washington Street between West Oak Street and Kneeland Street for a housing complex also found clay but only the thinner oxidized yellow crust (the marine clay) commonly found around the Boston area.

The clay is typically light greenish-gray to medium-gray, rather than blue, and usually weathers yellowish in its upper portion (see Figures 3-96, 3-97 & 3-98). Blue color is seen in the clay under the Boston Company Building and Millennium Place, where deformation of the clay was also observed. Throughout most of its thickness the clay is soft and plastic, but less so in the weathered zone and where it contains partings of fine sand, silt or sand lenses (Judson, 1949). Analyses show that the predominant clay mineral is illite. The clay is only slightly sensitive, with a natural water content of about 30 percent, but it also can be found in a sensitive state in certain areas, such as at Alewife Station. Where redeposited, the clay exhibits anisotropy. The contained lenses and layers of silt and sand increase with depth and in some places the clay grades downward into well stratified sand that becomes coarser with depth and finally grades into gravel (see Figure 3-98). Scattered through the clay are a few pebbles, cobbles and boulders (iceberg drop stones), which may reach several tons in weight (see Figure 3-98). A very large erratic boulder is incorporated into its base in the Fort Point Channel at the MBTA Silver Line crossing (Leifer, 2006). The clay and interbedded silt and sand grade up the valley of the Charles River into littoral sand and, thence, into outwash consisting of sand and gravel deposited by rivers. Because the topographic trough provided by the Boston Basin was a major drainage way for glacial melt water from the west, Boston became the apex of a large, submarine clay delta of outwash origin. Besides the low tidal areas around the Shawmut Peninsula, the clay can also be found in the Squantum area

From MHD (1996)



(see color version on page 465)

FIGURE 3-92. Variations of the glaciomarine deposit in section (north view) along the Central Artery/Tunnel Project, beneath Airport Access Road off the northwest corner of Logan Airport and west of MBTA Airport Station. Similar redeposited glaciomarine sediment (D_1) is also in the lower marine clay (C_3) in a channel above the lower outwash (F_1).

of Quincy to the south; in Charlestown, Cambridge and Somerville to the north and west; the Fenway; Roxbury, South Boston and Dorchester to the south; and East Boston to the east.

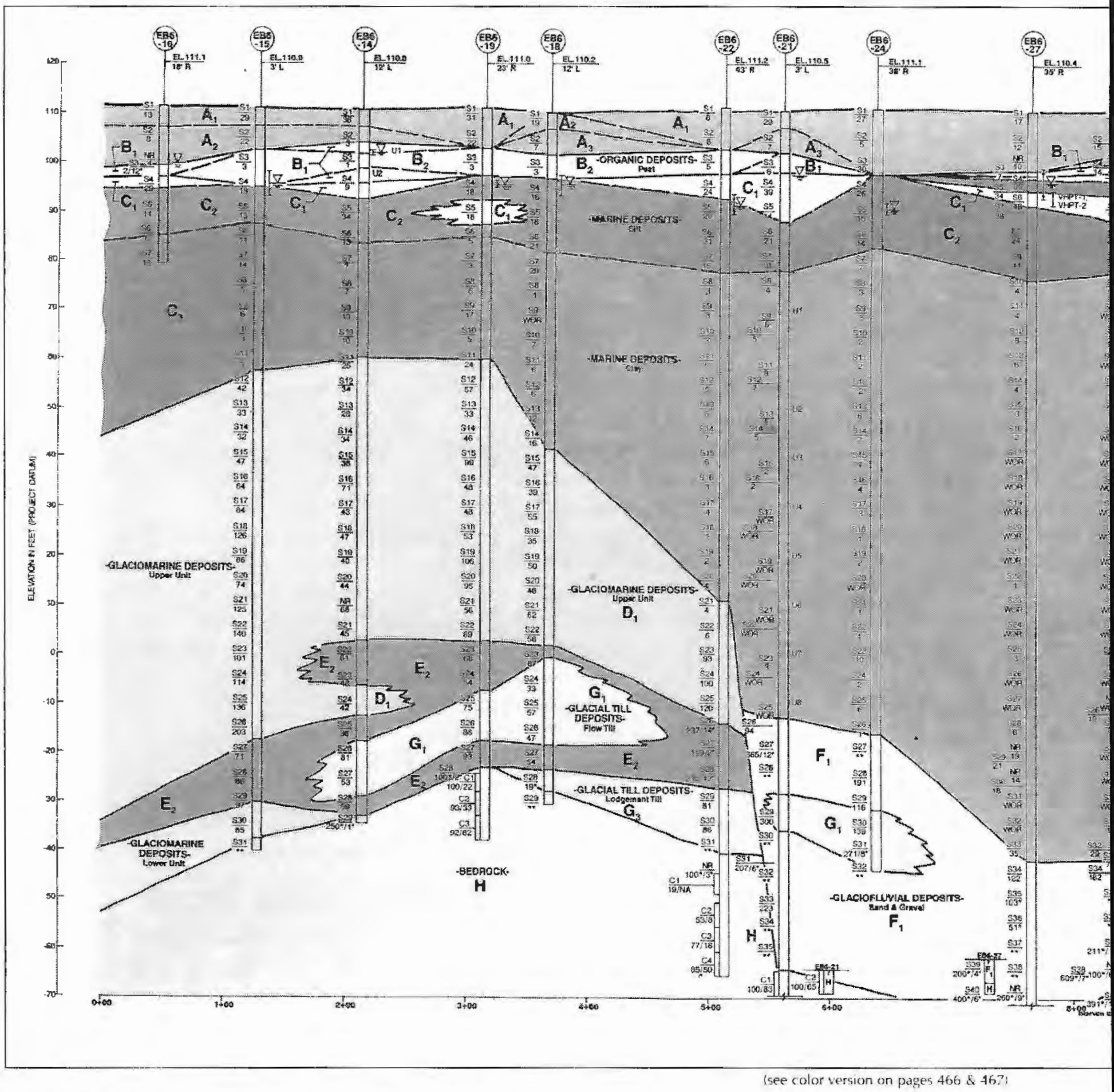
The top 1 to 5 meters (3 to 16 feet) of the clay stratum became generally oxidized during a period when it was exposed; much of this area is currently below sea level in Boston Harbor (Hughes & Edmunds, 1968). Borings indicate that where overlain by the Lexington outwash it is oxidized to a depth of 1 meter (3 feet) and to a maximum depth of 3 meters (10 feet) where exposed (see Figure 3-98) on the surface around the Back Bay and Cambridge (Kaye, 1961). A stiff, yellow crust of subaerial origin causing oxidation was formed by the desiccation and resulting over-consolidation that has taken place. Significant over-consolidation is generally limited to the upper 5 meters (16.5 feet), although less over-consolidation can be found to depths of 10 to 12 meters (33 to 39 feet). At depths lower than 18 meters (60 feet), the clay becomes softer, gray and essentially normally consolidated. Where the oxidized clay was overlain by substantial organic matter (such as peat), a chemical reaction involving iron reduction — *i.e.*, ferric iron, Fe^{+3}, is changed to ferrous iron, Fe^{+2} by bacterial action (Kusel *et al.*, 2008) — has created an upper zone of softened blue clay up to 2 meters (6.5 feet) thick. This zone, representing the top of the clay stratum, may also be silty or sandy and somewhat water bearing. The upper 2 to 5 meters (6.5 to 16 feet) of the clay is structurally disturbed and may be broken, folded and badly contorted in places in the Back Bay and parts of Boston Harbor. The upper clay also is seen in excavations to have prismatic structure or cubical jointing and fissuring, which appears to be evidence of having been frozen, probably at the time of the overlying upper outwash.

The clay may overlie any of the earlier surficial deposits or bedrock because of preceding erosion, and it is normally overlain by the Lexington outwash, Holocene organic deposits or fill. The unit is usually well-bedded with thin horizontal layers. However, both offshore and onshore profiles show it locally conforms to, or is draped over, the surface of the basement on which it was deposited, which imparts a folded appearance to the clay (see Figure 3-71 & 3-99). There are deep funnel-shaped "downfolds" on the order of 100 to 200 meters (330 to 660 feet) across.

The topographic trough provided by the Boston Basin was a major drainageway for glacial melt water from the west and Boston became the apex of a large, submarine clay delta of outwash origin. The marine clay, because it often contains more silt than clay, has lower plastic and liquid limits of its clay-sized material than would mineral clay. The marine clay represents a high percentage of fine-grained rock flour component of outwash that was carried farther and deposited in coastal marine waters. Miller (2010) considers a significant amount is reworked clay eroded during the Lexington Substage from the older clay-rich glaciomarine deposit based on evidence that indicates that the deposit was exposed at places during the time of Lexington clay deposition. The occasional glacial gravel to boulder clasts in the clay are apparently iceberg dropstones, perhaps rafted when the ice front was close to Boston (see Figure 3-97). The clay is thickest in the lower valley of the Charles River and Boston Harbor, where it wrapped around Beacon Hill, and thins under Massachusetts Bay to the north, east and south. In the Back Bay, as well as along marginal waterfront areas, the clay is typically 15 to 38 meters (50 to 125 feet) thick. Up the Charles River at the Mount Auburn Cemetery the clay is 25 meters (81 feet) thick near the present river and eroded to zero at short distances to the north beneath the upper outwash. Even greater thicknesses — up to 60 meters (200 feet) — are found west of Massachusetts Avenue and in Cambridge, where parts of Harvard University and MIT rest on it. Known clay thicknesses, as great as 75 meters (246 feet), occur in the Charles River area.

The top of the clay was deeply eroded by the ancestral Charles River and its tributaries during a drop in sea level associated with the Lexington Substage subsequent to 12,600 years ago and the contoured surface (Judson, 1949) shows a well developed stream pattern (see Figure 3-100). The main channel is closely aligned with the present Charles River, a second channel enters from the north between Charlestown and East Boston, and a third exists beneath Fort Point Channel. The surface of the clay is now generally below sea level around the Shawmut Peninsula and is estimated to descend eastward to nearly elevation –60 meters (–200 feet) MSL by Judson (1949). Judson (1949) also reported it rising to about elevation 9 meters (30 feet) MSL on the north and east sides of Beacon Hill. Kaye (1961) only found it reaching to thickness of about 4.6 to 7.6 meters (15 to 25 feet) over the upper till on the south side, which would be a Boston area local limit since the upper limit of the marine clay varies across New England because the post-glacial rebound has raised the land progressively higher to the north. At the northwest edge of the Boston area, clay has been found as high as elevation 22 meters (72 feet) MSL (Woodworth, 1897; Chute, 1959; Colgan & Rosen, 2001), but these deposits are apparently disturbed or from local ponding. I.B. Crosby (1934) found the highest known marine glacial clay in the environs of Boston (except for small deposits that obviously formed in glacial lakes) at elevation 7.6 or 10.7 meters (25 or 35 feet) MSL.

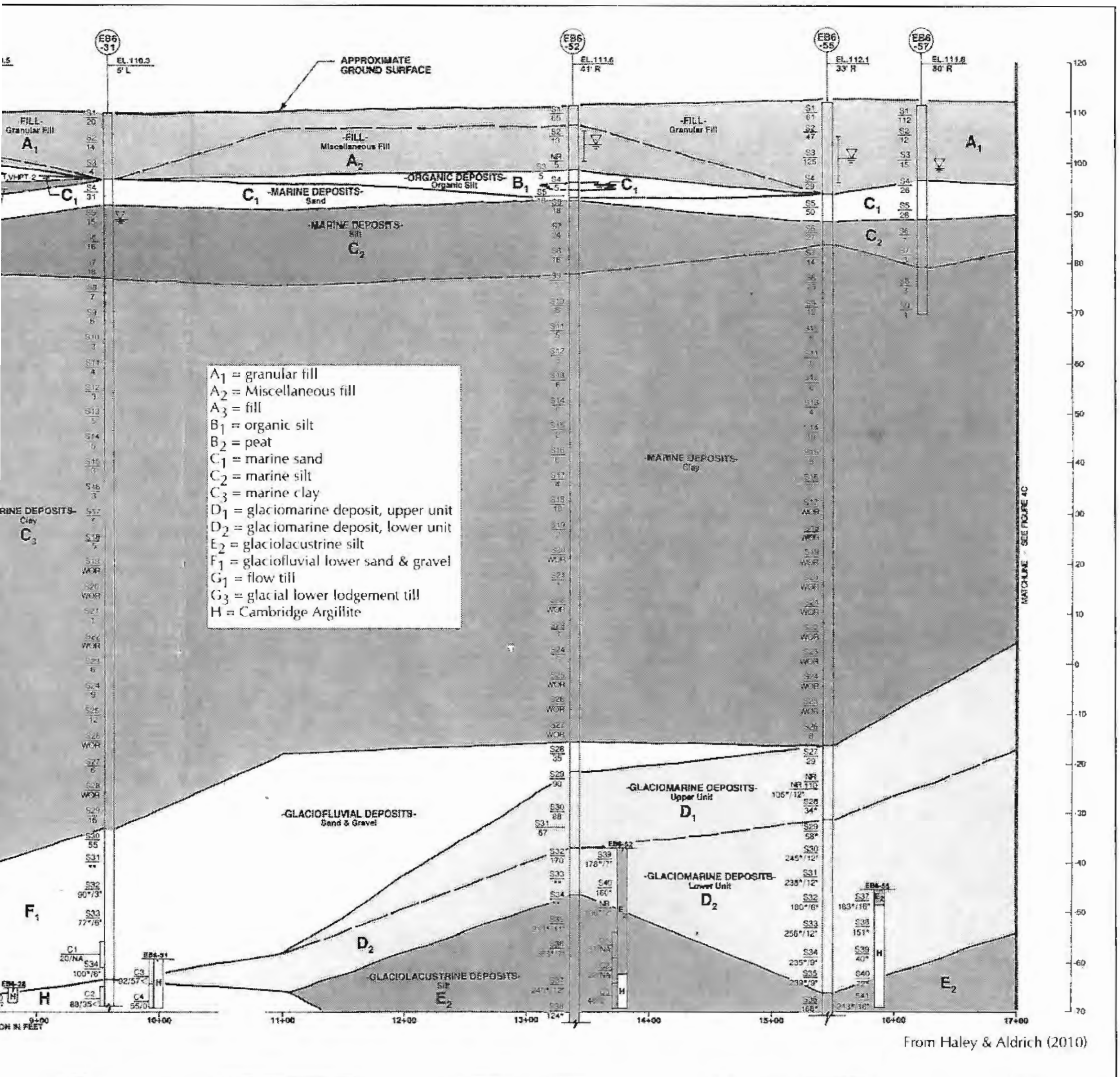
Marine mollusks, starfish, foraminifera, sponge spicules, echinoid spines and some diatoms occur in the clay at West Lynn at the north edge of the Boston Basin (Sears, 1905; Nichols, 1946; Kaye, 1961). Mollusks, barnacles, foraminifera and ostracodes also are



(see color version on pages 466 & 467)

FIGURE 3-93. Section from the Central Artery/Tunnel Project beneath Route 1 adjacent to MBTA Airport Station showing complex facies relations within the glaciomarine deposits resting on lower

found nearby in clay in Lynn, Revere and Winthrop, and have yielded a mean radiocarbon age of 14,000 years ago (Colgan & Rosen, 2001). Some sparse foraminifera occur in the Back Bay (Stetson & Parker, 1942), along with a few barnacles such as *Balanus hameri* (Ascanius). The latter yields radiocarbon dates that range from 13,230 (±320) to 14,420 (±300) years ago and average about 14,000 years ago (Kaye & Barghoorn, 1964; Kaye, 1976a). However, locally the clay at Lynn and in other pits bordering Boston, as well as in the Back Bay, is devoid of diatoms and foraminifera (Conger, 1949; Phleger, 1949). Beaver-cut twigs and peat embedded in the upper part of the clay in the Boston Common yield two dates that average 12,200 years ago (Kaye, 1972 & 1976a). The clay also is older than the Lexington outwash sand of circa 12,000 ago that overlies it. The general lack of



till and bedrock that are cut by a deep channel with lower outwash and marine clay fill, view northwest. The units labeled glaciolacustrine silt and enclosed till are facies of the glaciomarine deposit.

fossils, especially the microfossils, probably reflects the low salinity, excessive turbidity of the water causing diminishing light, and rapid deposition at the mouth of a major outwash river (Phleger, 1949; Conger, 1949). The clay thus appears to represent a Woodfordian, early Late Wisconsin, marine inundation, which is indicated to have occurred under cold conditions by the mollusks. The most abundant shell found by Sears (1905) was *Yoldia arctica* (Portlandia Arctica) which now lives in the Arctic at depths of 1 to 60 meters (3 to 197 feet). The spruce pollen that is very abundant in the upper 3 meters (10 feet) of the clay at West Lynn also supports a cold or periglacial depositional environment during its deposition (E.B. Leopold, in Kaye, 1961). The correlation by Sears (1905) with the Leda Clay is a misnomer since the Leda is the quick (sensitive) clay found in certain areas of

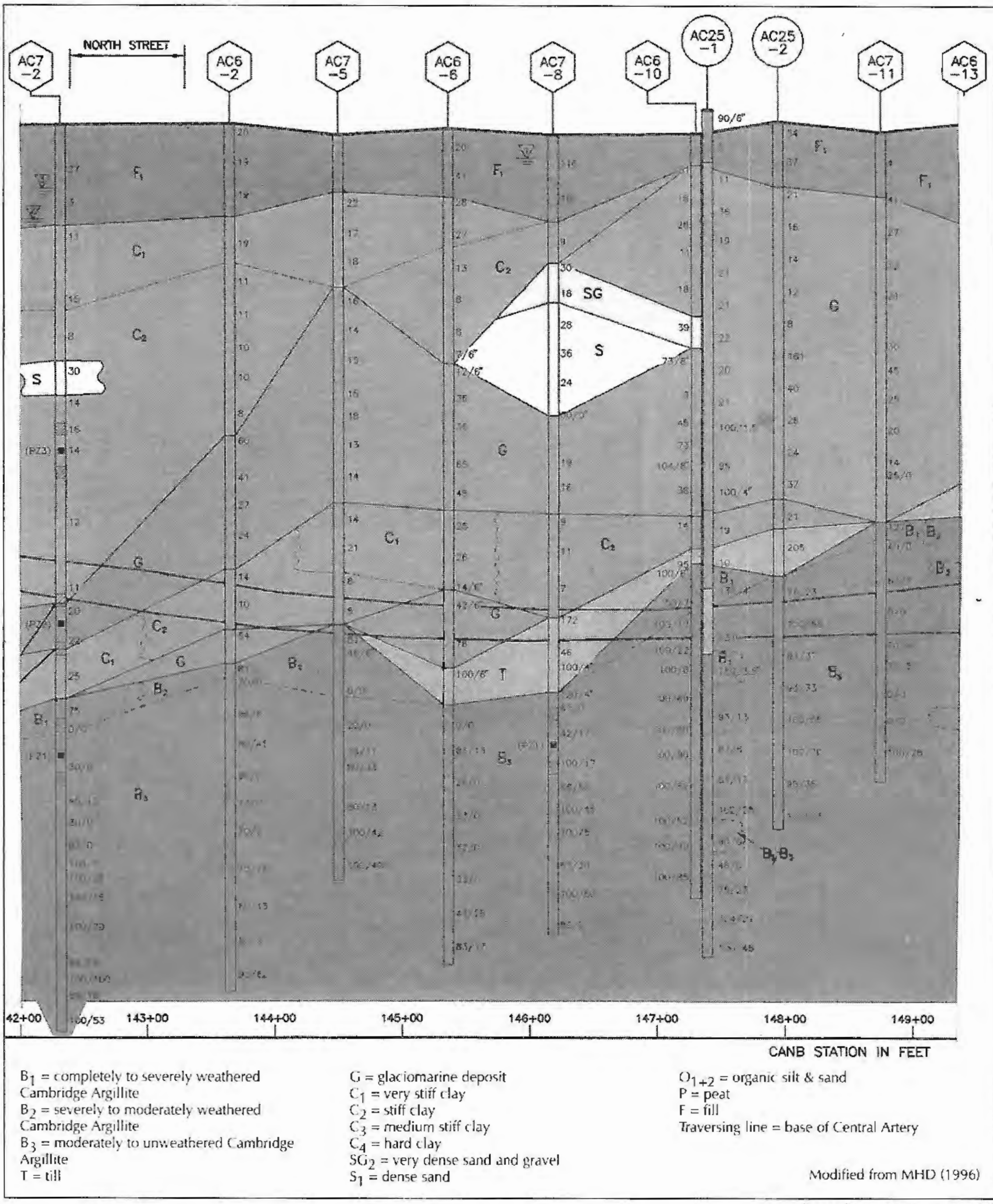


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FIGURE 3-94. Section along the Central Artery between North Street and North Washington Street (west tunnel wall; stations 142+00 to 150+00) showing glaciomarine deposit interbedded with and overlain by marine clay above thin till, which are undifferentiated; view southwest.

Canada. The Presumpscot Clay in Maine, however, has a much greater clay particle content than the Boston clay (*i.e.*, less silt), and has been leached of its depositional high salt and is unrelated. The Boston marine clay, however, does correlate northward of the

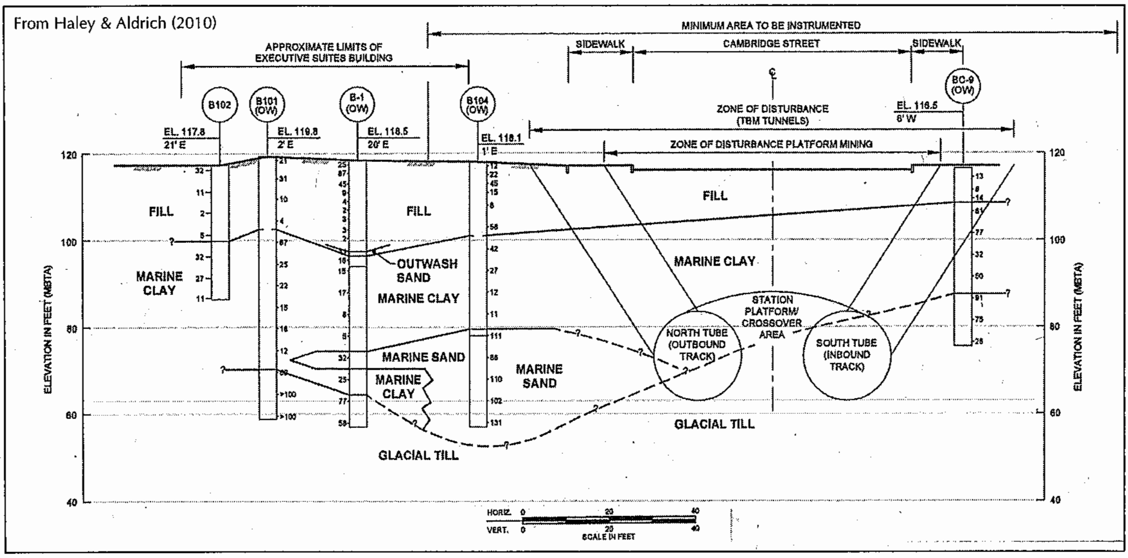

FIGURE 3-95. North-south section (view east) showing lower outwash with clay lens filling a channel cut in till beneath Cambridge Street between Grove Street and Strong Place (Station 13+00) and the proposed twin tubes of the Red Line/Blue Line Connector.

basin with some older clay that has been grouped with the generally younger Presumpscot Formation, also known as the Maine "Blue Clay" that formed after the later Lexington Substage.

Moraine Till. A last readvance of glacial ice reached into the western and northern fringes of the Boston Basin in the very Late Wisconsin to form a new cycle of moraine till and retreat deposits of outwash sand and gravel during what is called the Lexington Substage by Judson (1949) and is the youngest of the three recorded glaciations. This episode apparently coincides with the European glaciation known as the Younger Dryas that occurred between 12,900 and 11,500 years ago. The glacier front extended into the Charles River meadowland at the western edge of the basin and to the northern edge of the basin, as well as sending an ice lobe southward along the Aberjona buried valley, which now contains the Mystic Lakes and Fresh Pond (see Figure 3-101). During the start of this substage, the sea level was lowered 18 to 21 meters (60 to 70 feet) and meltwater streams of the ancestral Charles, Aberjona and Malden river systems cut channels deeper into the surface of the elevated marine clay along with smaller streams (see Figure 3-100).

Relatively thin till was deposited beneath the ice as it moved southward. Judson (1949) described the till to the west as a light gray fresh, slightly rusty weathered bouldery porous deposit, which averages about 4.5 meters (15 feet) in thickness, and Kaye (1982b) noted that it is patchy, poorly compacted and barely oxidized. Such till lies almost entirely outside the Boston Basin, and morainal till is much more important in the basin.

Till formed a double moraine near the terminus of the ice lobe that extended south through the Mystic Lakes-Fresh Pond area (see Figure 3-101). South of Fresh Pond the ice encountered a partially buried ridge west of Mount Auburn Cemetery and veered to the southeast. It produced a prominent moraine ridge, especially on the southeast side of Fresh Pond, above outwash to the south called the Fresh Pond Lobe (see Figure 3-102). The moraine swings from the west side of the pond around its south side to extend eastward through Observatory Hill toward the Spring Hill drumlin near Porter Square as a ridge with 6 to 12 meters (20 to 40 feet) relief. The moraine was recognized early and studied extensively (Woodworth, 1897; Lane; 1928; I.B. Crosby, 1934; LaForge, 1932; Chute, 1959). It varies considerably in composition, structure


(see color version on page 469)

FIGURE 3-96. Gray marine clay under the shovel, covered by reddish-brown organic silty sand in the foreground. (Photo courtesy of Bradford Miller.)

and topographic prominence from place to place and incorporates ice-disturbed pushed marine clay and some older sediment with a small admixture of outwash sand and gravel. Generally, the moraine consists of very clayey till that resulted from glacially eroded marine clay, with scattered cobbles and a few boulders (Chute, 1959). The till in the moraine has been thrust southeastward in places along N30°W dipping breaks (Lane, 1928), as well as being deposited over contemporaneous outwash in places, showing a minor readvance.

Kaye (1976a) hypothesized that some ice-disturbed sediments south of the Fresh Pond Moraine were actually the effects of another ice lobe that had extended eastward along the Charles River Valley to the south of Fresh Pond and then pushed northward into the area where Harvard University is now located to form a moraine (see Figure 3-103). But this hypothesis has not been borne out by more recent observations. This moraine is described as including the Mount Auburn Cemetery, Harvard Observatory Hill, Central Square, Shady Hill and Dana Hill, and consists largely of highly contorted marine clay that shows overturning outward to the north and north-east. However, there is no evidence for this lobe in the extensive fan deposit to the west flanking the Charles River, and Observatory Hill is the eastern part of the Fresh Pond moraine. The rest does appear to be part of a moraine, excepting Central Square, but this moraine developed earlier than the Fresh Pond moraine at the outer limit of the ice lobe from the north. Kaye also showed that the moraines extend farther to the east and make a single moraine system with a Back Bay lobe including Beacon Hill. However, the deformation in the vicinity of Beacon Hill is found to be related to the time of the older upper till, and is not a moraine, which appears also be the case for Kaye's report of a moraine of very compact, deformed marine clay overlain in places by lenticular till south of Boston Common, along the western side of Shawmut Peninsula, and

(see color version on page 469)

FIGURE 3-97. Marine clay rubble in excavation, including large boulders. (Photo courtesy of Bradford Miller.)

From Judson (1949)

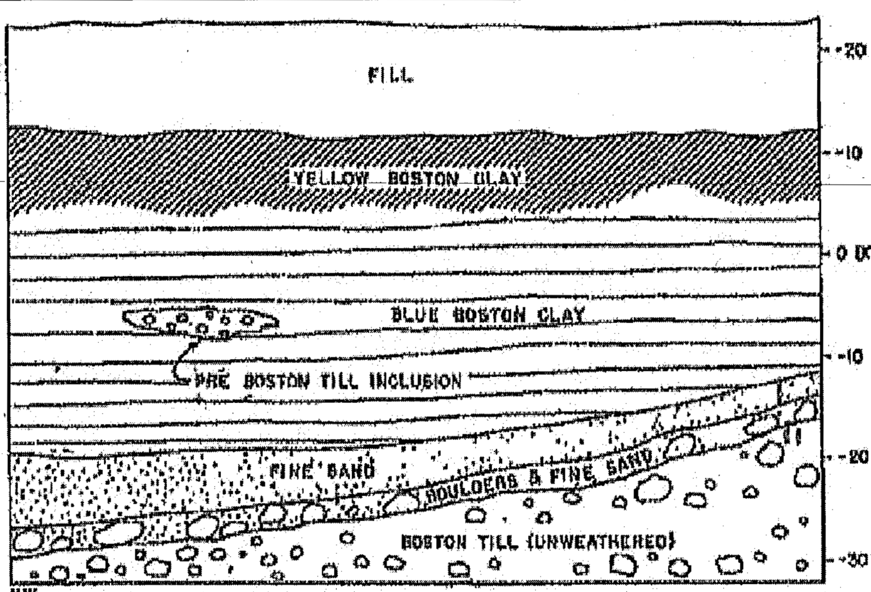

FIGURE 3-98. Section showing the marine clay and its oxidized top above the upper till and the lower outwash at the New England Telephone and Telegraph Company Building at Franklin and Congress streets.

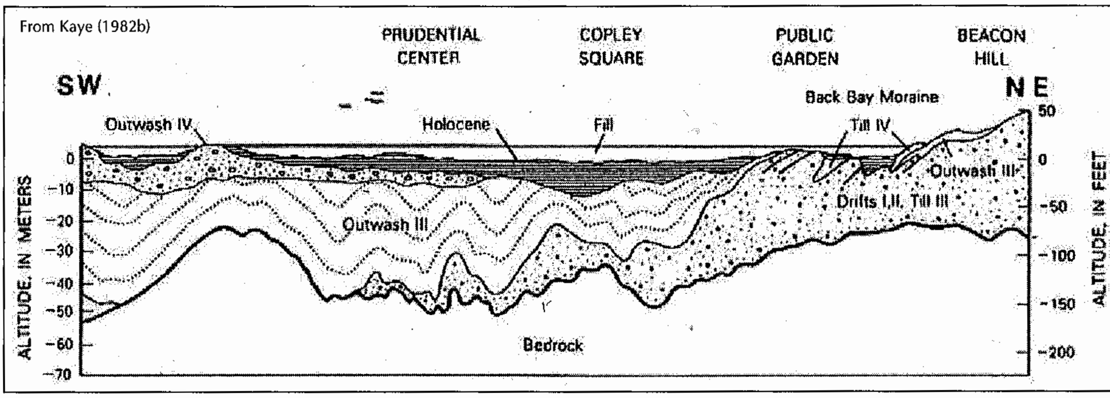

FIGURE 3-99. Section extending southwest from Beacon Hill across part of the Back Bay showing draped marine clay (Outwash III) over bedrock and the upper till and beneath the upper outwash sand and gravel (Outwash IV). Vertical exaggeration 20×.

along Boston Neck. However, excavations observed near the neck by Woodhouse along Tremont Street in the South End revealed only undisturbed marine clay as do the several excavations in central Back Bay (Judson, 1949; Rosen *et al.*, 1993). No other young till is known in the basin and none was found below the upper outwash in Lynn (Sears, 1905).

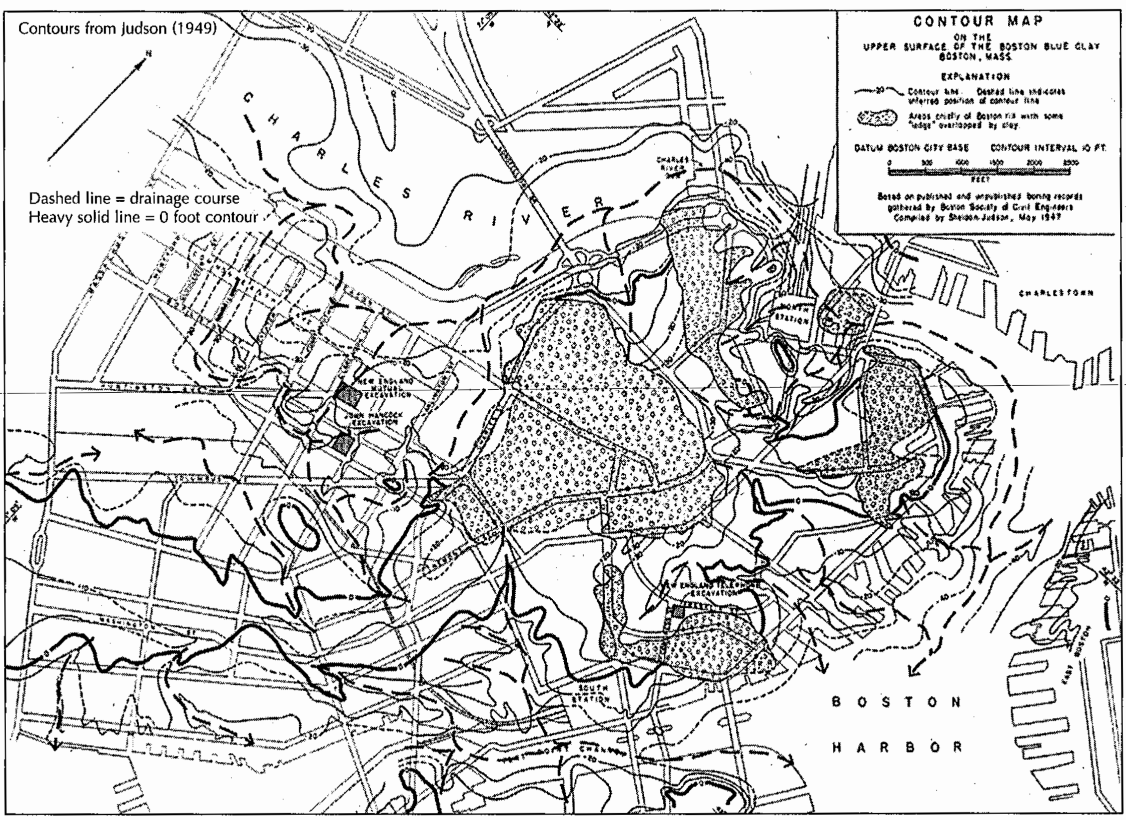

FIGURE 3-100. Central Boston showing the contoured top of the marine clay (Boston Blue Clay), areas of predominantly underlying till and the interpreted drainage system that incised the clay.

The deformation mentioned by Kaye in Cambridge is found to be part of an outermost moraine beyond the Fresh Pond moraine. Remnants of this earlier moraine, herein named the Mount Auburn moraine, extend southeastward from Meetinghouse Hill in Watertown as irregular hills, then to the area of the Mount Auburn Cemetery, and thence drops off to the northeast. Several small kettle holes lie between it and the Fresh Pond moraine, testifying to the former presence of ice along its north side. The high mound of sand and gravel outwash forming the Mount Auburn moraine, a hilly area of Cambridge characterized by kames and kettle holes, lies north of the Charles River and south of Fresh Pond. It is occupied by the Mount Auburn and Cambridge cemeteries. Mount Auburn probably formed where a river emerged from the ice and then was pushed up by a minor readvance of the ice. Chute (1959) thought that the Mount Auburn deposit was a remnant of earlier, pre-marine clay material, but drilling now shows that the southern portion overlies the clay. West of Mount Auburn, the sand is pebbly with some cobbles and boulders and resembles till (Chute, 1959). Boreholes around Mount Auburn record sand and gravel with clay. Chute considered the deposit to be an ice contact kame terrace deposit that had formed against the ice and filled in around ice blocks that later became kettles; he also considered that the deposit was slightly older than the Fresh Pond moraine. However, he did not follow it eastward. The moraine to the east consists of a subtle ridge that rises about 6 meters (20 feet) in a curve

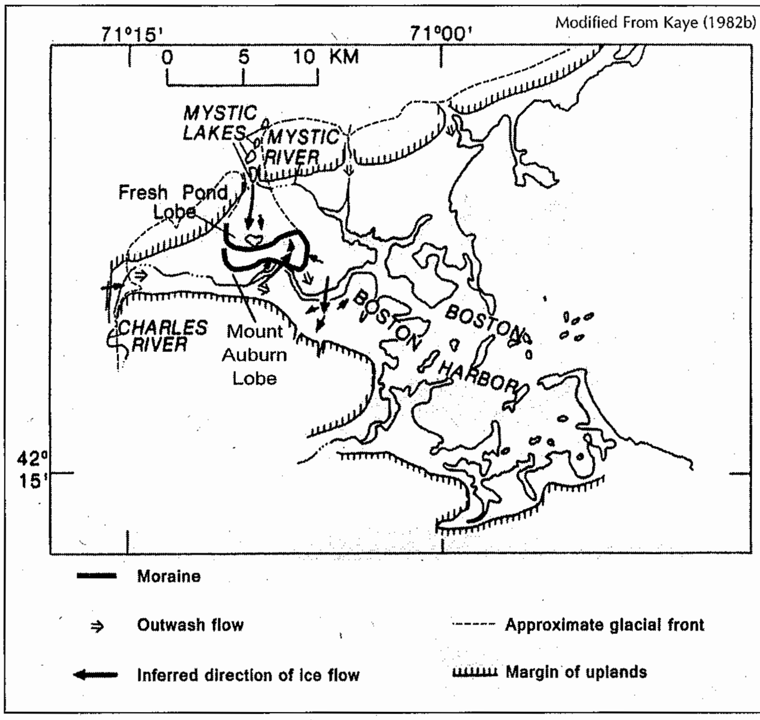

FIGURE 3-101. Map showing the position of the glacial front of the Lexington Substage ice lobe when the Fresh Pond and the earlier Mount Auburn end moraines were formed, as well as showing sources of outwash.

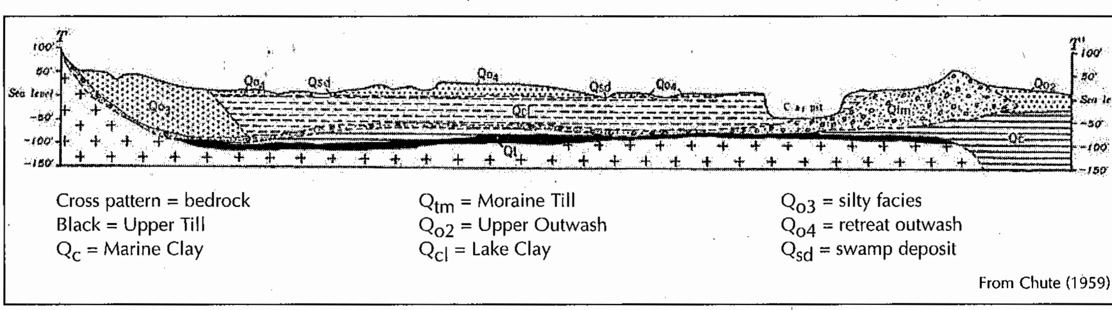

FIGURE 3-102. North-south section passing just east of Fresh Pond showing relations of the Lexington Substage deposits.

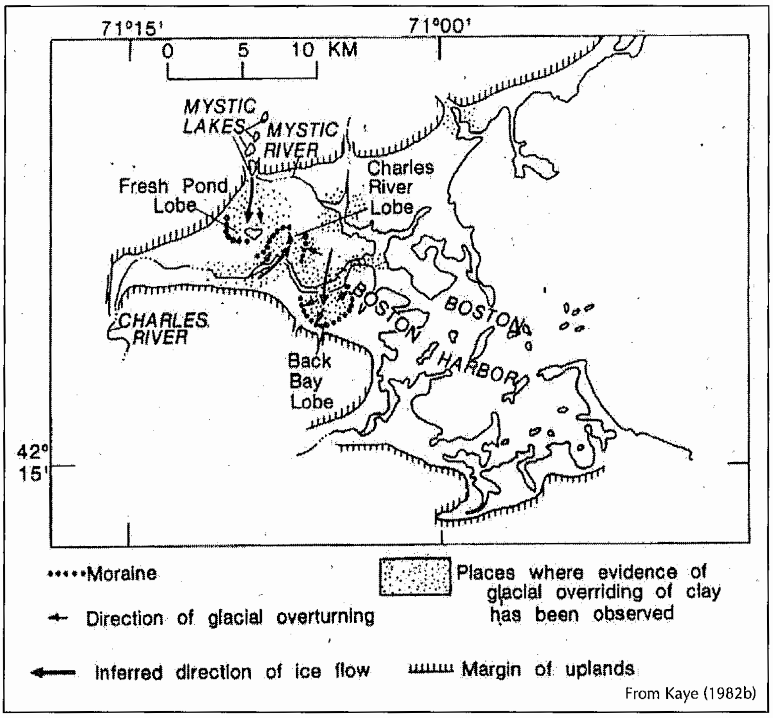

FIGURE 3-103. Map showing Fresh Pond, Charles River and Back Bay moraines and areas that have yielded evidence of glacial overriding of clay.

from Harvard Square southeastward through Dana Hill, about 15 meters (50 feet) in elevation, and hence northward and northwestward along the Somerville line to its end near Shady Hill. This moraine apparently records the very brief farthest extent of the ice lobe through Mystic Lakes. Yellow oxidized marine clay similar to that found on Boston Neck is present at Central Square farther southeast, but no disturbance was seen in exposures there by Woodhouse. When the ice retreated behind the Fresh Pond, outwash through the gap at Porter Square and elsewhere partially buried the Mount Auburn moraine.

Upper Outwash Sand & Gravel. Outwash sand and gravel spread outward from the glacial front during the Lexington Substage to extend into many parts of Boston to form an upper outwash deposit. A drop in sea level due to water being taken up as ice for the Lexington readvance exposed the top of the marine clay and resulted in partial excavation of old river valleys and in the cutting of new channels. The valleys helped confine the edge of the ice as it advanced on Boston and the channels guided the outwash away from the ice front and moraines (see Figures 3-101 & 3-102). Sand and gravel outwash was carried down these channels around the city and into the western side of the harbor to spread out into thin local aprons (see Figure 3-71). Rivers emerging from the glacier front along the meadowlands by the north-flowing stretch of the Charles River to the west built a large fan of outwash to the east (see Figure 3-101). The head of the outwash fan built up to elevation 33 meters (110 feet) MSL at the Newton-Waltham line and slopes eastward, filling the valley of the lower Charles River to form flats at elevation 15 meters (50 feet) MSL in Watertown and elevation 12 meters (40 feet) MSL at Mount Auburn Cemetery. The outwash banked against the western side of the Mount Auburn moraine and swept around its south end to form a relatively thin blanket over southern Cambridge and North Brighton. In this area it would have mingled with outwash from the Fresh Pond ice lobe to the north. Sand and gravel passed through a gap in the Fresh Pound moraine at Porter Square and to the west to spread toward Harvard Square, where it is 0 to 15 meters (0 to 50 feet) thick along the Red Line subway north of the square. Another western source delivered sand and gravel all the way to Nut Island. Farther east, discontinuous beds of sand and gravel were deposited along channels and as adjacent local thin patchy accumulations (Judson, 1949) that did not reach far into the harbor. A third source of outwash was the sand and gravel carried southward down the Malden Valley and rivers from the uplands of northern Medford to spread out across the north side of Boston (see Figure 3-104). The outwash debris funneled

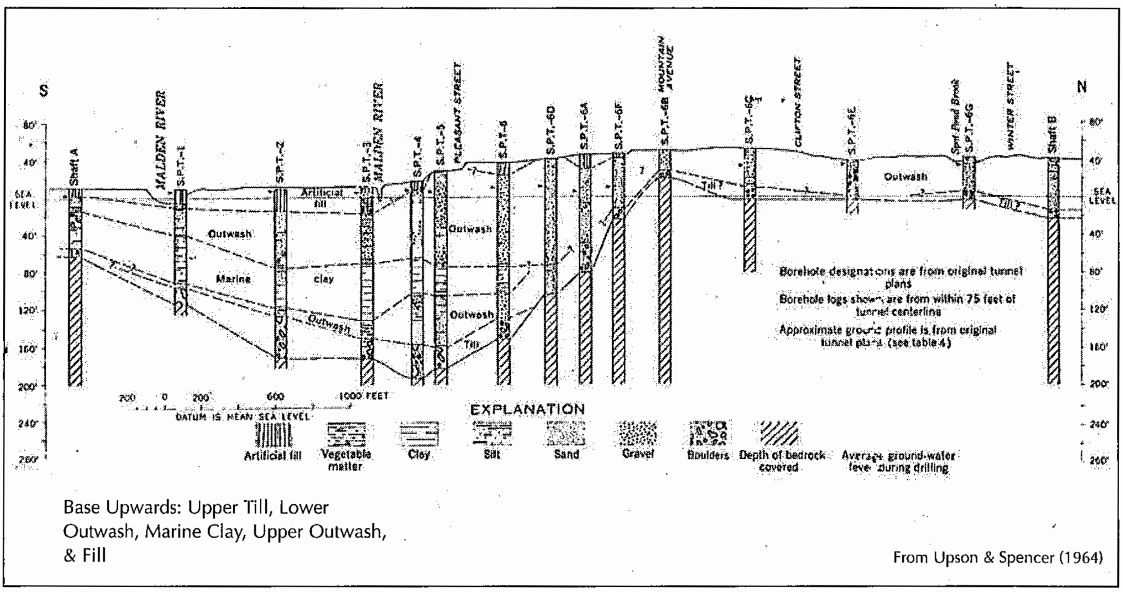

FIGURE 3-104. Section along the Malden (Spot Pond Flood Control) Tunnel (view west), showing the buried Malden Valley.

together to form a low fan between the Malden and Mystic rivers that narrows toward Charlestown.

Rivers and streams that were incised earlier in the marine clay guided the deposition of the upper outwash around Boston. These rivers and streams were the forerunners of the present drainage system. A southwest-sloping tributary to the ancestral Charles River channel passes beneath the southeastern part of the Mount Auburn Cemetery where it cut entirely through the marine clay and was filled with sand and gravel while leaving thick clay and much thinner outwash beneath the present river just to the south. Another channel extends from the north between East Boston and Charlestown, and one passes beneath Fort Point Channel. The ancestral Charles River at one time may have continued eastward along the Narrows and President Roads ship channels. A small tributary of the Charles River flowed northwest across Back Bay (see Figure 3-100) from the west end of Boston Neck and then northeastward to the ancestral Charles River (Judson, 1949). Other smaller channels, which appear to radiate outward beneath the harbor, were probably early ones abandoned as the Charles River cut deeper. Some small outwash-filled channels in the marine clay cross Pleasure Bay south of Castle Island and the edge of Dorchester Bay, but few occur farther south (see Figure 3-68). Some thin clay lenses overlie the sand and gravel in these channels (Parsons Brinckerhoff, 2006a & 2006b) and seem to represent finer material left in river channels, local ponds or backwaters as the glacial source receded to the northwest. Sporadic sand lenses also occur in shallow channels over the marine clay as far southeast as Quincy and a small filled channel is found to the north, crossing between the drumlins on Deer Island. Thin lenticular sand also is found in East Boston. The outwash is generally missing between the channels in the harbor and the overlying organic deposit rests directly on the marine clay. The channel fills diminish and pinch out seaward due to both their original distribution and the result of later erosion.

The Lexington outwash represents the last glacial deposit found in many places in Cambridge and the Back Bay and is only slightly oxidized. In the Back Bay, the top of the underlying marine clay displays freeze and thaw features and has a few wind-etched pebbles that attest to the periglacial conditions at the time of the outwash (Judson, 1949). The outwash deposit is generally thin, rarely

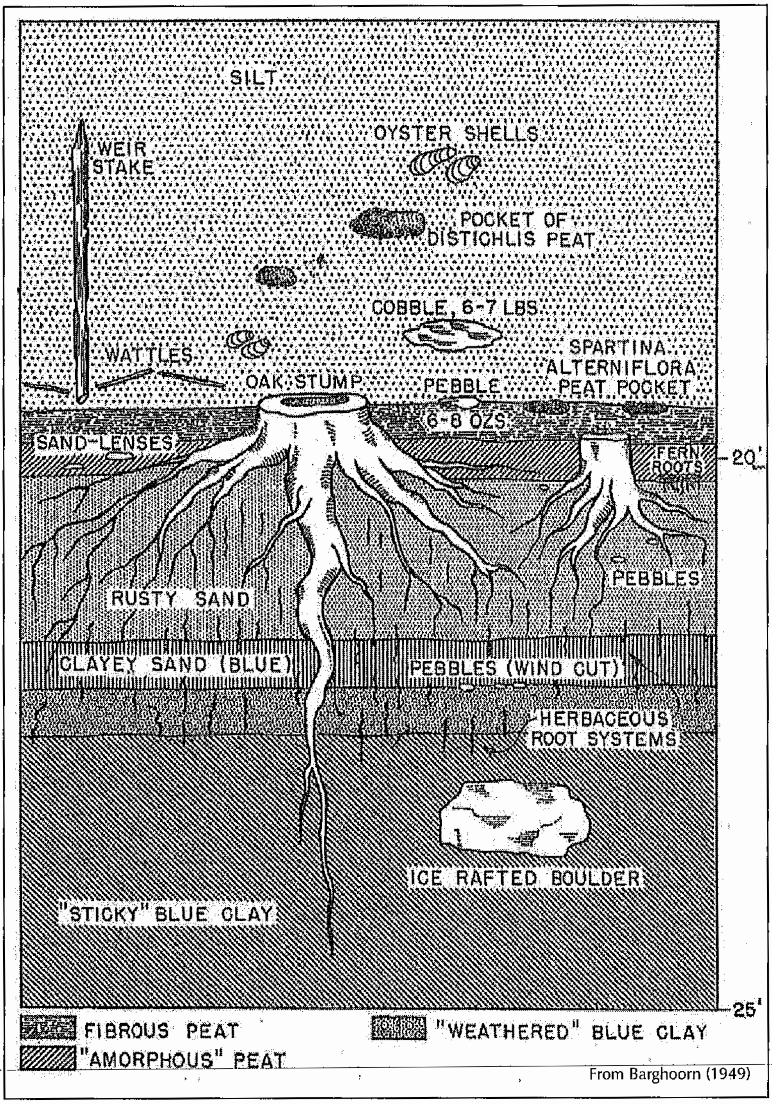

FIGURE 3-105. Diagram of the John Hancock excavation in the Back Bay showing the top of marine clay, the rusty sand of the upper (Lexington) outwash and the organic deposit with in-place tree stumps and other features. (Note that the top of the right-hand stump should have been drawn above the fibrous peat.)

exceeding 3 meters (10 feet), except in the ancient river channels. Along the Charles River in Cambridge, the sand and gravel is 9 to 15 meters (30 to 50 feet) thick, and upstream around Mount Auburn it varies from 2.7 to 26 meters (9 to 86 feet) depending on its relation to the buried channel. Along the Malden River the outwash is 12 meters (40 feet) thick (Judson, 1941; Upson & Spencer, 1964), but in the buried valley at Malden, the deposit is about 30 meters (100 feet) thick where it rests on eroded marine clay and locally on the lower outwash (see Figure 3-104); farther north it overlies till (Upson & Spencer, 1964). At least 3 meters (10 feet) of sand and gravel overlies the marine clay in Lynn (Sears, 1905).

The widespread sand and gravel in the Back Bay area is generally continuous west of Copley Square. It decreases in thickness eastward from near Massachusetts Avenue toward Dartmouth and Exeter streets. In the colonial era, this peninsula was appropriately called Gravelly Point and was centered at about Massachusetts Avenue and Berkeley Street. The thickness of these deposits is generally 3 meters (10 feet) or less, but it thickens to about 6 meters (20 feet) at the Christian Science Church Center, southwest of Copley Square. It is displayed as a thin, 0.3 to 1.0 meter (1 to 3 foot) thick layer of rusty sand in the John Hancock Tower excavation (see Figure 3-105) in the Back Bay (Judson, 1949; Barghoorn, 1949). Less debris-laden water eroded into the outwash as the glacial front receded, resulting in a patchiness of the deposit. This erosion continued in the Back Bay until it was reached by the rising sea and covered by organic deposits about 6,000 years ago. The rusty weathered top of the outwash may extend downward 0.5 to 1 meters (2 to 3 feet) and its surface may have some windblown sand, wind polished pebbles and frost disturbance (Judson, 1949).

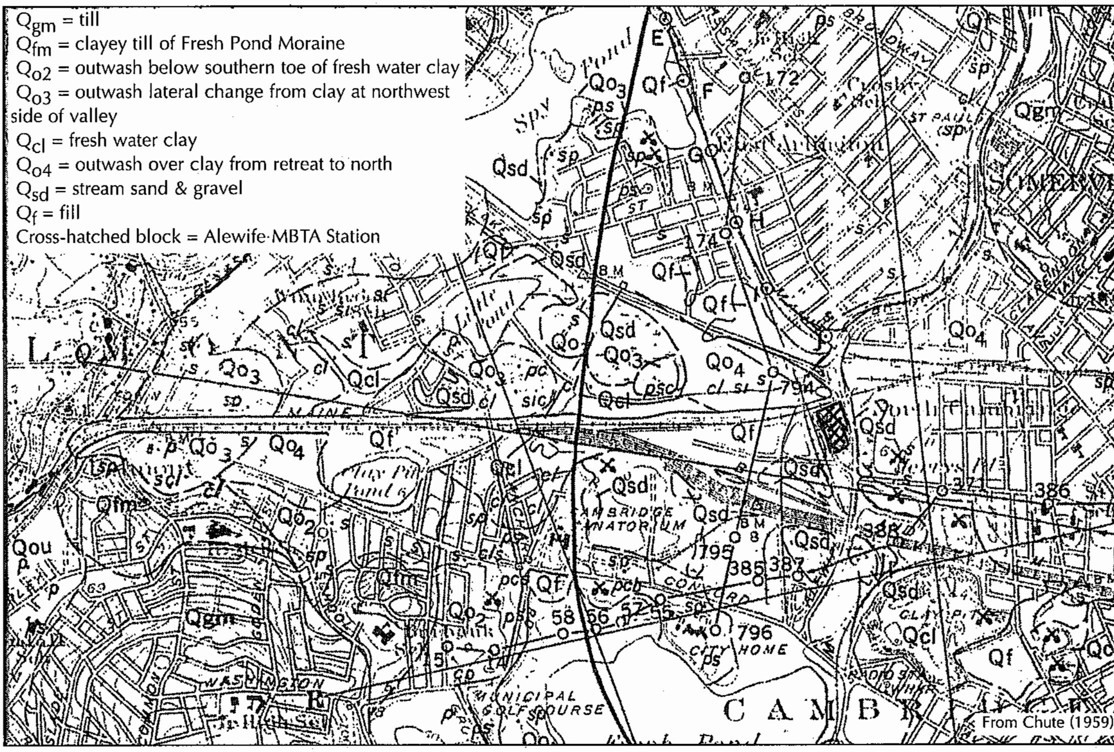

FIGURE 3-106. Map of Fresh Pond area showing freshwater clay deposit of the Lexington Substage.

Lake Clay & Capping Outwash Sand & Gravel. When the ice front of the Lexington Substage began to retreat, and shifted to the position of the Fresh Pond moraine, outwash sand and gravel partially buried the earlier Mount Auburn moraine (see Figures 3-101 & 3-102). Then, when ice further retreated to the Mystic Lakes area, the region behind the Fresh Pond moraine became a lake and filled with clay, which graded northward to deltaic sand and gravel outwash (see Figure 3-102). This younger clay deposit between the Fresh Pond moraine and the Mystic Lakes to the north served as the basis for a very extensive brick industry from the mid-1600s to 1923 (see Figure 3-106). The clay, as described by Chute (1959), is greenish medium-gray and similar to the older marine clay that covers much of the basin. It lacks varves and contains few interbeds of sand 2.5 to 30 centimeters (1 inch to 1 foot) thick. The bedding is generally horizontal but is locally disturbed from minor slumping or collapse as surrounded ice blocks melted. The clay is 15 meters (50 feet) or more in thickness. It rests on the moraine till of the Lexington Substage near Fresh Pond where it was deposited rapidly around ice blocks, which later melted to form the present ponds (see Figure 3-102). The clay grades northward into outwash sand and gravel, which lies about the Mystic Lakes and in the Mill Brook valley to the west. It is overlain by an outwash deposit formed during a later stand in the retreat of the ice front to the north.

Several geologists felt the clay could be either a lake or marine deposit. The clay contains both sponge spicules and plant spores (Knox, in Chute, 1959) that suggest deposition in a coastal embayment or estuary formed as the sea rose from meltwater over the still depressed crust. However, the clay is found in a basin only north of the Fresh Pond moraine and not other areas that would have been opened to the sea. No nearby shoreline features are found and no record of this inundation is found in the sea-level data. The top of the clay now extends to elevation 6 meters (20 feet) MSL (Chute, 1959). The Upper Lexington

Outwash was deposited subaerially at levels now beneath the sea level in the Back Bay. For the clay to have been deposited in an estuary, the sea level would have had to have risen quickly before ice blocks had a chance to melt and then just as rapidly fell. However, the sedimentary record in the Back Bay shows none of this activity. The sponge spicules might have been recycled from erosion of the underlying marine clay, which was disturbed and thrust when the ice lobe plowed into it. The distribution of the post-morainal clay, and lack of corresponding deposits and sea-level evidence, suggest that it is a lake deposit and, along with the overlying outwash, part of a normal terrestrial retreat sequence.

The clay is soft and sensitive around the MBTA Alewife Station in North Cambridge (GZA, 1978). The test borings found about 2.4 meters (8 feet) of miscellaneous fill overlying stratified sand and clay to 6 meters (20 feet). At this depth, soft sensitive clays were encountered to a depth of 24 meters (80 feet), where a very stiff yellow clay was found from 24 to 27 meters (80 to 90 feet) overlying the till layer of only limited thickness of less than 3 meters (10 feet) over the bedrock at about 30.5 meters (100 feet) deep. This sensitive clay is the equivalent of the reworked clay found elsewhere around the Boston area. While sampling the sensitive clay, thin 15-centimeter (6-inch) thick layer(s) of a stiffer clay that looked like BB to ¼-inch diameter sized balls of stiffer clay in a less stiff clay matrix were encountered in a few locations. This unusual clay likely represents the weathered top of the marine clay beneath the fresh water clay behind the Fresh Pond moraine.

The clay is covered to the north by an alluvial fan of outwash that extends from the Lower Mystic Lake and evidently formed when the ice front had retreated to that position as described by Chute (1959). It consists mainly of sand and pebble-sized gravel and grades to sand near its southern margin. It ranges in thickness from 9 to 12 meters (30 to 40 feet) at its north end to a few centimeters (inches) at the north side of Fresh Pond (Chute, 1959). The clay was laid down while ice blocks still remained at Spy Pond and nearby. These blocks later melted to form kettle holes.

The clay and capping outwash formed as the ice stagnated and the sea began its retreat after 12,000 years ago. The sea level fell quickly with crustal rebound following the Lexington Substage ice retreat. The limited clay and outwash form the last glacial deposits in the Boston Basin. The lake clay would be younger than the main part of the coastal clay in the Presumpscot Formation of the New Hampshire and Maine coasts. The Presumpscot Formation is estimated to date from 15,000 to 11,000 years ago by the Maine Geological Survey and would encompass an unconformity that represents a gap in time for much of the Lexington Substage. Logs and debris at the base of the Presumpscot Formation at Portland, Maine, yield dates of 11,750 and 11,900 years ago (Kilian & Nelson, 2008), and shells within it date at 11,720 years ago (Richards & Belknap, 2003). Plant debris in the Presumpscot along the Maine coast suggests rapid burial with marine regression from the area by 11,500 years ago (Anderson *et al.*, 1990). Paleo-Indians followed the retreating ice and established an extensive camp in Ipswich by about 10,000 years ago (Dincauze, 1996).

Holocene Deposits

Much of the Boston area was still high at the beginning of the Holocene about 10,000 years ago because of crustal rebound and was covered by a coastal forest as streams carried away some of the outwash sand and gravel. Coastal swamp sediments spread over the lower parts and gradually transgressed to be closely followed by marine sediment. This process continues today as marshes and estuarine sediments gradually extend inland. In addition, waters washed over the emergent marine clay to erode and re-deposit it in the lower channels being submerged in the rising sea. Much of the area of low deposits bordering Boston was then gradually covered by fill during urban expansion.

During this time, the Charles River gradually cleared a path to establish its present course. Because the pre-glacial drainage west of Boston generally flowed to the north and was blocked by the retreating glacier, a series of glacial lakes with lake clays and bordering deltaic deposits formed against the ice, such as in glacial Lake

Sudbury. Overflows from the glacial lakes gradually cut channels through the dams of outwash to drain the lakes south and eastward; at times this draining occurred catastrophically. The flow along the Charles River then slowed when the glacial lake at Concord drained and much of the rivers' headwater was diverted to the north into the initial Sudbury and Concord rivers (Koteff, 1964b; Barosh, 1999d). This process was very dynamic, with the rivers shifting their courses as lower outlets opened up and pre-glacial valleys were uncovered (Clapp, 1902). The valleys of the Charles and other rivers became well established in Boston and received sediment from the eroding marine clay as they began to fill with organic sediment.

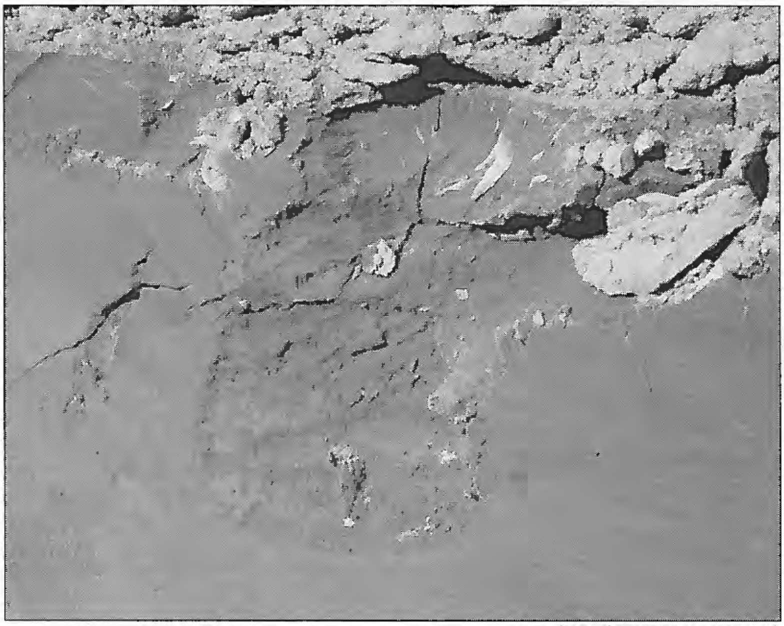

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FIGURE 3-107. Reworked clay over the weathered top of marine clay. (Photo courtesy of Bradford Miller.)

Reworked Marine Clay. The drop in relative sea level at the end of the Pleistocene resulted in the marine clay being progressively exposed to wave-base erosion and later to subaerial erosion. Much of the clay blanket was eroded, particularly at higher elevations. The clay was stirred back into suspension by wave action, and turbidity currents moved it downslope into closed depressions on the floor of Boston Harbor and Massachusetts Bay. These clay-filled depressions are seen in numerous profiles throughout the Boston area, including those for the Central Artery/Tunnel Project. The deposition of reworked clay apparently continued well into post-glacial time. Further oxidation of the exposed top of the marine clay likely occurred at this time. The clay is similar in appearance to the marine clay (see Figure 3-107) and may locally contain a basal layer of sand and gravel in channel fillings (Kaye, 1981). The clay is sometimes found to be somewhat sensitive and has a higher natural water content than the older more-consolidated clay.

These clays are found widely in the estuary systems of the lower Charles, Mystic, Malden, Aberjona, Fresh Pond and Neponset rivers (see Figure 3-1). These rivers are considered by Upson and Spencer (1964) to essentially follow buried valleys. Some till and outwash sand occur locally with the clay. The clay also is found in the lowlands separating Charlestown from Somerville and East Cambridge, and in the Fort Point-South Station area. The reworked marine clay, which reaches a thickness of 21 meters (70 feet) in the Fort Point Channel and almost 24 meters (80 feet) in the Logan Airport area, is (with the exception of Fresh Pond) not sensitive and has a higher natural water content than the older more-consolidated marine clay.

Organic Silt & Peat. An organic deposit consisting of both fresh water and salt water peat, and organic silt and clay, is found in the present and former tidal flats, estuaries and coastal lowlands that flourished along the margins of what was then the Back Bay and the Mystic River, that were at that time more restricted than today (see Figures 1-16 & 1-17). These marsh and tidal deposits gradually extended onshore and thickened as the sea level rose following the Lexington Substage. It is of particu-

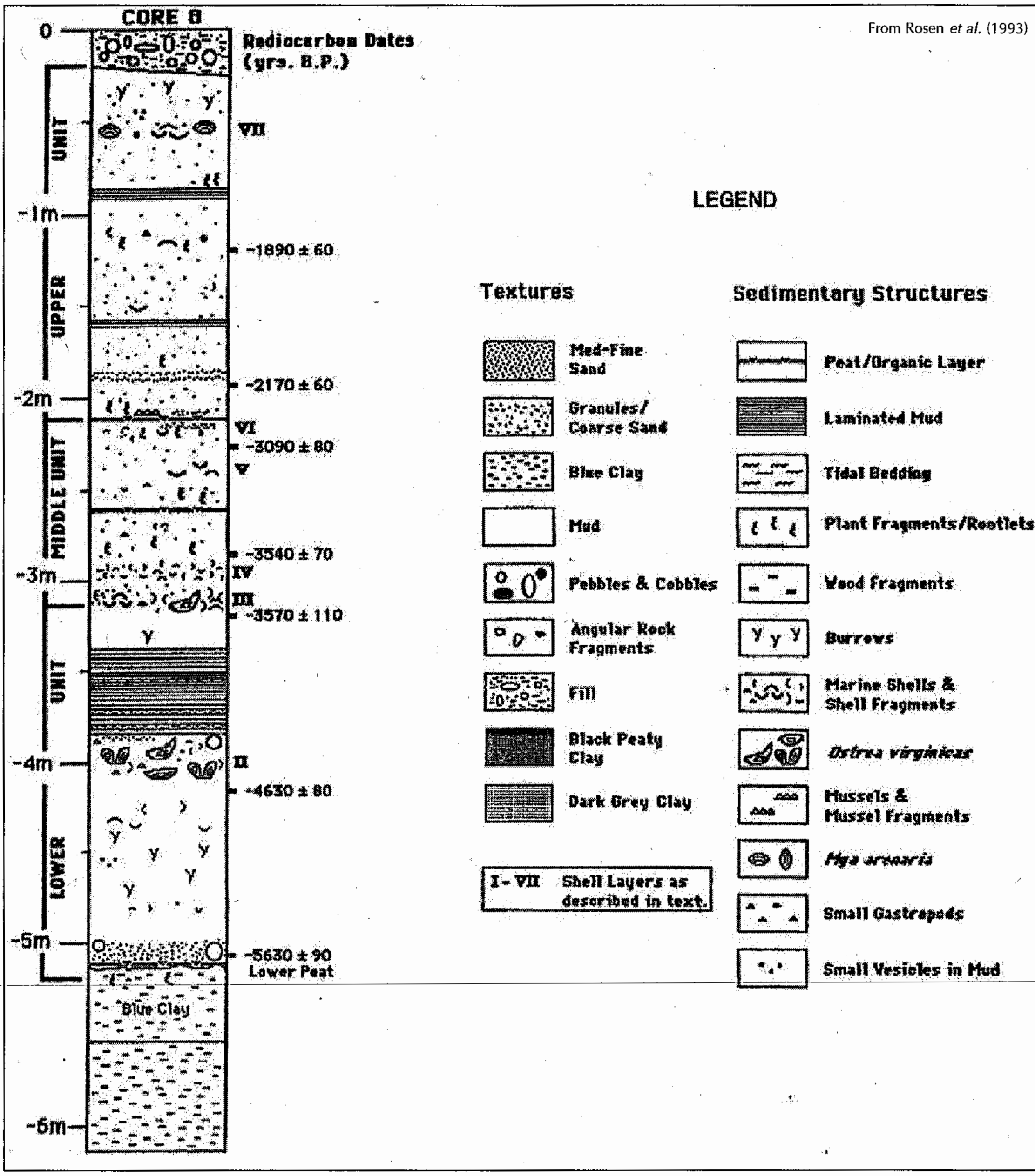


FIGURE 3-108. Columnar section of the organic deposit at 500 Boylston Street, Back Bay.

lar interest that Indians were established in Boston and building fishweirs while the deposits accumulated (Boston Transit Commission, 1913). The sediment grades shoreward into more typical alluvium, and toward the channels of the Charles and other rivers it becomes coarser, but it may grade into the reworked clay in places. The deposit ranges from a feather edge up to a total thickness of 12 meters (40 feet) in the channels. The organic silt usually overlies marine clay, but silt also is found above outwash sand and, in some cases, till. A recent saltwater or brackish estuary peat, usually less than 1.5 meters (5 feet) thick, is found locally on top of the organic silt, as well as the extensive fill placed around the city. The thickness and nature of the organic deposit is determined from the many test borings made for the numerous structures built on, or over, the wetlands and from the many foundation caissons that were augured through it and belled at the top of the underlying marine clay.

The deposit is best known in the Back Bay where it was encountered in early subway construction along Boylston Street and has been extensively studied (Boston Transit Commission, 1913; Johnson, 1942, 1949a & 1949b; Rosen *et al.*, 1993). Dark-gray to black organic estuarine and marine silt with low plasticity, and organic clay and fine sand were deposited on top of a basal fresh water peat layer and usually beneath a capping peat (see Figure 3-105). The basal peat and tree stumps, as well as ancient Indian fishweirs, have been found in excavations at levels from 5 to 7.5 meters (15 to 25 feet) or more below present mean sea level. The organic sediment, which smells of hydrogen sulfide (H_2S), also contains methane, and is highly fossiliferous with plant fibers and traces of wood as well as remnants of oyster banks predominantly composed of whole or parts of shells belonging to the species *Venus mercenarius*. Some oyster shells reach 25 centimeters (10 inches) in length and 1 kilogram (2.25 pounds) in weight (Boston Transit Commission, 1913). The stratum rests on the marine clay (see Figure 3-105) that generally has a thin, 0 to 1 meter (0 to 3 foot) cover of rusty upper outwash sand that supports tree stumps locally (Barghoorn, 1949). The organic deposit is laterally variable, but was found by Rosen *et al.* (1993) to be divisible into three units by subtle lithologic changes at the 500 Boylston Street building site (see Figure 3-108). Pond sediment and woody peat forms the base of these post-glacial organic deposits that spread over Back Bay. Dark gray to black, generally fibrous peat, which ranges in thickness from less than 0.3 to 1.5 meters (1 to 5 feet), is made up of decaying plants and wood formed over the clay and outwash and sometimes interfingers with dark silt and silty sand of the channels in a complex manner. In some places, peat about 0.3 meter (1 foot) thick is found totally decomposed and appears similar to diatomaceous earth. This decomposed peat is sometimes identified as *fine-grained peat* and has water content greater than 500 percent, according to Woodhouse. Diatomaceous earth is sometimes encountered at the bottom of the peat layer. Above this layer is an unweathered light greenish-gray to dark-gray marine silt in thin horizontal beds. Its thickness in most places is between 3 and 7.5 meters (10 and 25 feet) and probably does not exceed 12 meters (40 feet) (Judson, 1949). Locally, it contains great numbers of the stakes and wattles of fishweirs. A trace to 1 meter (0 to 3 feet) of dark-gray to gray-brown peat with local silt and sand tops the unit in many places. It is a saltwater unit, except for a freshwater facies found locally at the base, and occurs widely beneath the tidal marsh deposits of colonial Boston. Measured sections of the organic deposit (Rosen *et al.*, 1993) just west of the John Hancock site are about 5 meters (16.5 feet) thick, with their bases at about –6.8 meters (–22 feet) MSL in elevation. At the nearby John Hancock site, the base ranges from elevation –7.6 to –8.8 meters (–25 to –29 feet) MSL (Judson, 1949).

Dark-gray silty sand to sandy silt with organic material is also spread over the marine clay onto the east and north sides of Boston, reaching into East Boston. Its upper distribution limit lies near the 1630 shoreline (see Figures 1-16 & 3-109). Along the Central Artery O'Neil Tunnel on the east side of the Shawmut peninsula, the onlapping cover of organic sediment is 3 to 6.1 meters (10 to 20 feet) in thickness and increases northward to 10.7 meters (35 feet) beneath Causeway Street before thinning again (see Figure 3-110). The deposit intertongues offshore with lenses of less organic and coarser material, which covers extensive areas in the harbor (see Figure 3-111). The organic deposit borders the harbor in East Boston and Dorchester and has many interbedded sand lenses (Parsons Brinckerhoff, 2006a & 2006b), which apparently represent small banks from tidal currents or thin beach deposits. The black carbonaceous variety in the harbor is of concern in that it commonly contains trapped gases, which makes it very soft and compressible (Hughes & Edmunds, 1968). The normal thickness of the organic deposit is less than 4.5 meters (15 feet), but reaches 6 meters (20 feet) in the Dorchester Bay area and is thickest in the Neponset river channel (Hughes & Edmunds, 1968). At Nut

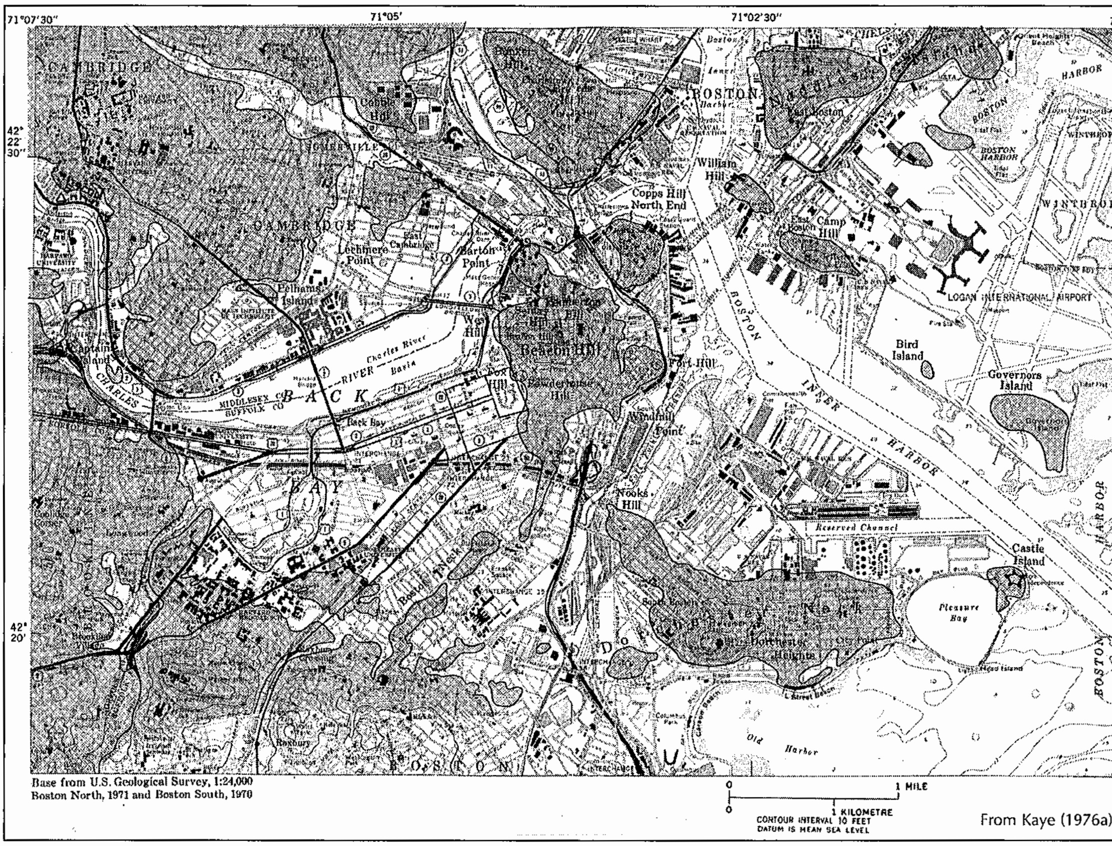


FIGURE 3-109. Map of the Boston area showing the mean high tide shoreline as it probably existed in 1630, on the basis of sub-surface, surface and historical data superimposed on the modern extent of greater Boston.

Island, it consists mainly of inorganic silty sand and is over 9 meters (30 feet) thick locally. The organic deposit overlies the yellow crust of the marine clay along the southwest shore of Deer Island and pinches out at its south end beneath sand and gravel, which is apparently a recent beach deposit (Goldberg-Zoino Associates, 1983). No definite organic deposit is known on the island. The thin patchy peat found (Metcalf & Eddy, 1990a & 1990b) could represent a local swamp deposit, and the patchy organic sediment and thin sand and sand and gravel over the marine clay found east of the island also may be younger deposits. The organic material was deposited adjacent to the shore and no organic deposit has been recognized between the southern tip of Deer Island southward to Nut Island where some organic sediment and associated sand are present (see Figure 3-89).

The original thickness of the organic deposit was much greater, but it has been reduced by autocompaction brought on by its weight and then been highly compressed by fill over the lowlands as the city expanded. The fill acted as a surcharge that caused primary and secondary consolidation. The top of the sediment is about 2.75 meters (9 feet) above sea level at the fringes of the Back Bay and on Gravelly Point (Massachusetts Avenue). However, where the deposit is thickest in central Back Bay, the top elevation has been reduced to about –1.5 meters (–5 feet) MSL by compression from fill; in places the deposit has a thickness of only 0.3 meter (1 foot) or less.

The falling relative sea level as the land rebounded after the Lexington Substage had caused the Back Bay to emerge as a poorly drained swamp forest and meadowland, dotted with shallow ponds, and with a low, drier

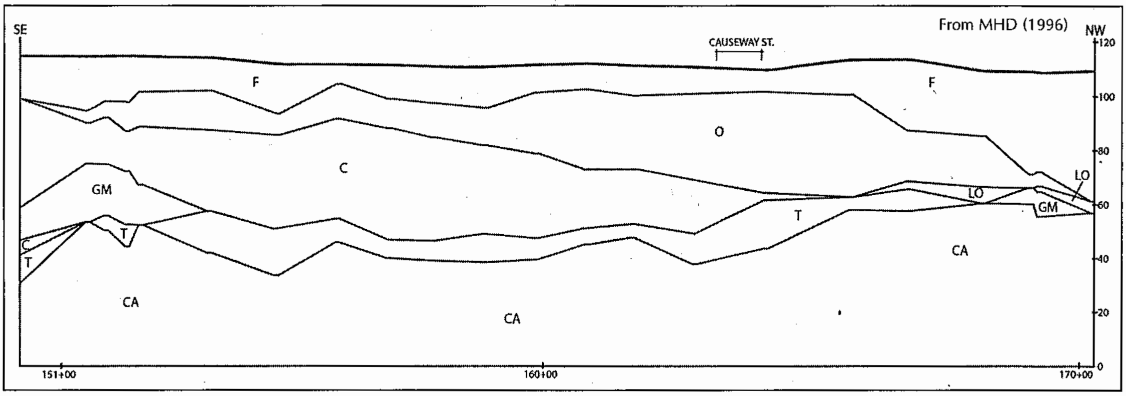
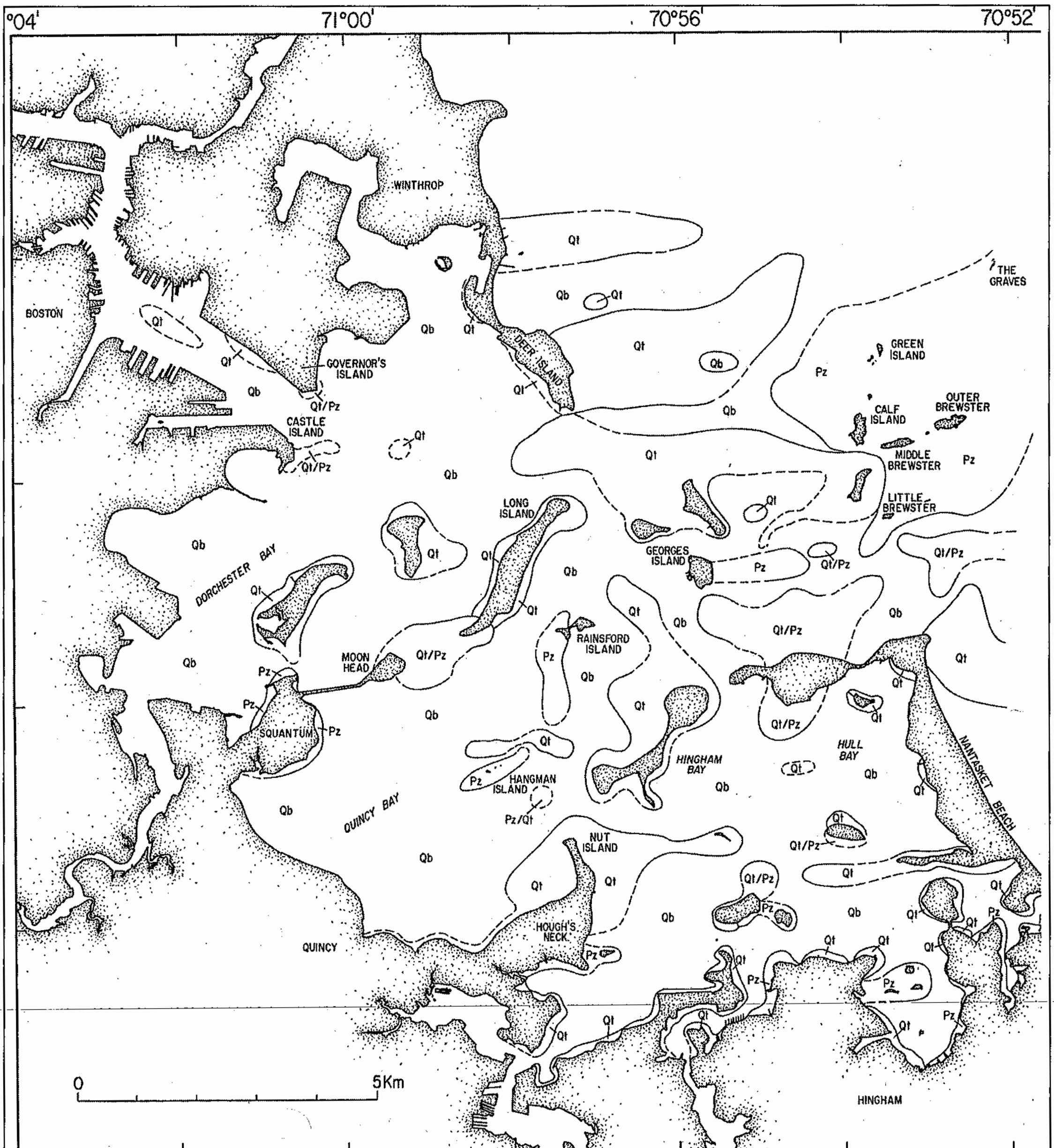


FIGURE 3-110. Simplified section along the northern Central Artery Tunnel, New Sudbury Street to North Station, showing the distribution of the organic deposit on the side of the early Charles River channel in the marine clay (west tunnel wall between Stations 150+00 and 170+00).

terrace rising in the central section. This terrace is now overlain, in part, by the Prudential Center and adjacent Massachusetts Avenue. The sea then began a slow rise about 8,500 years ago (Stuiver *et al.*, 1978). The forested, riverside land of the Back Bay and other low areas foundered slowly under the spreading estuary when the rebound slowed and was surpassed by the rising sea fed by melting ice to the far north. The oak and swamp maple trees were killed and the stumps were covered by peat, which formed in a freshwater swamp that soon changed into a marine marsh by about 5,650 years ago (Barghoorn, 1949; Rosen *et al.*, 1993). This change from swamp forest to grass-sedge-cattail swamp, freshwater pond to salt marsh to brackish water, and possibly estuarine to shallow marine environments occurred very quickly and is recorded by microfossils (Wilson, 1949). The continued flooding of the estuary resulted in the peat being rapidly buried by bay mud that was rich in marine life. Extensive fishweirs were built in the rising tidal flats over a period of about 1,500 years between 5,300 to 3,700 years ago, but after that the rise of the sea increased the rate of currents and ended this type of fishing (Decima & Dincauze, 1998; Newby & Thompson, 1994).

A northern type of mixed forest and climate similar to that of the present day in the region is indicated by the wood used in the weirs and pollen in the basal peat and associated sediment (Barghoorn, 1949; Wilson, 1949; Decima & Dincauze, 1998). The foraminifera found in the silt above also appeared deposited under conditions similar to those which now exist in the shallow marine waters of lower salinity from Portsmouth, New Hampshire, to Long Island Sound (Phleger, 1949). The diatoms suggest a possible upward cooling of the temperature at the time of silt deposition and the fewer diatoms present higher up might indicate a stronger tidal disturbance (Conger, 1949).

The climate represented during the peat deposition was thought to be that following the climatic or postglacial optimum, which is estimated to have taken place very roughly between 5,000 and 7,000 years ago by Wilson (1949) and others. However, they were using early radiocarbon dates, which have been improved since. Kaye and Barghoorn (1964) later recognized the difficulty of using the peat in dating because the autocompaction tended to push the younger wood fragments down into the older wood. The few warm-water foraminifera present in the silt are thought to represent detached segments of Gulf Stream water (Phleger, 1949), but others consider the climate was slightly warmer then (Johnson, 1949a & 1949b). The shelly fauna provides the best indication of the optima. Shells were identified early from dredged spoil presumably from the organic sediments from the Charles River at the Harvard Bridge and off City Point, South Boston, and from



DESCRIPTION OF MAP UNITS

Qb Undifferentiated Marine and Estuarine Sediments (Holocene)--Recent marine deposits consisting mostly of silty clay to clayey silt sediments which may locally contain gravel, shell and shell fragments, organic deposits and sand. This unit may be up to 5 m thick. Deposits are thought to be locally derived from the winnowing of glacial deposits during the last rise of sea level. These deposits may be locally overlain by estuarine deposits found mostly in quiet water embayment areas

Qt Glacial Drift (Pleistocene)--This unit consists primarily of a compact, dense till inferred to have been deposited during the Illinoian stage of glaciation about 80,000 years ago. The upper surface of this unit may show extensive weathering as evidenced from exposures on many of the drumlin islands in the harbor. This unit may locally crop out at the sea floor where it may be recognized by extensive lag deposits of cobbles and boulders covering the surface of the sea floor

Pz Bedrock (Paleozoic or older)--A complex suite of sedimentary and volcanic rocks which were deposited during the Proterozoic and Cambrian. Outcrops along the sea floor, harbor islands, and adjacent shoreline are localized and consist primarily of Cambridge argillite which may be cut locally by dikes and sills of diabase

Qt/Pz Undifferentiated Glacial Drift/Bedrock--Exposures along the harbor seafloor which are unable to be differentiated by major seismic reflectors or sidescan sonar patterns

—— Contact--dashed where approximately located or inferred

From Rendigs & Oldale (1990)

FIGURE 3-111. Map of the Boston Harbor showing bottom lithology interpreted from a sub-bottom acoustic survey.

deposits in place near Muddy River in Brookline. Twenty-one of a total of fifty-one species identified are more southern ones, which now are found south of Cape Cod and indicate a period of slightly warmer water than at the present (Upham, 1893), which subsequent studies have confirmed (Shimer, 1918; Clench, 1942; Nelson, 1942; Lindquist, 1942). The large oysters present appear to indicate optimum conditions for their growth.

Wind-Blown Sand & Silt. Patches of wind-blown sand and silt occur in many areas in the upland valleys around Boston and probably in the city as well. These deposits are commonly only a 1 meter (3 feet) thick and are easily overlooked beneath the soil. They are aeolian deposits that formed thin blankets or small dunes in the windy times following the Pleistocene and, at places, have associated wind-carved, sand-blasted stones called ventifacts (Woodworth, 1894a). They also frequently contain frost-heaved cobbles and boulders.

Shore & Harbor Sediment. Beach and near-shore sand and gravel, residual boulder gravel, and lagoon silt and peat have accumulated to some degree around the shores of the islands and mainland within the Boston Harbor and the ocean front. This variety of sedimentary environments within Boston Harbor has been delineated by side-scan radar surveys (see Figure 3-112) by Knebel and Rendigs (1991).

Extensive tidal marshes still exist along the Neponset River in Dorchester, a section of Boston bordering Quincy to the south, and in East Boston in the inner fringes of the harbor (Davis, 1910). They previously had been very extensive in the Charles River estuary, as in the northwestern Boston Common (see Figures 1-16, 1-17 & 3-113). Some of the marsh deposits may grade from organic sediment. Stumps of trees have been observed in the Wellington marsh along the Mystic River and in the Revere marshes to the north (Judson, 1949), and many more are seen off Nahant and along the coast to the north (Sears, 1905). Peat buried near the shore or offshore shows in places a similar change from a freshwater to a saltwater environment similar to the base of the organic deposit. Many more wide marshes are found north of Boston where early ditches and dams were built across them to lower the water level for salt-marsh haying in the past. Boston's low-lying areas were drained. (The draining used technology developed in England under Cromwell, apparently for malaria prevention Many of the early settlers of Boston, Massachusetts, came from that area in England.) Massachusetts' marshes have been narrowed by erosion and sea-level rise. It is not unusual to find peat from a marsh offshore of barrier beaches, north and south of Boston, where the sand has moved inland over the marshes (see Figure 3-114). In addition, the marshes have been narrowed on their landward sides by fill and development, especially around Boston.

Within the harbor, the sediment mostly came from the wave erosion of drumlins and from reworking the debris by waves and along-shore currents, but on the outer beaches offshore material is carried in as well (Knebel *et al.*, 1992). Erosional areas are found near the shore in large channels, atop submerged ridges and around the rocky islands across much of the harbor entrance. Also, there is reworking of sediment from variable currents in adjacent transitional areas. Organic sandy and clayey silt is accumulating in broad low areas at rates ranging from 4,000 to 46,100 metric tons (4,409 to 50,817 tons) per year.

The erosional rate is largely reflected in the rate of shoreline change, which is about –0.1 meter (–0.33 foot) per year in the greater Boston region (Hapke *et al.*, 2010), but locally this rate is highly variable. Residual boulder fields and coarse lag gravels may be left in front of drumlins after the fines are winnowed out, and may preserve their original outline (see Figure 3-79). Well sorted beach sand accumulates along the more exposed reaches in places and may enclose lagoons and estuaries in which organic sediment accumulates (Duffy, 1989). The type of deposit found is associated with an eroding bluff and has a geomorphic form, such as a spit, tombolo or before a lagoon that developed over time around the islands (Johnson & Reed, 1910; Colgan & Rosen, 2001; Rosen & Fitzgerald, 2004) besides spreading out on the harbor floor. Barrier beaches developed locally on the outer side of the harbor, such as Nantasket,

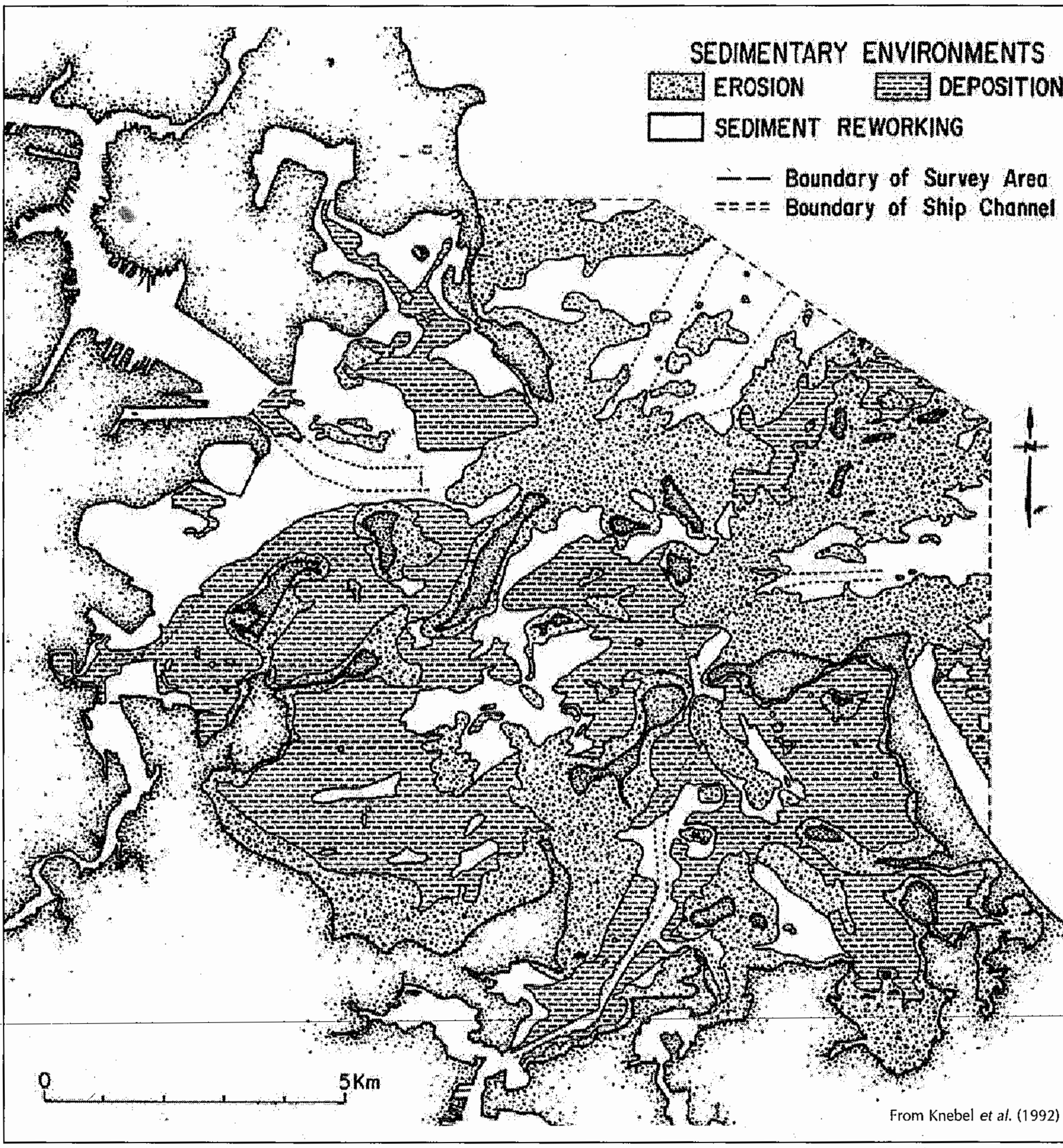


FIGURE 3-112. Map of the Boston Harbor showing present sedimentary environments.

under more active conditions (see Figures 3-73 & 3-111). The moved and sorted debris might form deposits such as the 1.5 to 9 meter (5 to 30 foot) thick layer present beneath the fill at the south end of Deer Island (see Figure 3-89) between elevation –3 and +3 meters (–10 and +10 feet) (Sverdrup, 1990b). It consists of loose to dense, brownish-gray gravel, sand and silt. Some older deposits from higher sea stands also are locally present. The lower deformed deposits of Beacon Hill are unconformably overlain up to an elevation of 10 meters (33 feet) MSL by undeformed beach sands (Kaye, 1982b), which is a little above the elevation of the eroded top of the marine clay here and the sands might possibly date from the time of the Lexington Substage.

This latest deposition in the harbor completes the Quaternary infilling of the harbor, except for fill around portions of the shore. The highly variable thickness of the Quaternary deposits reflects the described long histo-

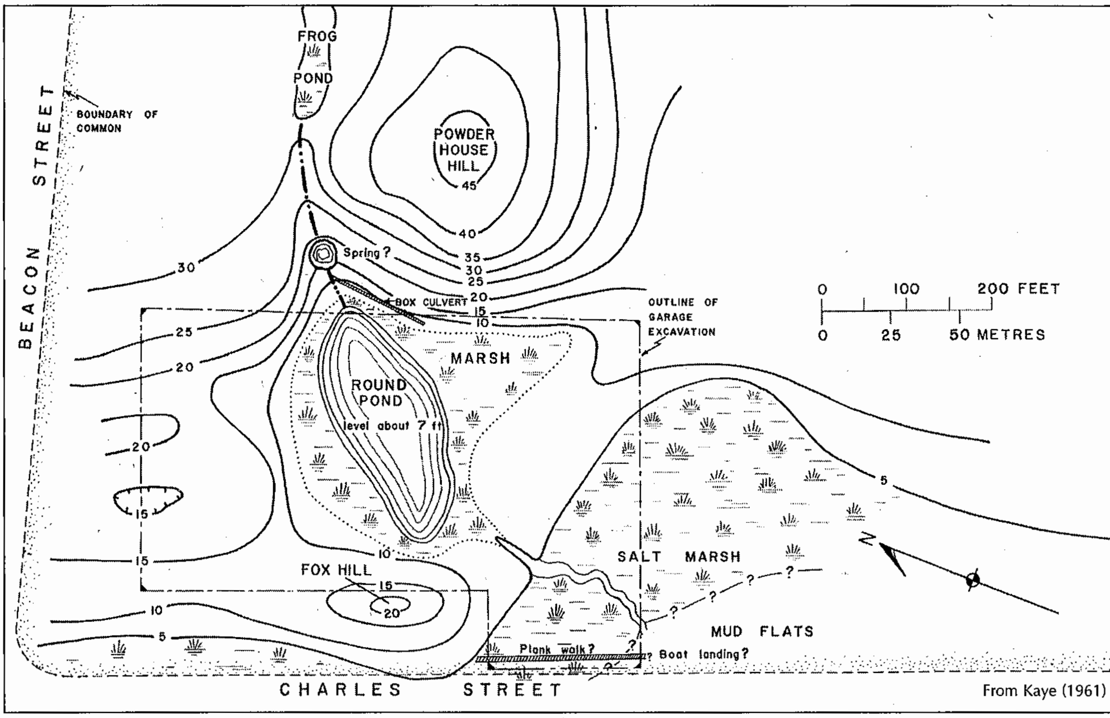


FIGURE 3-113. Site of the Boston Common Garage showing the reconstructed shoreline features of 1630.

ry of deposition and erosion in glacially scoured valleys and fault zones in the basin strata (see Figure 3-115).

Fill. Extensive filling expanded Boston from a small settlement on a peninsula into a major metropolis (Shurtleff, 1891; Whitehill, 1968). A very comprehensive and detailed description of this filling was presented recently by N. Seasholes in *Gaining Ground* (2003) and what follows is a very brief summary. When Boston was first settled, the town lay on a high-tide island, surrounded in many places by shallow mudflats. Most of these shallow areas were filled to provide land for the expansion as the town grew (see Figures 1-20 & 1-21) from about 715 acres (Seasholes, 2003) into a city (Aldrich, 1970). A record of the stages of filling is preserved in the city's somewhat confusing

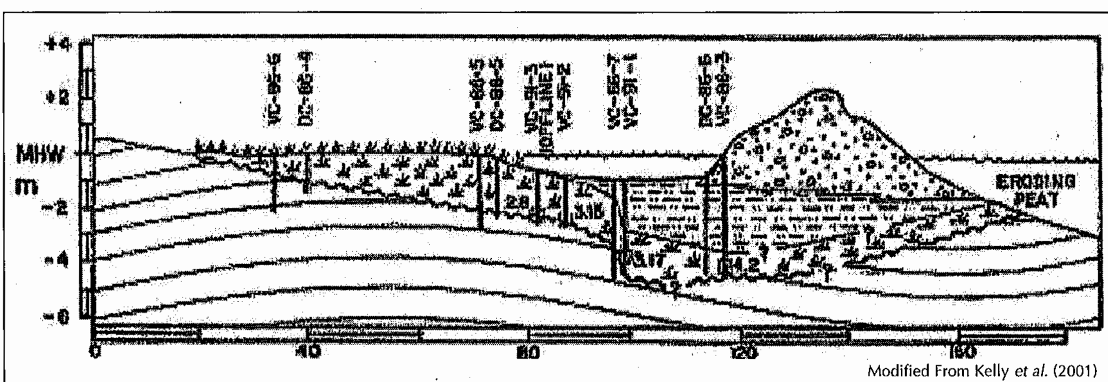


FIGURE 3-114. Section of a barrier beach (Jasper Beach, Maine, view northeast) showing the transgression of barrier beach sand over lagoon and marsh deposits.

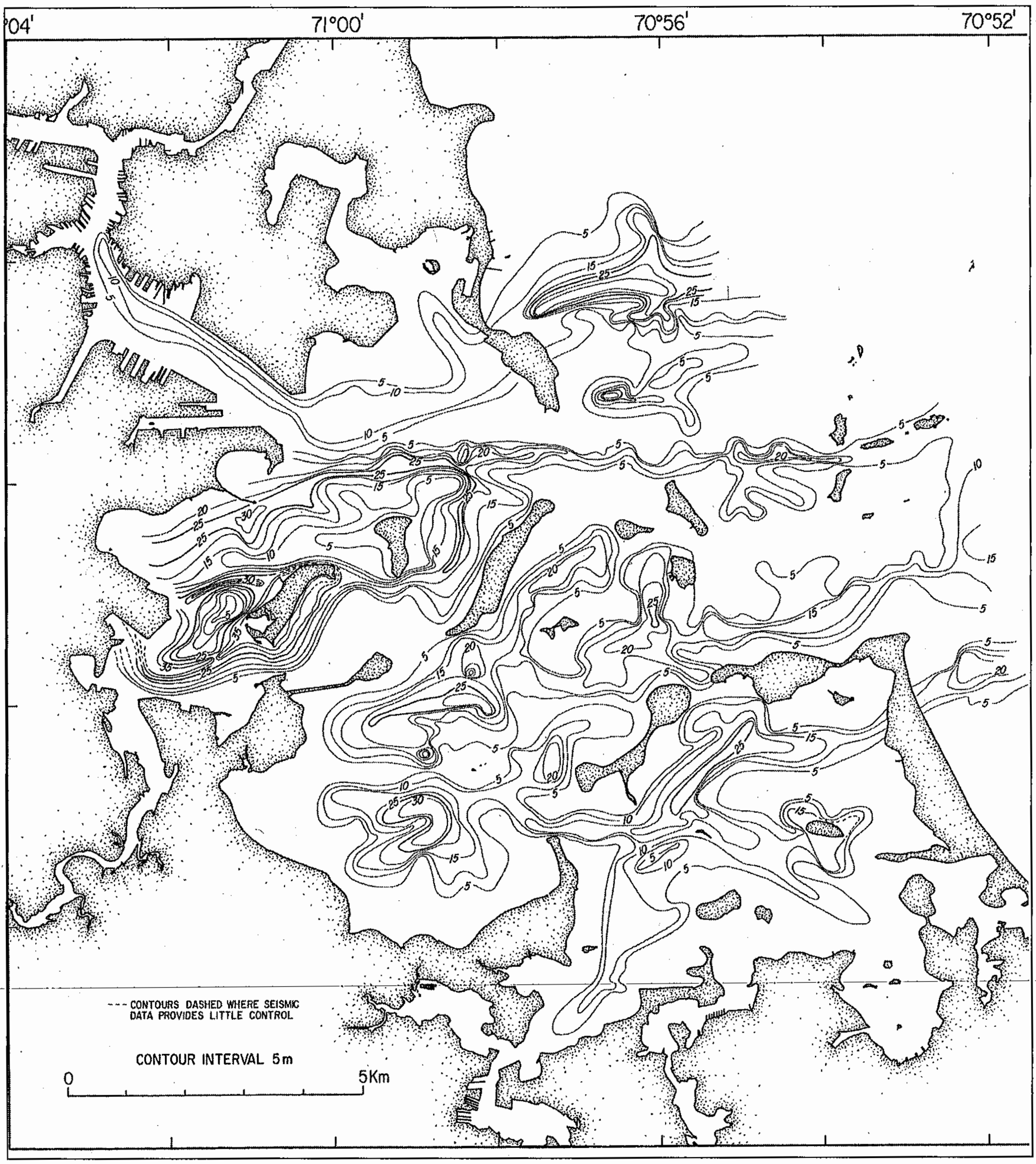


FIGURE 3-115. Contoured thickness of Quaternary fill in the Boston Harbor interpreted from a subbottom acoustic survey (Rendigs & Oldale, 1990), which reflects the acoustic basement and may not include all of the dense till.

street pattern because as each area was filled a new pattern of streets was usually laid out. A comparison of the areas of construction at different times with the original shoreline shows the history well. The variable thickness of fill used for the expansion creates an additional problem in building in the city.

Wharf expansion had been underway since the mid-1600s. Low-lying areas began to be filled in earnest in the late eighteenth century as Colonial Boston outgrew the limited area of the original peninsula. Initially, granular materials consisted of till and sand and gravel derived from the lowering of Trimountain

(West Hill, beginning in 1758 for Charles Street and continuing to 1830; Beacon Hill, beginning in 1807 for the Mill Pond filling; and Pemberton Hill in the 1830s for the railroads) and from lowering the ridge connecting Pemberton Hill and Beacon Hill in 1845 (see Figure 3-90). Fort Hill and other smaller hills also were used for the filling of the tidal areas of the city (see Figure 3-86). Because of the monetary incentives offered by the city, the waterfront areas facing Boston Harbor also were extended by stages using fill that is very heterogeneous. Pier and bulkhead construction over time added piles and granite caps as well as local granite seawalls (see Figure 1-11). Industrial waste, which may contain contaminants, was dumped in places, plus dredged material and demolition rubble.

The entire Back Bay area was a mud flat within the Charles River tidal estuary when it was enclosed in 1821 by the Boston and Roxbury Mill Dam. The dam was built to harness tidal power. It extended from Charles Street to Kenmore Square and was followed by what is now Beacon Street. Subsequently, two railroad causeways also were built across Back Bay, crossing at what is now Back Bay Station. These obstructions created stagnant water areas that eventually were filled in for development purposes. The Back Bay between Charles Street and the Fenway was filled in a massive program that lasted between 1856 and 1890. The early fill (pre-1856) locally consists of trash and cinders and mixed material for railroad embankments and dams. Most of the main fill material consists of clean sand and gravel, brought by rail from kame terraces and an extensive fan of outwash in Needham, Dedham and Auburndale about 14.5 kilometers (9 miles) to the west (Newman & Holton, 2006), since the sources of available granular fill within the city were almost depleted. After the construction of a tidal dam across the Charles River in 1910, which controlled the water level in the basin, fill was placed along the river embankment. Storrow Drive was later built just outside the margin of the 1800s fill and completed in the early 1950s (Haglund, 2003). Fill for the South End came from further lowering of Beacon and Copp's hills. Other sources of fill included cinders and coal ash (which were dumped throughout the city), street sweepings dumped in the Causeway Street area, hydraulic fill, dredged material and debris from the Great Fire of 1872. The heterogeneous nature of the fill in the city has been a cause of construction problems ever since.

On the Cambridge side of the Charles River, the tidal marshes were filled in behind a granite seawall, built about 1890 (Haglund, 2003), and the area developed, including Memorial Drive and the present campus of MIT. The waterfront areas facing Boston Harbor also were filled in stages by pier and bulkhead construction. By the beginning of the twentieth century, the filling of the waterfront in Boston city proper was essentially complete; however, filling of outlying areas — as in Dorchester, East Boston, South Boston, Charlestown and Logan Airport — has continued in stages to the present, using material from various sources (see Figure 3-116). Highway and expressway construction around the Boston area used large amounts of granular fill from the suburbs and New Hampshire. Albeit the road construction in central Boston used relatively little fill because the highways were usually in open cuts or raised on steel structures.

Late Pleistocene & Holocene Sea Level & History. The relative sea level fluctuated greatly as the Pleistocene and Holocene sediments were deposited. Water taken up as ice or released as meltwater, crustal depression or rebound from the addition or removal of the ice mass and tectonic movement all affected the relative levels of land and water. The interplay of these factors resulted in changing conditions in this coastal environment that both controlled the type of deposit and reflect its history. The sea-level changes in general can be inferred from the earlier deposits and the world-wide level has been rising since the last glaciation (see Figure 2-41). After 14,500 years ago the movement can be displayed by a sea-level curve. A sea-level curve, drawn back to 14,000 years ago, by Kaye and Barghoorn (1964), using sixteen radiocarbon dates (C14) from the Boston area, was revised by Oldale *et al.* (1993) for northeastern Massachusetts and extended to 14,500 years ago after the last ice sheet cleared the

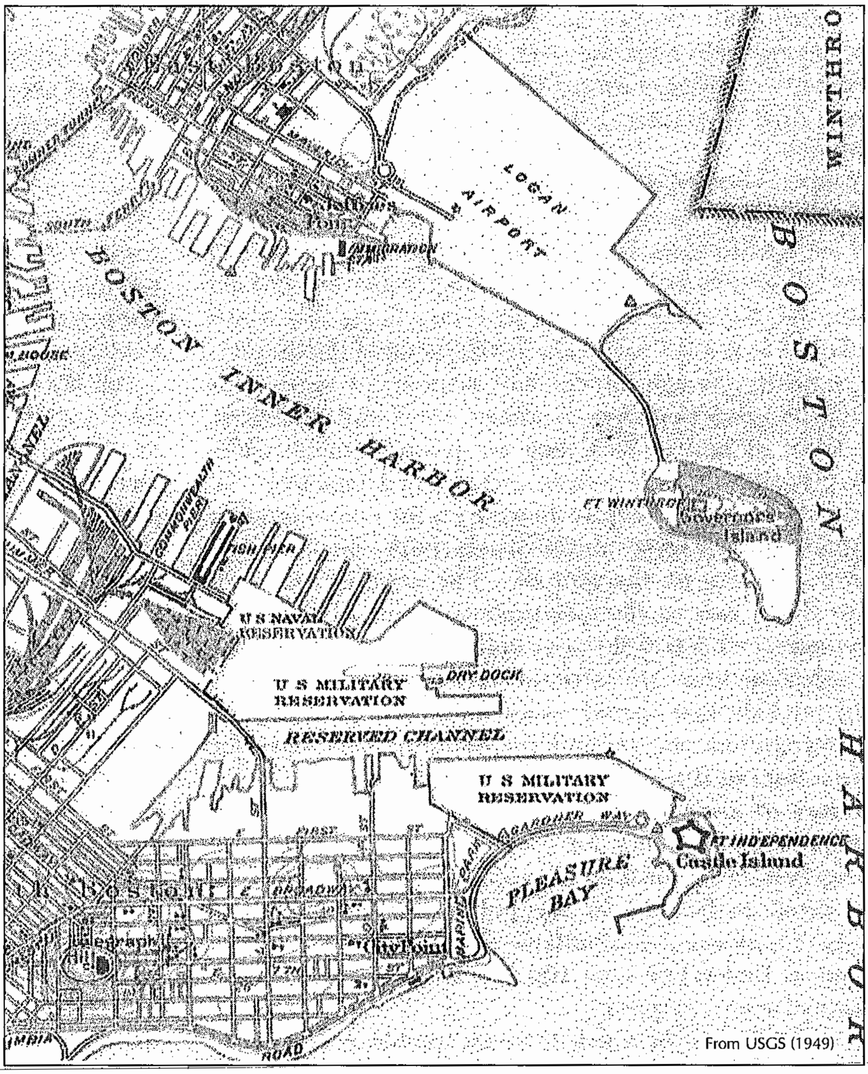


FIGURE 3-116. Map showing the extent of the fill for Logan Airport in 1946 and the excavation of the drumlin till forming Governors Island for fill prior to the present expanded airport.

Boston area (see Figure 3-117). The recorded changes in coastal Maine (Stuiver & Borns, 1975; Stuiver *et al.*, 1978; Barnhardt *et al.*, 1997; Kelley *et al.*, 2001) better reflect the retreat from the Lexington ice re-advance (see Figures 3-118 & 3-119) and can be used to temper a curve for Boston, as well as changes in marsh levels in eastern Massachusetts (Redfield, 1967; Donnelly, 2006).

The elevation and ages determining sea-level history need to be considered within their limits. The C14 ages have ranges, may have errors and are not always corrected. Elevation points commonly cannot be determined precisely and their lateral control varies because post-glacial rebound has produced a regional southerly tilt, which is commonly 1 meter per kilometer (4 feet per mile) in southern New England. Thus, the elevation of the same ancient shoreline at Boston is much lower than it is in Maine. Measuring changes from dating organic deposits in coastal marshes is extremely complex (Donnelly, 2006). Despite these limitations, meaningful sea-level curves can be constructed that are useful in presenting the Pleistocene-Holocene depositional history.

The region has been slowly subsiding from a combination of tectonic movements since the Mid-Cretaceous (Barosh, 1986a) and the depth of the buried river channels on the bedrock surface below Boston would partially reflect this action, in addition to changes due to glaciation and the more recent climate changes. The Tertiary drainage system indicates a low stand to perhaps as much as elevation –70 meters (–230 feet) MSL in Boston Harbor prior to the Sangamon interglacial period (circa 125,000 to 75,000 years ago) as rivers carved into the bedrock. The mouth of the ancestral Charles River channel extends deep to elevation –90 meters (–300 feet) MSL offshore of Dorchester (Kaye, 1982a), but some of this depth is probably the result of glacial deepening since no continuing channel this deep has yet to be found farther offshore in the mid-harbor. The sea level rose and was high during the Sangamon, when extensive clam flats covered much of the Boston Basin. The sea then retreated as the glacial ice advanced and the flats were torn up and incorporated into the lower till of the Beacon Hill Substage. When this ice melted, the sea returned and marine clay again capped this sequence. But the paucity of marine clay remnants and the general lack of marine shells in the later till, which incorporated them, suggests both the extent of the clay and the height of the sea were less than during the Sangamon. The sea level was drawn down again during the next glacial ice advance across the region when the retreat deposits were thrust and formed into the upper till of the drumlins of Beacon Hill and the islands.

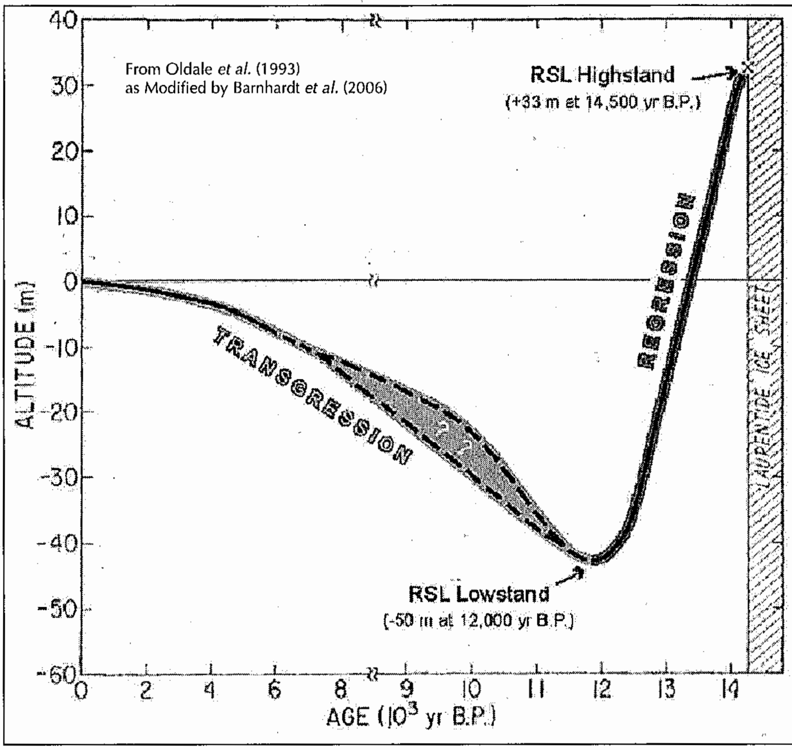


FIGURE 3-117. Late Quaternary relative sea-level curve for northeastern Massachusetts.

This second glaciation, the Boston Substage, was at its maximum south of Cape Cod at 21,000 to 20,000 years ago (Uchupi & Mulligan, 2006), when the sea level was again very low (see Figure 2-36). The ice wasted away and cleared Boston about 15,000 years ago, as glaciomarine debris accumulated above the till in the harbor area. This occurred while the sea level rose to near the present level relative to land, but still below the present sea-level elevation. The land then rebounded, causing the relative level to fall, and underwent moderate erosion, which cut channels down to at least to elevation –54 meters (–178 feet) MSL in East Boston. The lower outwash from the retreating ice front was deposited in the channels before the area once more slipped beneath the waves due to the influx of meltwater, and marine clay began to accumulate.

Relative sea level was at elevation +33 meters (+108 feet) MSL compared to the present sea level at 14,500 years ago (see Figure 3-117) following the Boston Substage and had dropped to a low stand at approximately –50 meters (–164 feet) MSL by about 12,000 years ago in northeastern Massachusetts (Oldale *et al.*, 1993). The high stand was probably lower close to Boston where the marine clay is found at lower elevations. A widespread erosional bench in Boston (Kaye, 1976a) and one on Nahant (Lane, 1888) at about 7.6 meters (25 feet) might reflect a sea level during the deposition of the marine clay. This clay, which was still being deposited 14,250 years ago by the radiocarbon dating of barnacles in the marine clay (Kaye & Barghoorn, 1964), was weathered and channeled as the sea fell and was unconformably capped by beaver dams by 12,200 years ago in the Boston Common. The drop

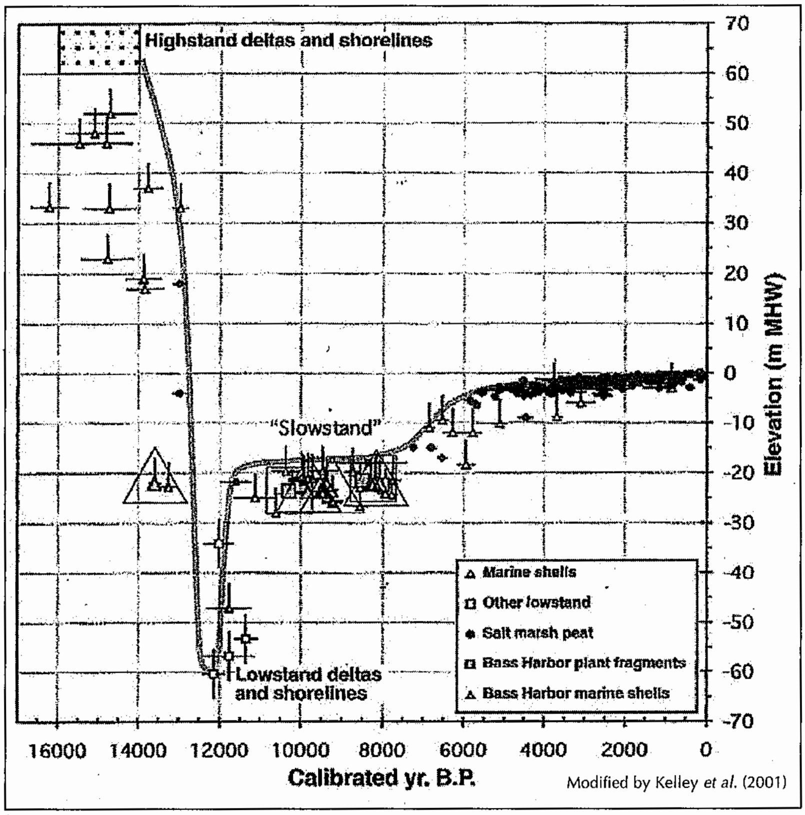


FIGURE 3-118. Late Quaternary relative sea-level curve for Wells, Maine. (Note that the horizontal scale is reversed from Figure 3-117.)

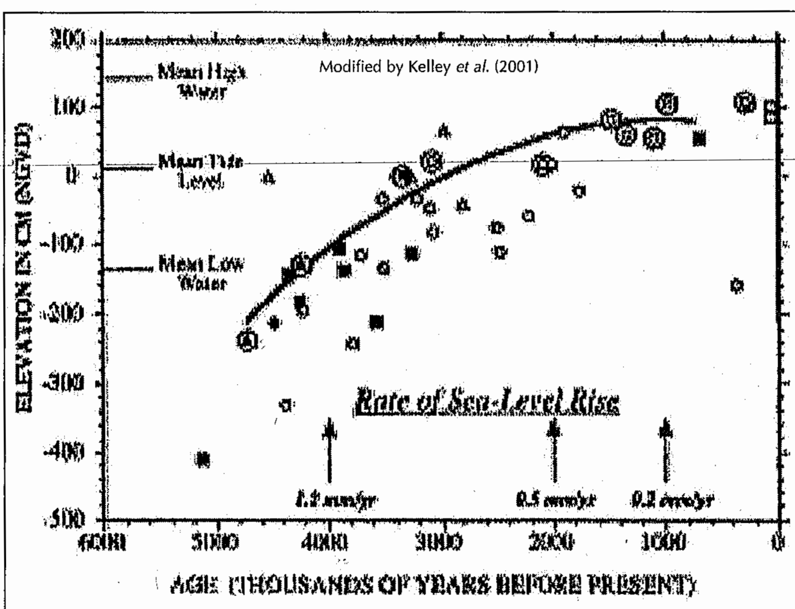


FIGURE 3-119. Late Quaternary relative sea-level curve for southern Maine.

was apparently due first to crustal rebound and then due to water being taken up as ice in the readvance of the Lexington Substage, circa 12,900 to 11,500 years ago, with some tempering by renewed depression of the crust due to the ice load. Channels, which then cut into the marine clay, were soon filled by an apron of upper outwash and Fresh Pond and Mount Auburn morainal debris.

As the ice front began to melt rapidly northward, the land rose quickly with rebound and the sea level relative to the present sea level again dropped. This lowering is described as occurring along the coast to the north where it dropped to –60 meters (–197 feet) on the Maine coast (Kelley *et al.*, 2001), where the crust had been more depressed and the rebound greater (see Figure 3-119). The glacial rebound, and consequent marine regression, along the New England coast was complete by about 11,000 years ago (Kelley *et al.*, 2001) or at least slowed to the amount of sea-level rise. The sediment resulting from the erosion of the marine clay was redeposited as Holocene marine clay in channels around Boston.

The sea level near Boston then rose steadily during the Holocene to approximately elevation –21 meters (–70 feet) MSL about 10,000 years ago, after which it may have remained about the same until 8,000 years ago. The rise was tempered somewhat by the possibility that the land was still rising slightly due to glacial ice load relief and subsequent rebound. The Back Bay was inundated by organic deposits at 5,650 years ago when the sea level was about elevation –6.8 meters (–22.4 feet) MSL (Rosen *et al.*, 1993). The extensive fishweirs found there record the rising sea level from 5,300 to 3,700 years ago (Decima & Dincauze, 1998). The sea rose to an elevation of about elevation –0.6 meters (–2 feet) MSL at approximately 3,000 years ago, after which it may have oscillated according to data of Kaye and Barghoorn (1964), and resumed rising steadily for at least the past two hundred years. However, studies of initial marsh deposits in Revere indicate that there was a rise in sea level of close to 2.6 meters (8.5 feet) in the past 3,300 years, with a possible decrease in the average rate of rise from 8.0 centimeters (3.2 inches) per century between 3,300 and 1,000 years ago to one of 5.2 centimeters (2 inches) century between 1,000 and the past 150 to 500 years (Donnelly, 2006). Changes shown by tide gauges, harbor structures, coastal rocks, extreme tides in great storms, in addition to many tree stumps found standing in salt marshes in the Boston Harbor and nearby coast, all demonstrate the rising sea (Davis, 1910; Sears, 1905; Woodworth & Wigglesworth, 1934; Johnson, 1942, 1949a & 1949b; Johnson & Raup, 1947). Marsh peat is found seaward of the beaches north and south of Boston and at Marshfield and Ipswich; farther south a low tide exposure of marsh clay forward of the beach even revealed wheel tracks and ox prints (Woodworth & Wigglesworth, 1934).

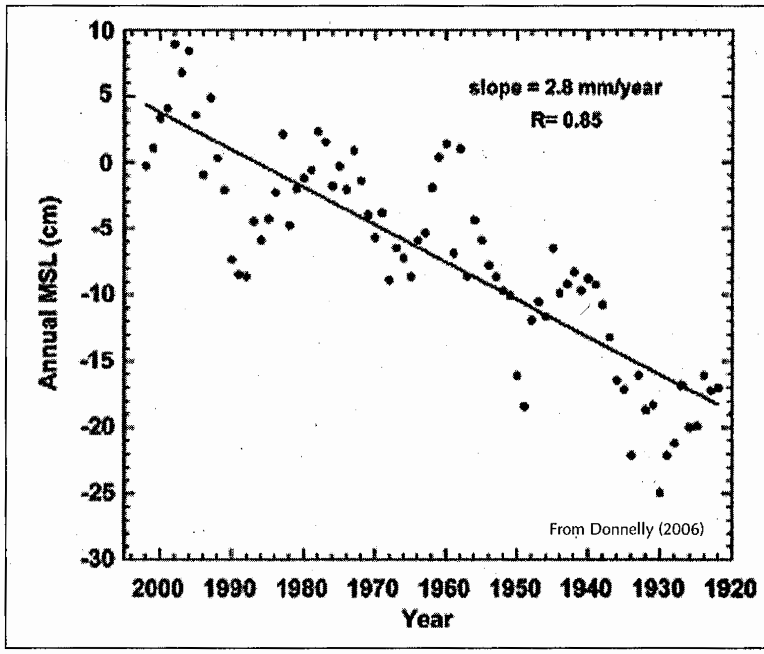


FIGURE 3-120. Tidal records for Boston Harbor between 1922 and 2002. (Note that the age scale is opposite that on Figure 3-119.)

The rise between about 1810 to 1902 in Boston Harbor is found to be 30 centimeters (1 foot) per century (Freeman, 1903). This rate is currently used by the Massachusetts Department of Coastal Zone Management and was earlier used to estimate the age of Holocene organic sediment in the Back Bay (Boston Transit Commission, 1913). Tidal records in the harbor between 1922 and 2002 show an average rise of 28 centimeters (0.92 foot) per century, but the rate of rise fluctuates (Donnelly, 2006). Between 1930 and 1937 the sea level rose at a rate of 61 centimeters (2 feet) per century, but it rose only one seventh that rate for the preceding 35 years (see Figure 3-120), yielding a variable rate between 8.7 and 61 centimeters (0.29 and 2 feet) per century (Marmer, 1948). But the rate in Salem Harbor between 1804-5 and 1894 was found to vary between 52 and 67 centimeters (1.7 to 2.2 feet) per century (Sears, 1905) and locally to the north it may be more (Barosh, 1986c). The rate of worldwide sea-level rise has remained relatively steady for the past 6,000 years at an average rise of about 18 centimeters (0.6 feet) per century (Howard, 2008) and is estimated to be rising now at a rate of about 30 centimeters (1 foot) per century, as measured by satellite since 1993 (Carpenter, 2008) and between 2003 and 2005 (UN, 2007). The sea-level rise for 1993 to 2010 offshore of Massachusetts, as measured by satellite, ranges between 1 and 3 mm (0.04 and 0.1 inch) per year, which equals 10 to 30 centimeters (0.33 to 1 foot) per century, and the global rise is about 3 mm (0.1 inch) per year (European Space Agency, 2012).

These different rates are not necessarily contradictions because the crust is moving as well as the sea level. Tectonic movements of the earth's crust cause both the world-wide and local relative levels to differ and even the local levels may vary over short distances. Kaye and Barghoorn (1964) considered that the rise was due in part to crustal subsidence that occurred in Boston from 6,000 to 3,000 years ago and may be still continuing. Once the formation and retreat of the glacial ice mass was complete, which caused the crust to depress and then rebound, other tectonic factors affecting relative sea level become more noticeable (see Figure 2-40), including a northerly downward tilting of the entire East Coast and local areas of subsidence (Barosh, 1986c & 1990a).

There are now vastly increased estimates of future global sea-level rise based on the thermal expansion of sea water from increased temperatures and findings of increased rates of melting of the Greenland and Antarctic ice caps. These two sources alone are calculated to have contributed 13 centimeters (5.2 inches) per century to the rise in 2006 (Rignot *et al.*, 2011). The estimates for the overall rise range from 18 to 59 centimeters (0.6 to 1.92 feet) (UN, 2007) to 90 to 160 centimeters (2.95 to 5.25 feet) (AMAP, 2011), or about 16.2 to 53.1 centimeters (6.4 to 21 inches) and 81 to 144 centimeters (32 to 56.7 inches) per century, respectively. These estimates come with the caution that a high uncertainty surrounds them and the measured rise has held about steady between 1950 and 2010 and has yet to reflect such high rates.

Geotechnical Factors in Boston

The geotechnical factors associated with Boston's complex soils and bedrock need to be understood to design and build suitable structures.

DAVID WOODHOUSE & PATRICK J. BAROSH

It is critical to understand the important geologic constraints of the various soil units and the geologic control for appropriate foundations, as well as the engineering properties of the overburden soils and bedrock and their influence on constructed facilities. The geotechnical factors associated with, and caused by, the complexity of the soils and bedrock underlying the Boston area include: bearing capacity (sometimes overestimated, leading to settlement), behavior of foundations in certain problematic soils, defining the rock/soil interface surface, the nature of the bedrock that can be soft as clay and groundwater conditions. (This discussion expands on a previous summary by E.G. Johnson and other workers at Haley & Aldrich, Inc., as well as Woodhouse [in Woodhouse & Barosh, 1991].)

Geologic Constraints

The Boston area is spared many of the geologic hazards of the type that plague other parts of the nation other than those imposed by occasional coastal storms accompanied by local flooding, and moderate earthquakes. Surface fault rupture, volcanism and land failure due to landslides, expansive soils or natural subsidence are unknown in the Boston area. However, when considering the geology of the Boston Basin and its influence on the development of Boston, it is seemingly paradoxical to discover that a large metropolitan area has flourished within a coastal basin where marine and glacial processes, in combination with significant past tectonic deformation, have produced one of the most geologically complex areas on the eastern seaboard.

The variable condition of the overburden and the complicated nature of the bedrock geology of the Boston Basin imposed limitations on urban construction that hindered the city's early development. Because of these conditions and the efforts necessary to overcome them, many early advances were made in the world-wide body of knowledge on subsurface exploration, soil mechanics and geotechnical engineering. Today, thanks to this pioneering work, the stratigraphy and engineering properties of the overburden and bedrock in the Boston area are, for the most part, understood and easily explored for any given site using state-of-the-art methods of subsurface exploration and geotechnical laboratory testing.

FIGURE 4-1. Colonial shoreline superimposed on a modern map.

Unique or unusual elements of the geologic setting and subsurface conditions of the Boston Basin have influenced foundation designs and construction practices. Unfortunately, there are still too many times when challenging geologic conditions are discovered late, or are "unseen" and discovered only during construction.

Fill & Organic Sediment. One of the more unusual features of the Boston area, and one that continually presents problems to foundation design in and surrounding Boston, has been the extensive areas reclaimed by filling since Colonial times (see Figures 1-21 & 4-1). The reclaimed lands include the extensive tidal marshes around Boston and along estuaries and rivers entering Boston Harbor (see Figure 1-17). Large tracts of salt marsh still remain outside the city where reclamation focused on draining the areas sufficiently to produce salt marsh hay.

The nature, quality and thickness of fill in and around Boston vary greatly from place to place. Fill encountered in Boston may consist of till excavated from original hills, local sand and gravel, trash, cinders and ash, miscellaneous rubble from construction demolition, silt and clay dredged from Boston Harbor or from excavations, imported sand and gravel, or any combination of these. The heterogeneity of fill in Boston is further complicated by the presence of old wharfs and bulkheads that have been buried by later extension and improvement of the Boston waterfront. Problems associated with potential obstructions in the fill — which may preclude or restrict the use of steel sheeting, tiebacks or piles — must be addressed in the design of foundations. A thorough and comprehensive chronology on the land filling within Boston is given by Seasholes (2003) and that book should be referenced for any site development being planned within the city of Boston.

Fill is often underlain by highly compressible deposits of peat, organic silt and other similarly compressible soil strata such as clay, especially in reclaimed salt marshes. These organic materials create problems associated with foundations, and foundation design must take such conditions into account. Also, the consequences of significant settlement due to the placement of additional fill over existing compressible deposits must be considered wherever site development occurs.

Upper Outwash. The upper outwash sand and gravel that is associated with the Lexington Substage is only sporadically found in the Boston area. The thickness based on the results of test borings can reach up to 6 meters (20 feet), as found in the Copley Square-Christian Science Church area. Geotechnical engineers have taken advantage of this shallow deposit to design buildings bearing on pressure-injected footings, especially in the area of the Christian Science Church complex (see Tables 4-1 & 4-2) with no known problems in the downtown area. However, foundation

TABLE 4-1.
Allowable Bearing Pressures for Foundation Materials in Massachusetts Earthquake Design Codes

Material Class	Description	Consistency in Place	Allowable Net Bearing Pressure (tons/ft^2)
1	Massive bedrock: granite, diorite, gabbro, basalt, gneiss.	Hard, sound rock minor jointing	100
	Quartzite, well-cemented conglomerate.	Hard, sound rock moderate jointing	60
2	Foliated Bedrock: slate, schist.	Medium hard rock, minor jointing	40
3	Sedimentary bedrock: cementation shale, siltstone, sandstone, limestone, dolomite, conglomerate	Soft rock, moderate jointing	20
4	Weakly cemented sedimentary bedrock: compaction shale or other similar rock in sound condition.	Very soft rock	10
5	Weathered bedrock: any of the above except shale.	Very soft rock, weathered and/or major jointing and fracturing	8
6	Slightly cemented sand and/or gravel, glacial till (basal or lodgement), hardpan.	Very dense	10
7	Gravel, widely graded sand and gravel, and granualr ablation till.	Very dense Dense Medium dense Loose Very loose	8 6 4 2 *
8	Sands and non-plastic silty sands with little or no gravel (except for Class 9 materials).	Dense Medium dense Loose Very loose	4 3 2 *
9	Fine sand, silty fine sand, and non-plastic inorganic silt.	Dense Medium dense Loose Very loose	3 2 *
10	Inorganic sandy or silty clay, clayey sand, clayey silt, clay, or varved clay; low to high plasticity.	Hard Stiff Medium Soft	4 2 *
11	Organic soils: peat, organic silt, organic clay.	—	*

Note: * Requires evaluation by registered professional engineer.

TABLE 4-2.
Recommended End Bearing & Side Friction for Piles

Depth Into Rock (m)	End Bearing (kPa) at 6.35 mm Downward Socket Movement			End Bearing (kPa) at 12.7 mm Downward Socket Movement		
	Bedrock Area					
	A	C	D	A	C	D
0 - 1.5	—	—	—	—	—	—
1.5 - 3	1,910	—	—	3,830	—	—
3 - 6	2,870	480	385	5,750	575	575
6 - 9	2,870	1,440 - 2,870	670	5,570	1,910 - 3,830	960
>9	—	2,870 - 4,310	1,440	—	3,830 - 5,750	1,910

Depth Into Rock (m)	Side Resistance (kPa) at 6.35 mm Downward Socket Movement			Side Resistance (kPa) at 12.7 mm Downward Socket Movement		
	Bedrock Area					
	A	C	D	A	C	D
Glacial Till	—	140	140	—	170	170
0 - 1.5	140	140	140	205	170	170
1.5 - 4.5	690	170	170	830	205	205
4.5 - 7.5	690	205	205	830	275	240
>7.5	—	205	205	—	275	240

Note: From Gorczyca *et al.* (1999)

construction problems arose earlier on some projects in this area, with older buildings presumably because the outwash's presence was not known and wood piles that were to bear on or in the marine clay unexpectedly "took up" in the outwash. The results were "brooming" of the tops of piles and displacement of some piles which, in the case of the Christian Science Church's new facade where the old pile caps were exposed, ended up as battered. Some of the piles under the church piles were actually pulled out of the pile cap, which was attributed to negative skin friction.

Marine Clay. The marine clay, known as the "Boston Blue Clay," can cause problems. In some areas of the Boston Basin, the clay deposit is extensive, thick and homogeneous, but elsewhere lenses of other material are present within the clay and the stratigraphic sequences are difficult to explain or predict. The local presence of till-like material that usually occurs as lenticular masses of limited thickness and lateral extent can be of concern. These layers may be easily misinterpreted in borings as being the lowermost till sequence that generally blankets the bedrock surface. Such a layer was encountered during the preliminary phase test borings for the Massachusetts Bay Transportation Authority (MBTA) Southwest Corridor Project east of Back Bay station in 1977. Design phase test borings showed this apparent till to be underlain by 6 meters (20 feet) of marine clay (Lambrechts, 2012). If buildings and other structures were to be founded on or within these "apparent till" sequences that overlie soft clay, unacceptable structural settlement may occur. To avoid this problem, foundation borings need be advanced to a sufficient depth to investigate for any underlying, low-strength soils and to penetrate bedrock, thereby verifying the presence of a firm-bearing basal unit.

Another recurring problem is caused by the local interbedded, clean, permeable sand or gravelly sand layers. These layers range from less than a centimeter to over a meter (0.4 inches to several feet) in thickness, and are typically laterally discontinuous over relatively short distances. When undetected in exploratory borings, these layers are often the source of unexpected water inflow into excavations. Thicker layers, if not properly supported and dewatered, are easily undermined or otherwise disturbed. The sand layers pose similar problems in jetted pile operations, slurry wall construction and caisson installation. These layers within the clay also have been responsible for stability problems in tunneling projects and have occasionally caused erroneous interpretations of bearing values during pile driving.

Till. Significant variations in the stratigraphy and engineering characteristics of till require it to be thoroughly investigated for all moderate to heavy load-bearing foundations in the basin. The variable nature of till deposits must be addressed in foundation design since the bearing strength and engineering characteristics of the lodgement till can vary from place to place due to the composition and characteristics of the till matrix. For example, where till is almost entirely derived from less-resistant rock of the Boston Basin, degradation and incorporation of this rock produced a deposit with an appreciable amount of plastic silt and clay. Where the till is largely derived from granitic or other intrusive rock from areas adjacent to the Boston Basin, or even the granular Roxbury Conglomerate, the deposit tends to be silty or sandy with little or no plastic material. This condition was reported along the MBTA Southwest Corridor Project in Roxbury in the early 1980s where the bedrock changes from argillite to conglomerate and notably coarser till was excavated (Lambrechts, 1983). Variation in the matrix characteristics of till deposits may control the effort needed in excavation, the allowable bearing pressures, the potential for foundation settlement, the pile types needed and the dewatering requirements.

Occasional, localized pockets of sand, gravel or other permeable material within the till, especially those not revealed until construction begins, pose another concern in constructing foundations (see Figure 3-76). Such pockets have resulted in water inflow to excavations and installation problems for certain types of piles, caissons and slurry walls. The anomalous lenses are remnants of retreat deposits, likely glaciofluvial, between the two tills, or material deposited beneath glacial ice. These lenses are commonly not detected by exploratory boring due to sample spacing, poor recovery or misinterpretation of recovered soil.

Till-Bedrock Contact. Problems arise about the till-bedrock contact in locating the actual contact, determining the character of the contact and evaluating the water flow potential at the contact. Till usually contains boulders and dislodged wedges and slabs of bedrock. Where the lithology of a large boulder is identical to that of the bedrock, which is a common occurrence, boulders can be erroneously interpreted as the top of bedrock, when intersected in boreholes. To prevent this mistake, rock should be cored a minimum of 3 meters (10 feet) to differentiate between boulders and actual bedrock. False interpretation of the bedrock surface may result in piles and other deep foundation supports that require deeper and more costly penetration than originally expected.

The character of the contact between till and bedrock can vary considerably in the Boston area depending on the rock hardness and integrity. Where bedrock is hard and cut by only a few joints, the till rock contact tends to be distinct with little or no transitional material. Where loosened slabs rest on bedrock, identifying the true bedrock surface may be problematic. The contact appears gradational where bedrock is relatively soft, highly fractured or has undergone pre-glacial weathering. The latter transition may range over 1 to 3 meters (3 to 10 feet) or greater. This zone is typically characterized by an increase of the size and frequency of rock fragments in the till with depth and may contain large blocks or slabs of the underlying bedrock at its base. Seams of till have been encountered in exploratory borings as much as 5 to 6.5 meters (15 to 20 feet) below what would otherwise be considered the top of competent, intact rock. It may be difficult to distinguish borehole occurrences of thin till layers that are beneath basal slabs and till surrounding boulders from fracture fillings in intact bedrock. This situation occurred in the excavation in Somerville for the MBTA Davis Square Red Line Station. Clay infillings of fractures may also be interpreted as gouge.

A unique geotechnical problem is associated with the till-bedrock contact on some construction projects. The "top of rock" shown in contract drawings for foundation design purposes often corresponds to an elevation where competent or intact bedrock was encountered in exploratory borings. However, the transition zone immediately above this elevation may be difficult to excavate using conventional drilling and sampling equipment. As a result, the position of the contact may become the subject of heated debate between engineers and contractors during construction when its elevation forms the basis for payment for rock excavation for basements, slurry walls, and shafts and tunnels because rock excavation is usually five to ten times more expensive, particularly when blasting is required.

Top of rock on some projects might be defined by the amount of effort required to excavate rock with heavy construction equipment. However, the character of till or bedrock at such excavations may be inadequate in terms of foundation support requirements. Therefore, the excavation requirements for each project must be clearly established in geotechnical reports and contract documents. The till-bedrock contact in some areas of the Boston Basin is a highly permeable zone that has caused water inflow problems in excavations. This inflow may result from:

- greater frequency of fractures in the upper meter (few feet) of bedrock due to pre-glacial weathering, freeze and thaw, residual strain release or strain from glacial loading or subsequent elastic rebound;
- altered permeability characteristics of the base of the till due to groundwater seepage for a number of centuries over the relatively impermeable rock surface, perhaps when the sea level was lower than the present;
- coarser matrix around the rock debris at the base of the till;
- coarser water-laid deposits from sub-glacial channels; and,
- permeable, pre-glacial residual weathered material at the top of the bedrock.

Whatever the cause, the recurrence of this problem at this till-bedrock contact zone on many construction projects over the years suggests that design schemes should incorporate the need for dewatering where this condition may exist.

Properties & Condition of Bedrock. The bedrock in the Boston Basin generally has adequate strength to support most engineered structures. The great length penetrated by the numerous bedrock tunnels in the Boston area and the many high-rise buildings founded on rock provide testimony to the overall structural integrity of the bedrock. However, faulting and soft-rock alteration have occasionally required design modification for tunnel support and for deep foundations supported on rock.

Soft-Rock Alteration. By 1914, geologists had noted that in certain areas of the Boston Basin (see Figures 3-48 & 3-49) the normally hard Cambridge Argillite had been altered to "whitish and more or less plastic clay" (Worcester, 1914). This alteration is due to kaolinization, produced by either deep-weathering or hydrothermal alteration (Kaye, 1967a). The effects produced by the kaolinization on the engineering properties of the argillite and other basin rocks depends on the degree of alteration. Slightly altered rock tends to retain its original color and brittle strength properties. As the degree of alteration increases, there is a corresponding but slight decrease in unit weight and considerable loss of strength. Where alteration is extreme, the rock is very soft and somewhat plastic, and when dry, is very light in color, porous and chalk-like. The advanced stages of alteration produce a weak rock with strength and consolidation characteristics similar to that of over-consolidated clay as shown by triaxial compression tests.

Where the degree of alteration is advanced, conventional diamond rock coring equipment can sometimes deteriorate, break up or smear rock core, masking the structural characteristics and altering the engineering properties. Special drilling techniques are needed to obtain undisturbed samples of altered rock for either consolidation or triaxial testing. Pitcher-type sample barrels or saw-toothed carbide bits used in conjunction with conventional coring equipment have been successful in preserving the properties of the extremely altered bedrock. These sampling techniques usually show relict structures of the rock mass, such as jointing, foliation and bedding. The alteration appears to have been caused by leaching that has not disrupted the rock fabric or structural discontinuities, regardless of the degree of alteration. Design requirements for tunnels and deep foundations constructed on kaolinized rock vary with the degree of alteration. In rock-socket testing for the Central Artery/Tunnel Project at Fort Point Channel, deeply weathered argillite was determined to have only 10 percent as much end bearing capacity for drilled shafts as did hard argillite on the 27-acre site (see Table 4-2) of the Interstate 90/Interstate 93 Northbound Interchange Project (Gorczyca *et al.*, 1999). Tunnels encountering weak, extremely kaolinized zones have needed the use of steel support and concrete lining (Kaye, 1967a). The few high-rise buildings in Boston that are wholly or partially founded on altered bedrock have incorporated the use of belled piers, mat foundations and, in one instance, socketed piles to provide adequate support of these structures.

Faults. The bedrock of the Boston Basin has been broken by several episodes of faulting to form a mosaic of fault blocks. These faults include the principal high-angle, east-northeast trending faults and the myriad later complex series of intersecting transverse faults of smaller lateral displacements (Kaye, 1980b). The nature of the faults is displayed in the approximately 100 linear kilometers (60 miles) of bedrock water supply and drainage tunnels constructed in the basin that afforded an opportunity to observe the nature of faulting. Most fault displacement (where measurable) in these tunnels is limited, less than 3 meters (10 feet), and produced only minimal breccia and gouge. The majority of faults observed in these tunnels are characterized as localized zones of closed, tight fractures. Breccia and fault gouge (where present) is limited in thickness to a few decimeters or less. However, several of the large faults encountered in the tunnels are characterized by wide zones of highly fractured rock and structural steel support was needed in some of these zones, for distances up to about 100 meters (300 feet). However, modern tunnel design generally does not require such a heavy degree of ground support in similar rock. Most of the faults are characterized by minor fracturing and limited displacements and do not require substantial modification of support requirements for either tunnels or foundations. Due to the exhaustive compilation of boring logs, geologic maps and construction records over the past forty years, most of the large faults of the Boston Basin have been located. The potential for adverse bedrock conditions in these areas calls for consideration of their effects, as weak-rock zones, in designing construction projects. Additional large faults and many small faults are not yet mapped and, therefore, can lead to design modification during construction.

Artesian Conditions. Natural and man-made artesian conditions have caused failure in the Boston area. The natural ones occur along major buried valleys, four of which extend into the Boston Basin, and roughly correspond to present drainage courses and rivers flowing toward Boston Harbor (Upson & Spencer, 1964). Depths of these valleys extend up to 76.2 meters (250 feet) below mean sea level (MSL). However, glaciers have eroded some of these valleys to produce local enclosed basins (Kaye, 1982b). The unconsolidated deposits within these valleys tend to be locally complex, but the stratigraphy is generally similar to depositional sequences observed elsewhere in the Boston Basin. The valleys are filled typically by sequences of alternating marine clay and outwash, underlain by basal till. Estuarine silt, peat and alluvium commonly form the surficial strata adjacent to present-day streams and their tributaries. Groundwater in the outwash layers is commonly under artesian conditions due to confinement by relatively impermeable clay or estuarine deposits. Because of a general inclination of flow gradients toward the ocean (Cotton & Delaney, 1975), it has been observed that upward gradients from a steep hydraulic gradient in a kame moraine in Plymouth, Massachusetts, produced artesian flow at the ocean surface with attendant erosion of ground.

Buried valleys outside of Boston generally have not been sites for large-scale underground construction. Excavations for subways and large buildings at the fringe of the Boston Basin, however, have locally penetrated outwash deposits overlain by impermeable clay or estuarine deposits, and have encountered unexpected artesian conditions. If artesian conditions are not properly considered in foundation design, they may lead to troublesome water inflow into excavations, disturbance of the subgrade by seepage or bottom heave and contribute to excessive uplift pressure beneath certain foundation types.

Woodhouse observed that artesian pressure from the unlined Dorchester water-supply tunnel drilled in the Cambridge Argillite south of the city caused considerable damage to the basements of homes that were about 30 meters (100 feet) above the tunnel and hundreds of feet away. The tunnel failed under hydrostatic pressure when the rock expanded, causing the joints to both open and close, which allowed the pressurized water to migrate along the joints to the surface (in some cases the surface is a hundred feet above the tunnel) and harm residences. Water inflow along a fault zone in the construction of the Deer Island Inter-Island Tunnel also caused major problems.

Slope Stability. Rock falls occurred in Acadia National Park, Maine, from a local earthquake in 2007, but rock falls and slides in highway cuts and excavations are rare in the region around Boston with or without earthquakes. Most rock falls are very small and occur in highway cuts containing joints that are adversely dipping into the cuts. The few rock bluffs present appear stable and granite quarries south of the city maintain very high rock faces.

In 1994, a toppling failure in a 9 to 12 meter (30 to 40 foot) high cut of fractured felsite of the Lynn volcanic rock (being quarried for use as "road metal") occurred in a quarry on Neal Street in Malden (McKown, 2012). The failure dumped more than 230 cubic meters (300 cubic yards) of rock and soil onto a residential property, destroying a car and a house. Fortunately, there were no injuries or loss of life. A contractor doing nearby construction work using a hoe ram to excavate the bedrock with resulting vibrations was held liable. However, the failure was more likely caused by water in joints in the bedrock from heavy rain over a period of a week.

The Massachusetts Turnpike (Interstate 90) from Boston to Auburn has numerous cuts in batholithic granite and metamorphic rock that have planes dipping adversely down toward the roadway (Barosh, 1976c & 1996a), chiefly in cuts along the southern side (outer edge of eastbound travel lanes). In the western portion, a parallelism of northerly-dipping foliation, shears, joints and small faults may result in open fractures along which the rock slides to the north into the roadway. Cuts along the turnpike in central Massachusetts intersect certain units of the Brimfield Group containing abundant sulfide minerals. The rock is hard, resistant gneiss that stands up well in high cuts when fresh, but it crumbles and blocks may fall owing to a general disintegration as the sulfides weather (Pease, 1975). Despite their name, most rock slopes are not composed of solid, homogeneous rock. They consist of intact rock separated by numerous joints, bedding planes, plants, shear zones and faults. These discontinuities can form blocks and wedges that slide or topple from the rock slope to the roadway or railway below when disturbed. There are three main mechanisms — planar, wedge and toppling — for slope failure (McKown, 2012).

Wedge failure has resulted in rock falls along highways. These failures occur where two intersecting joint planes form a wedge of rock that slides along the angle of intersection and out of the rock face. In the 1960s, a large wedge failure deposited approximately 765 cubic meters (1,000 cubic yards) on the turnpike near Westfield, Massachusetts, killing a motorist. In the 1980s, the cut for the eastbound on-ramp to Massachusetts Turnpike in Auburn was closed for a week by a simple slide along northwest-dipping planes. In 1997, an extensive failure occurred along a 92 meter (300 foot) long portion of rock face in the same area, when rock slid on a continuous joint dipping toward the Massachusetts Turnpike, dumping more than 10,700 cubic meters (14,000 cubic yards) of rock on the heavily traveled on-ramp roadway. The rock slope failure closed the eastbound on-ramp of Exit 10 for ten days, and cost the Massachusetts Turnpike Authority approximately $230,000 to clean up and repair. The rock cut slopes failed due to hydrostatic pressure buildup (McKown, 2012).

The Massachusetts Turnpike undertook a multi-year rock cut slope scaling and stabilization program from 1992 to 1998 in order to stabilize rock cuts that by then had been exposed for about forty years. However, in spite of these efforts, another rock slope failure occurred in 1997, attesting to the unpredictability of rock slopes and the difficulty of prevention. Many small individual blocks at joint intersections above such planes come down during the winter and spring along the turnpike and other roads. These rock falls can be managed and largely prevented by simple periodic inspection and removal of rock blocks before they fall and bounce onto the roadway. Some commercial developments also have cut into hillsides undermining the toes of such dipping planes and making parking lots and buildings vulnerable to such rock falls (McKown, 2012).

Landslides are common in the marine clay, the Presumpscot Formation, in the Rockport area of the central Maine coast (Berry *et al.*, 1996). The Presumpscot is Maine's "Blue Clay" and is glaciomarine in origin, similar to Boston's marine clay. However, there are no problems around Boston with the clay because it is lower and does not form coastal bluffs susceptible to slides. However, if a high face of clay were exposed, a problem could develop. Failure of this clay did occur during construction at the Portsmouth, New Hampshire, Interstate 95 interchange, which was rectified by the installation of sand drains.

Standard Penetration Test for Soil Property Assessment

Foundation engineers need a system to estimate the density and friction angle of granular material and, in the case of cohesive soils, their consistency. Charles Gow, of Raymond Concrete, in 1902 and Harry Mohr (consulting engineer) in the 1920s, in concert with the drilling firm of Sprague and Henwood, developed equipment and techniques to sample soils. Mohr used the blows from a 63 kilogram (140 pound) hammer falling 76 centimeters (30 inches) onto a split spoon sampler (the *N*-value) to estimate the strength of the material. Karl Terzaghi, after meeting with Mohr, designated the technique as the Standard Penetration Test (SPT) in 1947 that is still used at present. In the case of granular soils, the presence of cobbles and boulders can inflate the SPT's *N*-value as the sampler meets resistance and give a falsely dense rating. The soil logger can mis-classify soils in the sampler if the person fails to distinguish the wash from the actual sample. In addition, driving the sampler through loose soils underlain by denser soils can compact the looser soils giving erroneous high blow counts. In deep holes, the weight of the drilling rods, especially in cohesive soils, decreases the *N*-value and the true measurement of the strength of the soil. Sampling of silts can prove troublesome depending on their moisture content. A dry silt of inherent low strength can have a high *N*-value. Silts with higher moisture contents can also give erroneous *N*-values as they dilate and the potential for liquefaction can be misinterpreted.

Soft rock in the Boston area is represented by the altered argillite and to a lesser degree the altered conglomerate. Kaolinized rock shows a consistency equal to that of clay based on the results of test borings but is confined within the unaltered bedrock. Examination of the altered rock in-situ finds the rock to be actually more competent. Sand and gravel can erroneously produce *N*-val-

TABLE 4-3.
Typical Engineering Properties of Foundation Material in Boston

Geologic Unit	General Description	Saturated Unit Weight kg/m^2 (lb/ft^3)	Natural Water Content (percent)	Atterberg Limits (percent) LL	PI	Undrained Shear Strength kg/m^2 (lb/ft^2)	Other	Allowable Bearing Pressure kg/m^2 (lb/ft^2)
I Miscellaneous Fill	Loose to very dense sand, gravelly sand or sandy gravel intermixed with varying amounts of silt, cobbles or boulders, & miscellaneous brick, rublle, trash or other foreign materials	1600-2000 (100-125)						
II Organics	Very soft to medium stiff, gray clayey organic silt or brown fibrous peat with trace amounts of shells, fine sand & wood	1440-1760 (90-110)	40-100			1465-3900 (300-800)	Organic content 5-25 percent	
III Outwash Deposits	Medium dense to dense, brown coarse to fine or medium to fine sand with varying amounts of gravel & silt	1760-2160 (110-135)						19,500-48,800 (4000-10,000)
IV Marine Clay	Stiff, yellow-gray silty clay.	1840-2160	25-35	40-55	15-30	3900-9760	Compression	14,650-39,000
	Medium stiff, gray silty clay, occasional layers of fine sand or silt.	1824-1920 (114-120)	30-40	40-55	15-30	2930-5860 (600-1200)	Ratio = 0.15-0.25	9760-19,500 (2000-4000)
	Soft to very soft, gray silty clay, occasional layers of fine sand or silt. **(Note:** This unit sometimes becomes stiffer at lower levels.)	1810-1890 (113-118)	30-50	40-55	15-30	1950-3900 (400-800)	Recompression Ratio = 0.02-0.04	4880-9760 (1000-2000)
IV-A Marine Deposits	Interbedded gray silty or sandy clay, silty fine sand & fine sandy silt.	Too variable						Variable
V Outwash	Medium to dense, stratified sands & gravels in discontinuous layers.							Variable
VI Glacial Till	Dense to very dense, heterogeneous mixture of sand, gravel, clay & silt with cobbles, & rock fragments	2000-2240 (125-140)	10-20	15-30	10-20	9760-39,000 (2000-8000)		39,000-98,000 (8000-20,000)
VI-A Moraine Deposits	Miscellaneous deposits of deformed glacial till, outwash & clays.	Too variable						Variable
VII Bedrock	Cambridge Argillite							78,000-195,000 (16,000-40,000)
	Roxbury Conglomerate							195,000-975,000 (40,000-200,000)

Note: From E.G. Johnson, in Woodhouse & Barosh (1991)

ues in excess of 50 due to cobbles or boulders, and the presence of iron and manganese oxides cement in, and otherwise a loose deposit can inflate the *N*-value. In-situ plate bearing tests made in the clay-rich Boston till found its high bearing capacity can be exaggerated.

Stiff soils by definition are clays with *N*-values between 15 and 50, corresponding to a consistency of stiff to hard. They represent mixtures of clay and silt of varying cohesiveness and plasticity. Pure clays are not found in the Boston area. The high N values would rule out any sensitivity and liquefaction

TABLE 4-4.
Engineering Properties of the Cambridge Argillite

Location & Rock Type	Unit Weight (kg/m^3; pcf)§§				Unconfined Compression f_c (N/m^2; psi)§§				Tangent Modulus E_{t50} (N/m^2; psi)§§			
	Low	Average	High	No. Tests	Low	Average	High	No. Tests	Low	Average	High	No. Tests
Dorchester Tunnel* Argillite	2,691 168.0	2,747 171.5	2,810 175.4	15	34,480 5,000	103,430 15,001	236,840 34,350	15	39,990 5,800	62,740 9,100	84,120 12,200	15
MBTA Red Line Extension** Argillite	2,538 158.4	2,747 171.5	2,844 177.5	52	41,990 6,090	131,420 19,060	255,120 37,000	50	20,690 3,000	47,580 6,900	63,430 9,200	18
MBTA Red Line Extension** Melaphyric Dike Rocks***	2,606 162.7	2,738 170.9	2,861 178.6	12	12,620 1,830	67,570 9,800	166,860 24,200	10	14,480 2,100	24,130 3,500	31,030 4,500	3
MBTA Red Line Extension** Tuff/Trachyte§	2,518 157.2	2,739 171.0	2,884 180.0	6	29,650 4,300	103,620 15,030	250,980 36,400	6	29,650 4,300	59,300 8,600	74,470 10,800	5

Notes: Table data from Hatheway & Paris (1979).
*Data taken from Haley & Aldrich (1977).
**Data taken from Bechtel (1978).
***Rock types include diabase, andesite, basalt & altered varieties of these rocks.
§ Rock previously identified as dark gray to black tuff; believed to be analogous to dark gray to black trachyte appearing as irregular sill-like intrusion in Porter Square exploration shaft.
§§ Metric units shown above English units in each data group.

potential. Clay with an N-value of 15 or less is defined as soft, but the soil classification system defines soft clay as having an N-value of 0 to 4. Greater than 4 and less than 15 are medium stiff. Low blow-count clays can be sensitive, as found, for example, in the reworked and redeposited clay in the Fort Point Channel and Charles River area. Their behavior in a major earthquake could produce significant damage to structures and the infrastructure.

Engineering Properties of Geologic Materials

Overburden. The variability in the surficial deposits forming the overburden in the Boston area affects foundation construction and its expected problems. Each type of deposit has its own characteristics for engineering purposes and the combination of deposits present beneath a site creates highly variable conditions across Boston. The chief variability comes from the amount and kind of marine clay, organic material and fill near the surface (see Tables 4-3, 4-4 & 4-5). Each type of soil is numbered as a key to the type of foundation (see Figures 4-2 & 4-3).

Fill. The previously discussed fill in and around Boston (exclusive of engineered fill) dates back to the seventeenth century along wharves and to major land fillings made in the nineteenth and twentieth centuries. Fill is generally considered to be deleterious and unsuitable for bearing structures. In rare cases, some of this old fill is compact and granular, which warrants a close look by the engineering community as a bearing stratum for lightly loaded buildings. The suitability of the fill has to be tested by borings.

Organic Sediment. The organic silt and clay, and peat deposits that were laid down throughout much of the lower lying areas surrounding the Shawmut Peninsula following glaciation vary greatly in overall thickness and content, but are generally from 1.5 to 7.5 meters (5 to 25 feet) thick. In those filled-in areas of the Back Bay, the layer has been compressed considerably due to the weight of the fill. Marsh gas that results from the decomposing organic matter is sometimes encountered in excavations.

TABLE 4-5.
Engineering Properties of Materials in Boston

Stratum	Consolidation Condition	Effective Friction Angle	Total Unit Weight (pcf)	Allowable Bearing Pressure (tsf)
Fill Sands distributed along entire project	Loose to medium dense	28-33	110-120	1.0
Sands & Gravels Glacial outwash deposits; sands, gravelly sands, silty sands	Medium dense to very dense	32-36	110-125	1.0-2.5
Marine Clay Silty clay	Over-consolidated	24	110-120	2.0-4.0
Till Glacially deposited mixture of sand, gravel, cobbles, boulders, silt & clay	Dense to very dense	36	125-140	3.0-5.0
Cambridge Argillite Bedrock (slightly indurated)	Medium hard to hard with locally weathered & broken layers	45	165-170	10-20

Note: Table data from Cullen *et al.* (1982).

Reworked Marine Clay. In some limited areas of Boston and Cambridge (such as around the Charles River and the Fort Point Channel), the marine clay was eroded after the Lexington glacial re-advance and redeposited with lower shear strength. The reworked post-glacial clay in Boston is sensitive in places. In the Fresh Pond-Alewife area of Cambridge

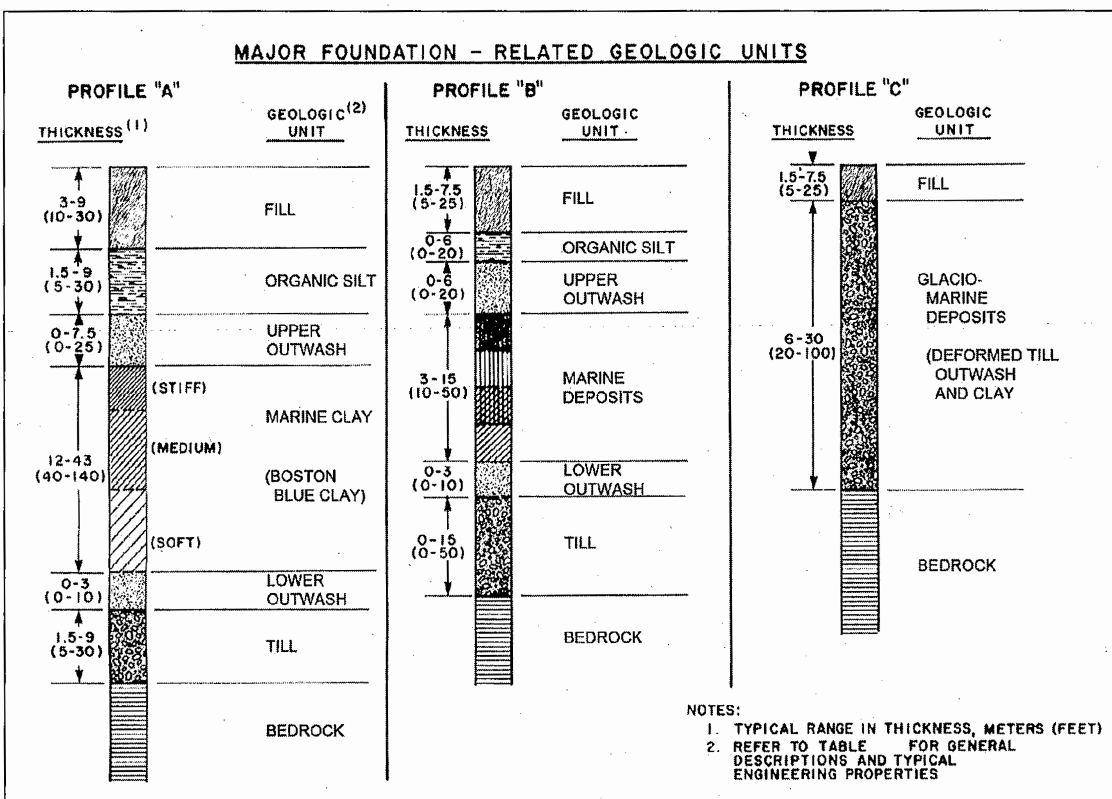


FIGURE 4-2. Geologic units encountered in typical deep foundations.

where the marine clay was eroded and redeposited in fresh water, it is very sensitive, with a higher natural water content than older, more-consolidated marine clay. Problems occur when the reworked clay is not recognized or its weaker condition is not fully taken into account.

Upper Outwash Sand & Gravel: Sand and gravel were deposited over the weathered surface of the marine clay in some areas following the last readvance of glacial ice. These well-stratified sands and gravels range in thickness from 3 to 7.5 meters (10 to 25 feet). They are medium compact to compact and are considered an important bearing stratum for the support of light- to medium-weight structures. These sand and gravel deposits have relatively high permeability, which is an important characteristic and construction consideration. They are generally found to underly organic soils and to direct-

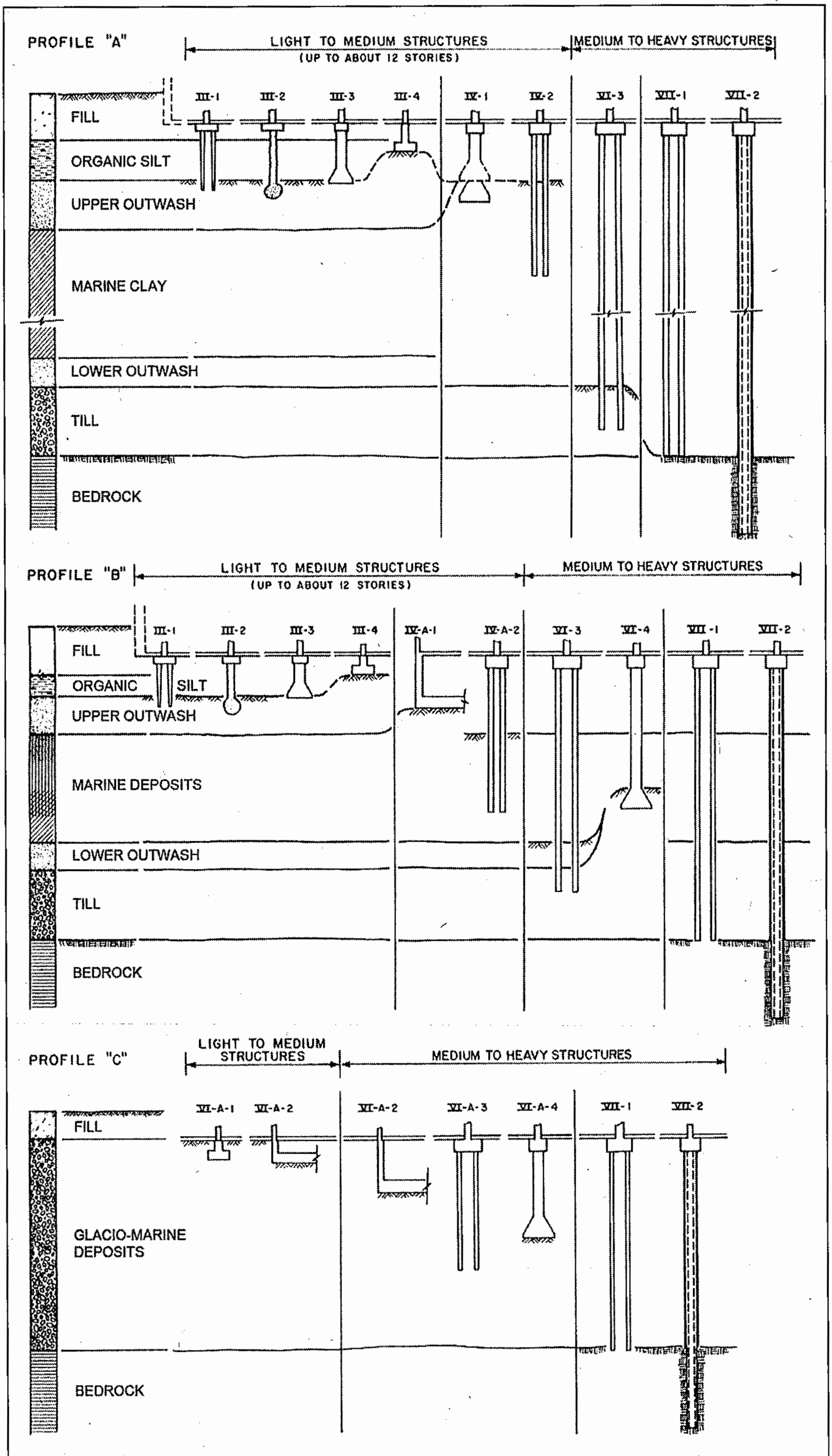


FIGURE 4-3. Typical foundation types used in Boston. (See Figure 4-2 for details on geologic columns.)

ly overly marine clay, particularly in the Copley Square/Christian Science Church area.

Marine Clay. The marine "Boston Blue Clay" varies in thickness and depth all around Boston, and its properties have been investigated thoroughly for foundation design. A weathered crust is present at the top of the clay as a result of desiccation, oxidation and capillary stress. The crust is yellowish or brownish in color, in contrast to the normal gray or olive-gray color of the lower clay. The presence of the stiffer crust plays an important role in the support of structures in the area. Extensive laboratory tests, such as those performed on clay from the Prudential site (Casagrande, 1958) and the Massachusetts Institute of Technology (MIT) (Ladd & Luscher, 1965), reveal that the stiff yellow clay has been pre-consolidated to four or more times the present overburden stress. The over-consolidation ratio decreases quite rapidly with depth so that the clay below about elevation –15 to –21 meters (–50 to –70 feet) MSL is considered to be normally consolidated to just slightly over-consolidated (with an overconsolidation ratio of 1.1 to 1.2). Discontinuous layers and lenses of sand and silt are common within the clay. Therefore, horizontal permeability is generally several times greater than the vertical. Typical ranges of undrained material shear strength and other engineering properties have been determined (see Table 4-3).

Lower Outwash Sand & Gravel. This glacial deposit consists of medium dense, stratified sand and gravel that form a discontinuous deposit over the lodgement till. It has similar characteristics as the upper outwash no matter its thickness.

Glaciomarine Clay. The till-like glaciomarine clay is highly variable and it is impractical to try to typify its engineering properties. The properties would vary from those of clay to very locally reaching almost those of till, which can be misleading. *N*-values generally lie between 25 to more than 100, but typically range around 45 to 60 as a rule of thumb to differentiate them from the denser till (Miller, 2012). The misidentification of this material as till prior to about 1990, when the results of the Central Artery/Tunnel Project borings allowed the proper identification of this deposit, resulted in over-estimating its bearing capacity.

Till. Till directly overlies the bedrock throughout much of the Boston area. For foundation purposes, the till is extremely variable as a result of the very complex processes of deposition with pockets and lenses of pervious sands and gravels, as well as zones of plastic silts and clays that are often encountered within the mass. The lower till may have a greater silt and clay content from the underlying argillite and have low plasticity, and its plastic nature has caused foundations problems when end-bearing piles failed to "take up" as expected in the till.

The SPT (*N*-value) is usually the only practical way to determine an indication of density of the in-situ material. *N*-values of over 80 blows per 30 centimeters (1 foot) are typical where there is more than 15 meters (50 feet) of overburden. Lesser values of *N*, from 40 to 80, are obtained in reworked till, glacial overthrust deposits and at shallower depths. It must be re-emphasized that the method by which *N*-values are determined is not always precise, and unusually high values for individual tests may reflect sampler impact on gravel, cobbles or boulders as noted above. Sample recovery may be poor, and visual examination and classification are often made on very limited quantities. Testing in place with pressure-meters may be appropriate for certain projects. Whenever possible, grain-size and hydrometer tests should be performed as well as finding Atterberg limits on cohesive portions. Typical grain-size distribution curves usually indicate a widely graded material with 10 to 25 percent finer than the Number 200 sieve.

Bedrock. Only the relatively shallow bedrock is of significance for foundation engineering purposes. The predominant upper bedrock underlying much of Boston and Cambridge is the Cambridge Argillite. A lesser amount of Roxbury Conglomerate is encountered locally, especially under the south and west portions of the city in Roxbury, and Brookline.

Argillite. The Cambridge Argillite has extremely variable engineering properties. The unweathered, unaltered rock may be quite sound so that vertical cuts will remain stable with little or no support, and bearing intensities of up to 1,000 kilonewtons per square meter (60 tons per square foot) or more may be appropriate. The argillite provides satisfactory support for most engineering structures if it is not affected by soft-rock alteration or intense jointing or faulting. Steel piles under the John Hancock Tower were driven into the surface of this rock and the caissons under the Prudential Tower are socketed 3 meters (10 feet) deep into argillite. The unconfined compressive strength of unaltered argillite (Woodhouse & Barosh, 1991) ranges from 355 to 2,650 kilograms per square centimeter (5,050 to 37,690 pounds per square inch) with a mean value about 1,335 kilograms per square centimeter (19,000 pounds per square inch). On the other hand, highly altered zones may have properties similar to a medium or soft cohesive soil material. This potential variability, both vertically and laterally over short distances, requires a very thorough, well-planned exploration program if foundation support or other construction is planned on or within the rock (Kaye, 1982b). Such exploration planning begins with geologic research about the area and nearby sites to see if troublesome conditions were encountered.

Blasted fresh rock commonly shows only sparse joints. However, in shear zones, joints may be spaced as closely as 2 centimeters (0.8 inches) apart and form two or more sets. Cleavage has not been found to seriously affect strength of the argillite in tunnels or under buildings. Single bore tunnels, which in Boston have generally not exceeded 4 meters (13 feet) in diameter, have shown the argillite to be strong enough not to require steel supports, except where it has been altered, or where the tunnel parallels the strike of beds that are badly broken by joints, faults or dike-filled faults. This condition was true even for the Cambridge subway tunnel (Red Line NW) that is 6.5 meters (21 feet) in diameter. Soft-rock alteration probably is responsible for most of the bad tunneling ground in the Boston Basin. Unfortunately, these potentially problematic conditions are easily missed by exploratory borings since much of the alteration is restricted to relatively narrow zones or beds. In tunnels, the altered rock almost always requires steel support. The altered rock and sheared argillite have been commonly mislabeled as "shale" in geotechnical reports. Sheared argillite was found in the bedrock borings for the 500 Boylston Street project near the corner of Berkeley Street. The need for thorough understanding of the geology of the project/site alignment is imperative.

Cleavage and joints in deeply buried argillite have been found to be a source of water, which can be under considerable artesian pressure. The sockets drilled dry into argillite at the base of the caissons under the Prudential Tower rapidly filled with water that could not be controlled sufficiently to allow close inspection of the sockets (Ball, 1962). In building the new Charles River Dam between Boston and Charlestown in the 1974 to 1978 period, borings showed that hydrostatic pressures in fissured argillite were such as to be a threat to blow out the overlying till inside the construction cofferdam (U.S. Army Corps of Engineers, 1972). A ring of relief wells was drilled into bedrock, and these wells reduced uplift pressures to a satisfactory level (Kaye, 1982b). The hydrostatic head varied with the tides in Boston Harbor, an observation that had been made much earlier by Lathrop (1800) in a deep well for what was the then-new State House on the slope of Beacon Hill.

The effect of soft-rock alteration on the construction of surface engineered structures has, thus far, been relatively slight. In Boston, these rocks are generally eroded and deeply buried beneath thick clay and other overburden. Surface structures have relied in varying degrees on overlying materials for bearing. The slightly altered argillite and tuff beneath two large corner piers of Boston Company Building caused no apparent loss of rock strength (Johnson, 1973), although it seemed weaker at first. The use of water during the exploration coring process apparently softened the rock and made it appear more altered and weaker than it actually was. The gross bearing pressure on the altered rock here was 293,000 kilograms per square meter (30 tons per square foot).

Sandstone intervals in the argillite have held up well in several of Boston's tunnels. No support was required in approximately 460 meters (1,500 feet) of sandstone exposed in the west part of the City Tunnel (Tierney *et al.*, 1968). Two short sections of sandstone in the City Tunnel Extension required support, either because of excessive splitting parallel to the bedding or due to joints that were too closely spaced (Billings & Tierney, 1964).

Conglomerate. The Roxbury Conglomerate, in contrast with the argillite, is a very hard, durable stone that was commonly used in the late nineteenth century for building, such as for the Old South Church on Boylston Street in Boston, and for retaining wall construction (Kaye, 1976a). It is usually mottled brown in color, with embedded round to angular pebbles, and resembles a dense concrete with very large coarse aggregate. Surfaces on the conglomerate may be extremely uneven since they were not easily eroded by glaciation. Construction excavation or drilling in this massive rock may be very difficult, due to its hardness, sparse jointing or other discontinuities, as well as the presence of hard, embedded gravels.

The conglomerate is a strong rock when not weakened by soft-rock alteration. Only about 12 percent of the 900 meters (3,000 feet) of the Main Drainage Tunnel that were driven in conglomerate (Rahm, 1962) required steel supports. Most of the weak rock is badly altered and faulted and cut by a diabase dike. The Dorchester Tunnel pierced the entire width of the conglomerate cropping out in Brookline, Jamaica Plain and Roxbury (Richardson, 1977). About 13 percent of the 6,300 meters (20,700 feet) of conglomerate traversed by this tunnel required steel support because of soft-rock alteration, which seemed to be concentrated along a very wide fault zone. Another 2 percent of the tunnel required support of rock due to close jointing, faulting and the effects of a thick diabase dike and interbedded argillite (Kaye, 1979).

Volcanic Rock. About 880 meters (2,900 feet) of volcanic rock was pierced by the Dorchester Tunnel (Richardson, 1977), of which only 46 meters (150 feet) required steel support that was necessary due to a local concentration of jointing. No support was needed in the approximately 2,100 meters (7,000 feet) of andesite found in the City Tunnel (Tierney *et al.*, 1968), nor was any support required for the approximately 760 meters (2,500 feet) of this andesite rock in the City Tunnel Extension (Billings & Tierney, 1964).

Groundwater Level

The original groundwater level in the Beacon Hill area in colonial times was relatively high and responsible for the springs around its base. However, the lowering of the hill, reduction of recharge by man-made cover and other effects of construction have lowered its slope toward the original shore where the groundwater level may now be critical. The normal groundwater level in Boston's Back Bay area now is generally somewhat above mean sea level, as might be expected. The normal tidal range in the harbor is about 1.5 meters (5 feet) above and below mean tide and tidal fluctuations of groundwater levels below the city are seen only around the older part of the city along marginal waterfront areas, as measured in observation wells and some construction sites. However, it is usually not observed locally, due in large part to the stabilizing effect of the Charles River Basin being maintained at about 0.73 meters (2.4 feet) above MSL. Water rose and fell with the tide in the cellar of 80 Broad Street where the USGS previously had its offices — a location at the original shore, but now a few blocks from the harbor.

Variations and anomalies in the piezometric surface often are related to dewatering for construction projects or pumping from deep basements. However, leakage from or into storm sewers is another factor. The many subway tunnels and deep utilities conduits commonly form either barriers or drainage paths that interrupt or control normal groundwater flow and create local variations in its level that can cause serious problems, as in the Back Bay (see Figures 4-4 & 4-5).

Influence on Constructed Facilities. Groundwater levels are a key factor in any geotechnical assessment of conditions in the area. The determination of realistic present water levels, as well as past and potential future variations, is of major significance. In Boston, the conse-

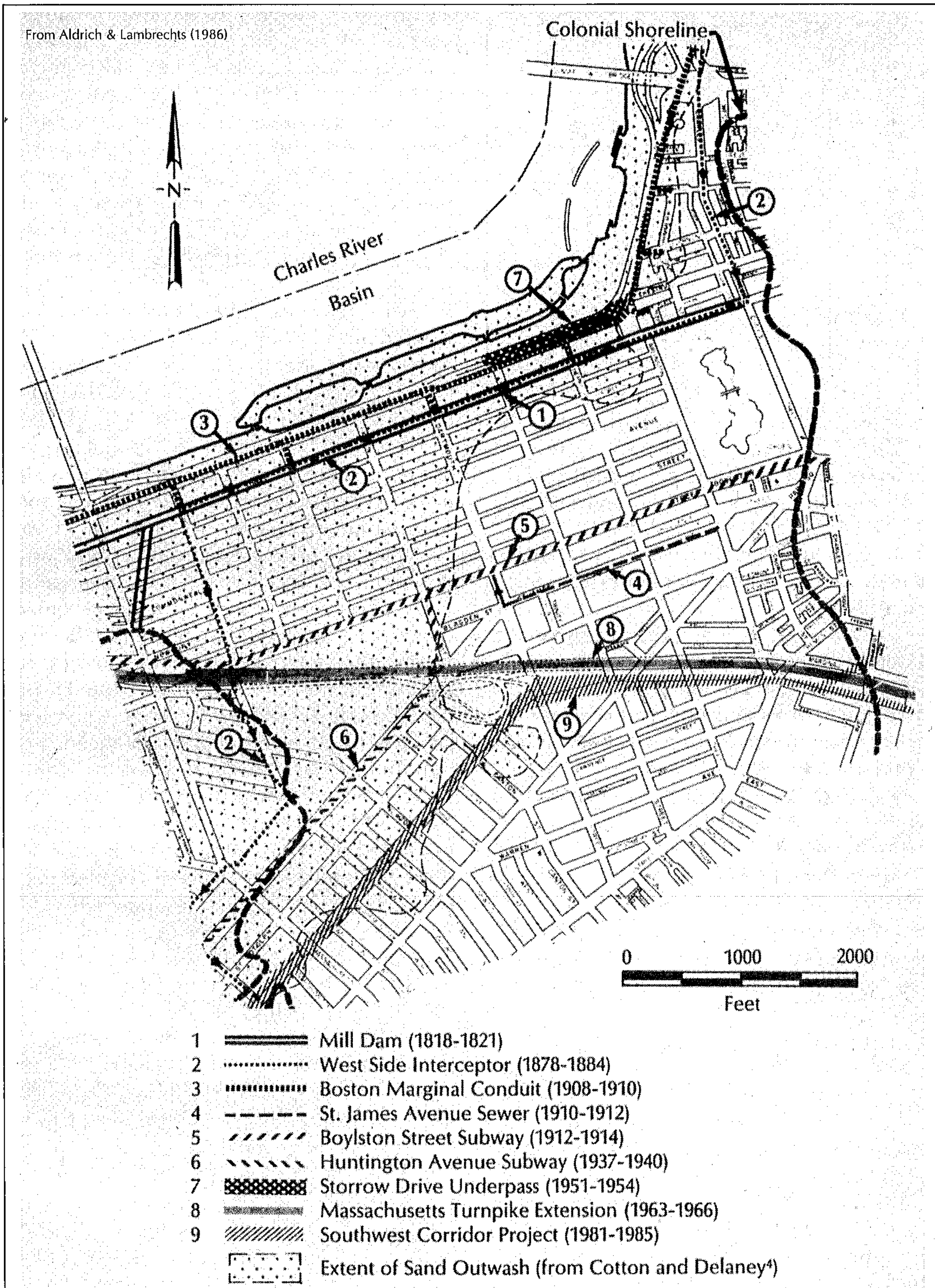


FIGURE 4-4. Map of the Back Bay showing locations of sewers, drains and major transportation routes.

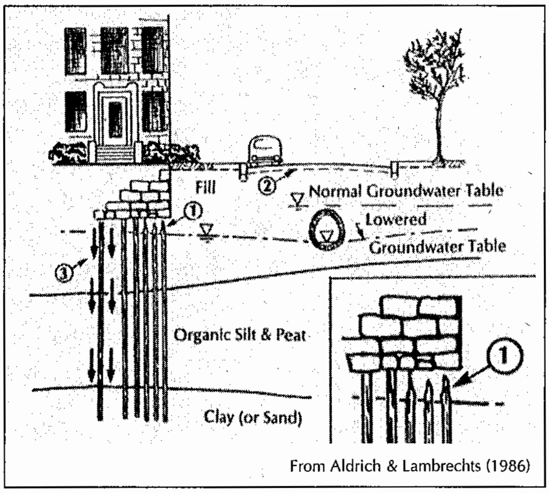


FIGURE 4-5. Diagram of Back Bay foundations showing the effects of lowered groundwater levels.

quences of lowering the water levels below normal, even temporarily, fall in two general categories:

- General subsidence of the land, including streets, utilities or buildings founded at shallow depths. Subsidence may occur if the water level is depressed in areas underlain by soft compressible layers, as in the filled areas of Back Bay. The settlement occurs very slowly and the magnitude reflects the relative thickness of the soft underlying material.
- Settlement of individual buildings supported on untreated wood piles. This type of settlement occurs if the pile butts (tops) are exposed to drying and decay.

The maintenance of "normal" water levels became a very important concern to city officials during the past century. After the filling of the Back Bay in the nineteenth century, most structures were supported on untreated wood piles, driven to bearing in the sand layer below the organic deposit or to/into in the marine clay (see Figure 4-5). Experience showed that the best-performing piles were Maine spruce, which was harvested in the summer months, and, later, Southern yellow pine (Worcester, 1914; Aldrich, 1970). The pile lengths were between 6 to 12 meters (20 to 40 feet) with tips usually 20 centimeters (8 inches) in diameter and the butts up to 30 centimeters (12 inches) in diameter. The clear distance between piles was as little as 30 centimeters (12 inches) to maximize friction, but center-to-center spacings of two to three diameters was commonly used. Since the groundwater level then was approximately 0.7 meters (2.3 feet) above MSL, piles were commonly cut off at elevation 5 Boston City Base (BCB). Experience has shown that if the wood piles are always thoroughly dry, or the piles are constantly submerged and not exposed to air, they will not be attacked by fungi and deteriorate. However, it is not considered practical to keep the piles dry when embedded in the ground so they must be kept submerged. However, with the subsequent effects of decreased surface infiltration as the areas were developed, dewatering for tunnels and by drainage systems, sewer and drain leakage and groundwater infiltration, and other local pumping activities, it was discovered that wood piles below many structures were no longer permanently submerged, and therefore became exposed to loss of saturation, exposure to air and subsequent decay that caused settlement (see Figure 4-5). The lowered water level also may result in consolidation of the material surrounding the piles if the lowering is great enough, and therefore the frictional forces that develop along the piles may create additional loads for which the piles were not designed. The settlement of this material is called negative skin friction and can pull a pile right out of the pile cap, which occurred under the Christian Science Church. Such was the case during the construction of the new entrance to the Mother Church in the late 1960s when the existing pile caps were uncovered and underpinned (Woodhouse & Barosh, 1991).

A notable example of the groundwater lowering problem occurred in 1929, when major cracks were discovered in the walls of the Boston Public Library at Copley Square that was constructed on wood piles in 1888 when the groundwater level was higher (Aldrich, 1979). Upon investigation by the city and its consulting engineers, it was discovered that the tops of wood piles were decaying. A major underpinning effort ensued and about 40 percent of the wood piles supporting the building were affected. The efforts to restore the foundation system cost over $250,000 (in 1929 dollars). The affected pile heads were cut off and replaced with concrete. At the same time, the trustees of the nearby Trinity Church became alarmed that their church might be suffering a similar fate. City engineers discovered that deterioration of a few piles had occurred on one side of the church. These piles were stabilized with steel supports. Settlement of all the piles also had been caused by the very large structural load of the church itself. During the construction of the nearby John Hancock Tower in the 1970s, the Trinity Church and the Copley Plaza Hotel were damaged by the excessive lateral deflection of the steel sheeting and bracing of the Hancock's excavation support system along Clarendon Street and St. James Avenue. The wall warped inward because of insufficient internal support to counteract the load from the exterior overburden, which caused the ground to settle many inches under the transept wing of the church. Failure was avoided because of the inherent factor of safety in the wood pile foundation that used 4,500 piles. According to information made available by the church, the Hancock Tower now collects storm water, which is then used to recharge the area of the Trinity Church.

The apparent reason for the general lowering of the groundwater surface in the 1920s was traced back to earlier construction in 1912 of storm and sanitary sewer lines, with invert levels about 1.8 and 4 meters (6 and 13 feet) below the groundwater surface. Steps were taken to control the infiltration and restore normal levels by the construction of a permanent dam to partially block the sewer. Further remedial measures were carried out in 1955 at the northeast corner of Copley Square, where perforated metal pipes (designed to recharge the groundwater) were installed to intercept surface water flowing to the drain. The Boylston Street subway tunnel also was thought at the time to have contributed to the problem but this theory was never proven.

More recently, problems with foundation distress and rotted piles have occurred in the lower Beacon Hill area. Investigations have revealed that groundwater levels were as much as 1.8 meters (6 feet) below the water level in the Charles River. The lowered levels are attributed to leakage into sewers and lack of sufficient surface recharge. A comprehensive historical perspective on groundwater fluctuations in the Back Bay (see Figures 4-6, 4-7, 4-8 & 4-9), and the adverse effects of lowered levels, is provided by Aldrich and Lambrechts (1986). In the 1980s, seventeen wood-pile-founded homes on Brimmer Street that were built on filled land of the 1860s and 1870s at the base of Beacon Hill were initially condemned by the Boston Inspectional Services Department and some were temporarily vacated. In addition, more than a hundred homes in the area were placed under observation. Since 1929, over two hundred buildings in the lower Beacon Hill and Back Bay area have had their wood pile tops repaired. The residential repair usually consists of having the rotted wood pile tops cut off and replaced by steel and concrete at a cost that is currently on the order of $400,000 to $600,000 per building.

In response to these problems, the Boston Groundwater Trust was founded in 1986 in order to monitor groundwater levels in the affected areas. Existing wells and new monitoring wells were to be measured and the data compiled in yearly reports; however, funds were not then available. The trust was revived in 1997, and in 2002 the Massachusetts Legislature passed the Environmental Bond Bill to provide future funding. In 2005, city and state officials signed a memorandum of understanding to continue to monitor water levels, which resulted in a Groundwater Conservation Overlay District and the publication of well readings via the Boston Groundwater Trust web site (www.bostongroundwater.org).

During any construction excavation below the water table, it is now a requirement that an adequate cutoff system be installed to control drawdown beyond the site area. Adjacent areas must be monitored and, if necessary, remedial action be taken, such as modifying the pumping operation or installing a recharge system.

Geologic Control on the Selection of Appropriate Foundations

Early construction in Boston relied on granite

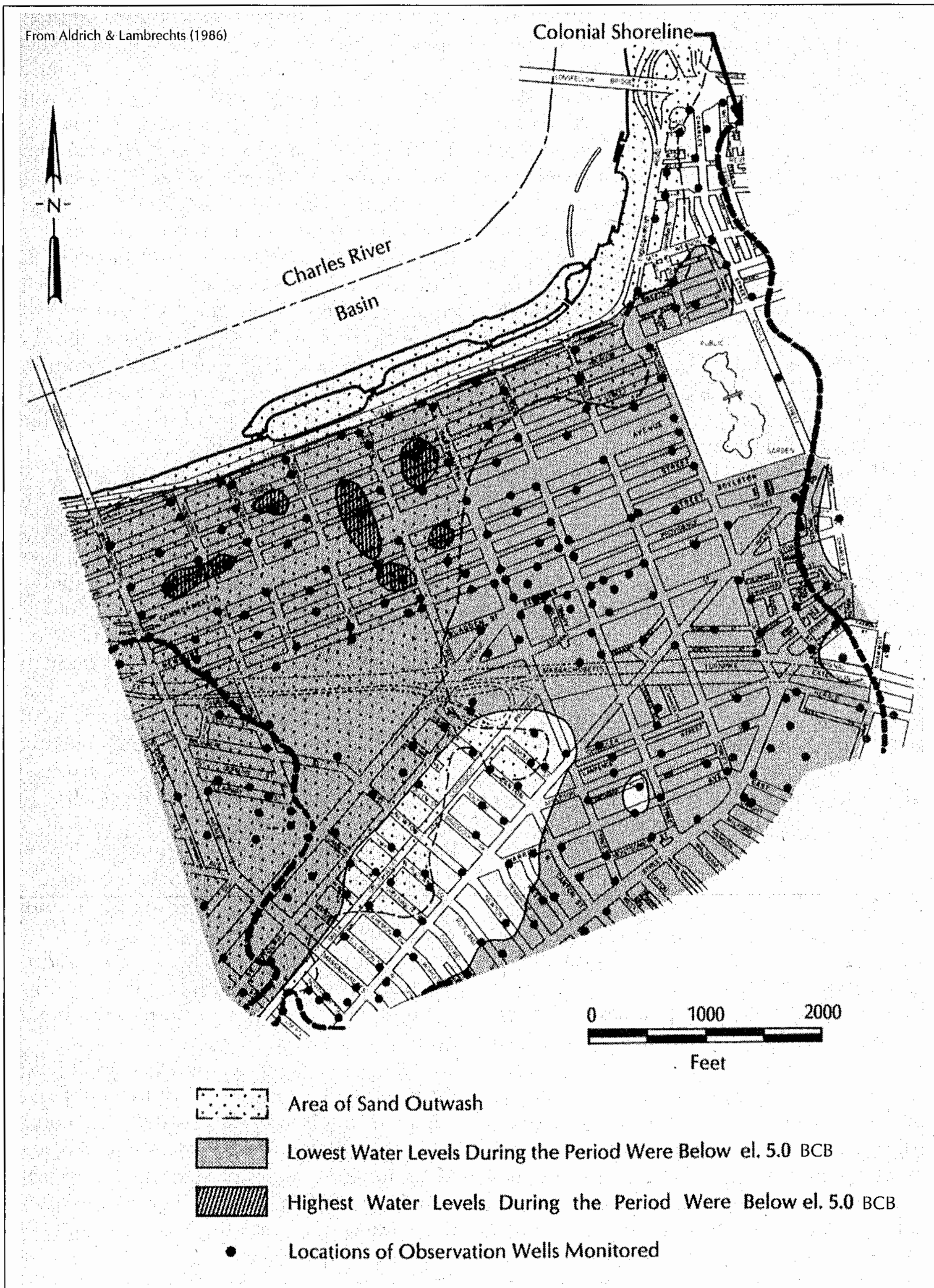


FIGURE 4-6. Areas of Back Bay having groundwater levels below elevation 5.0 BCB at some time from 1936 to 1940.

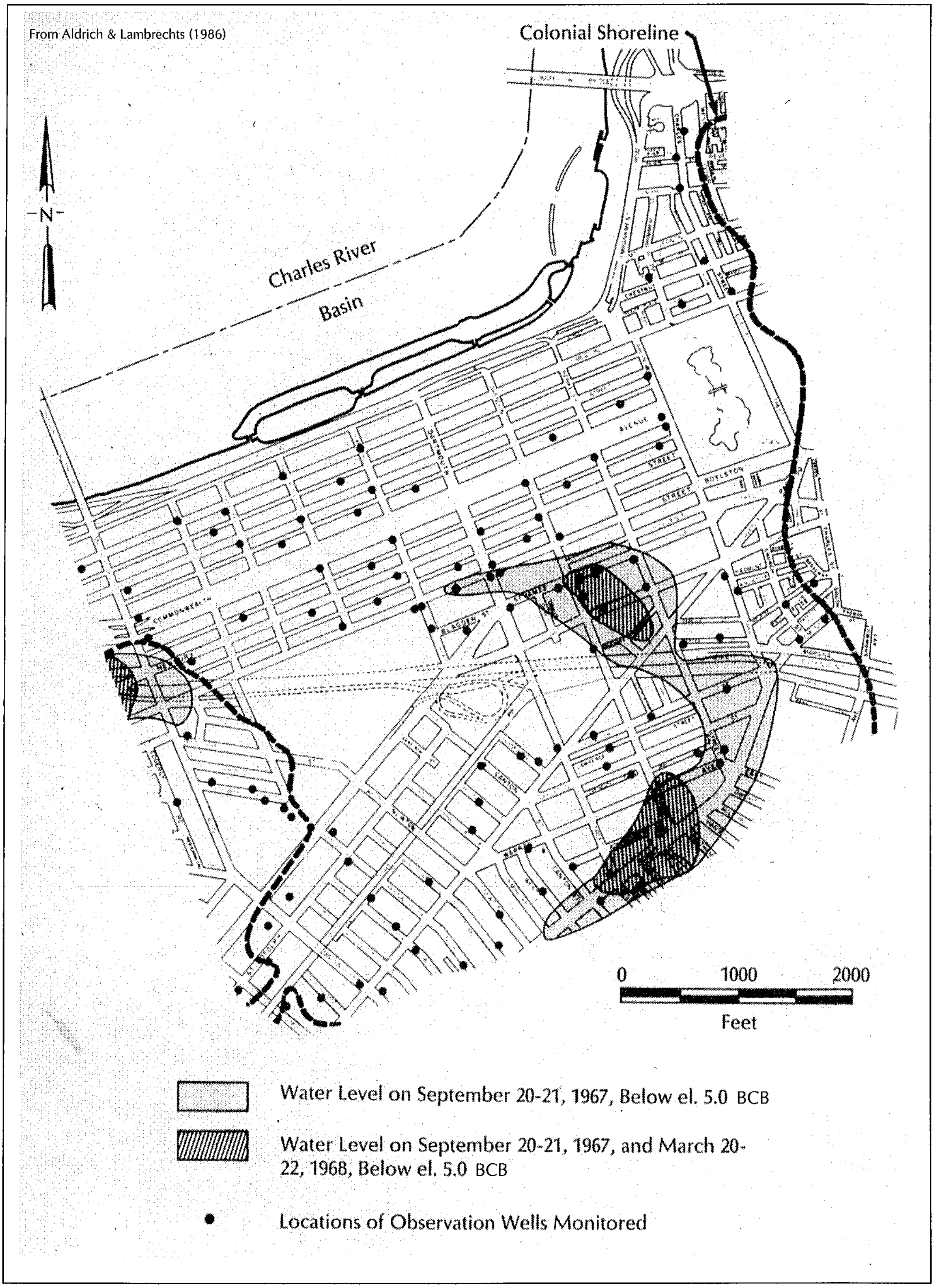


FIGURE 4-7. Areas of Back Bay having groundwater levels below elevation 5.0 BCB during measurements from 1967 to 1968.

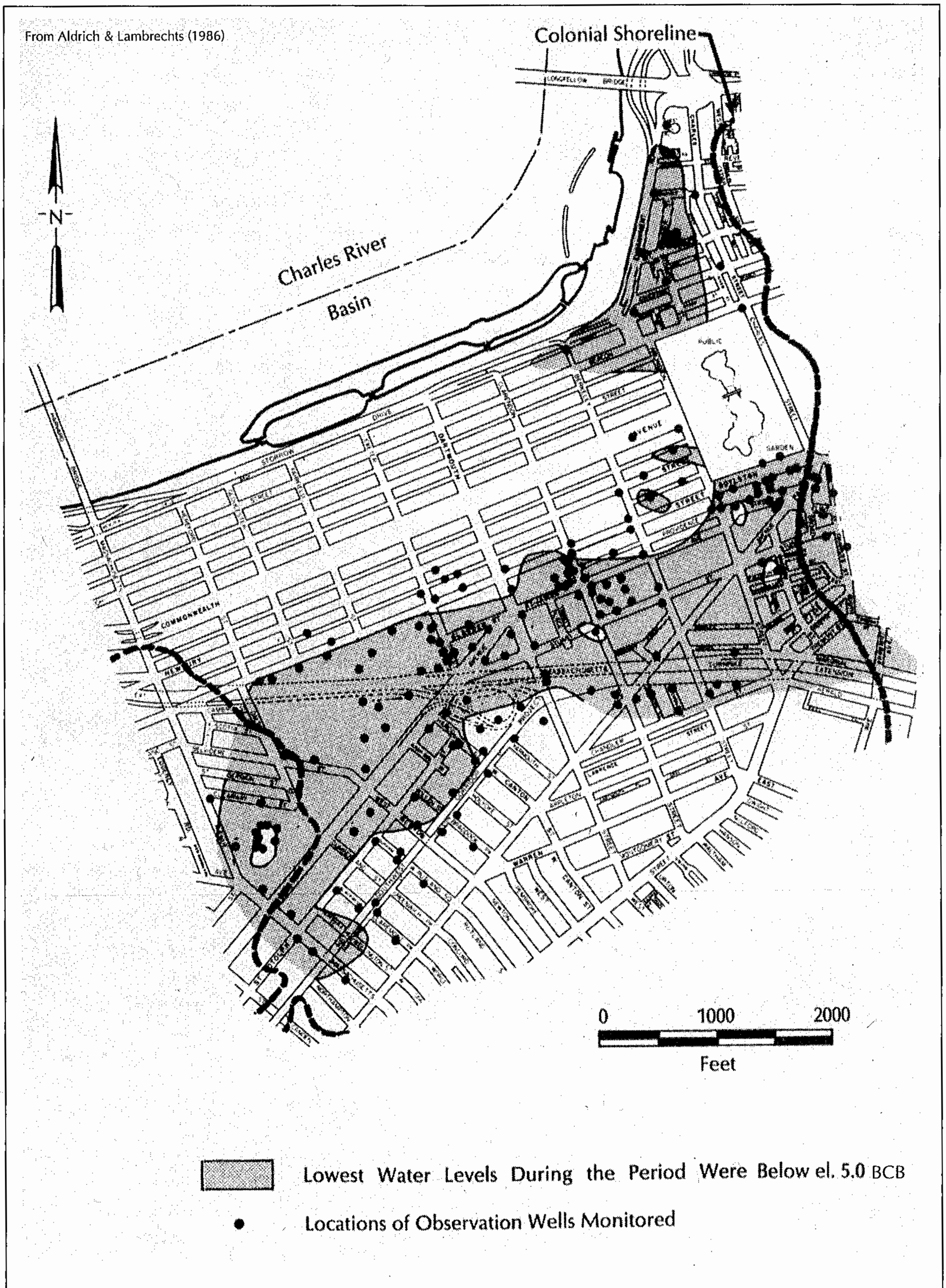


FIGURE 4-8. Areas of Back Bay having groundwater levels below elevation 5.0 BCB from 1970 to 1985.

block footings and walls (see Figure 4-3). The geologic layers were not given too much study except where soils were deemed soft enough to require wider footings or wood piles. The advent of large buildings in the twentieth century focused much more attention to the geology in designing for the mass of an edifice and later for seismic forces. The various geologic layers on which a foundation is to bear determine the selection of the appropriate type of foundation system to be used. Much of the current details and load limits, and to some extent selection, are determined by building code, and the code itself is based on long experience. Foundation designs in Boston must now comply with the International Building Code (IBC).

Three typical geologic sequences found in Boston were evaluated for suitable foundations for large buildings (see Figures 4-2 & 4-3). These sequences are arbitrarily designated as A, B and C. Foundation types considered appropriate for bearing within the separate geologic units are found in each of the sequences (illustrated and keyed into Figure 4-2). The types mentioned are representative of most, but not all, kinds of foundations used. The complex geology does not allow specific areal limits to be defined for the application of this simplified system of three typical geologic sequences and only general areas are indicated.

Geologic Sequence A. This sequence covers deposits below the filled-in Back Bay; areas of Cambridge, Charlestown and Somerville; East Boston; the Fenway; the Charles River, including Gravelly Point; and marginal waterfront areas that make up the most typical condition in Boston, although the upper outwash may be locally absent. The upper Lexington outwash is more commonly found from Copley Square to the Christian Science Church complex and south of Boston in the Quincy-Squantum area.

Geologic Sequence B. This sequence covers deposits in intermediate areas adjacent to the original Shawmut Peninsula that may be more heterogeneous and contain glaciomarine deposits such as along the route of the Central Artery O'Neil Tunnel B from South Station to North Station (following Atlantic and Commercial avenues), Haymarket Square and Post Office Square.

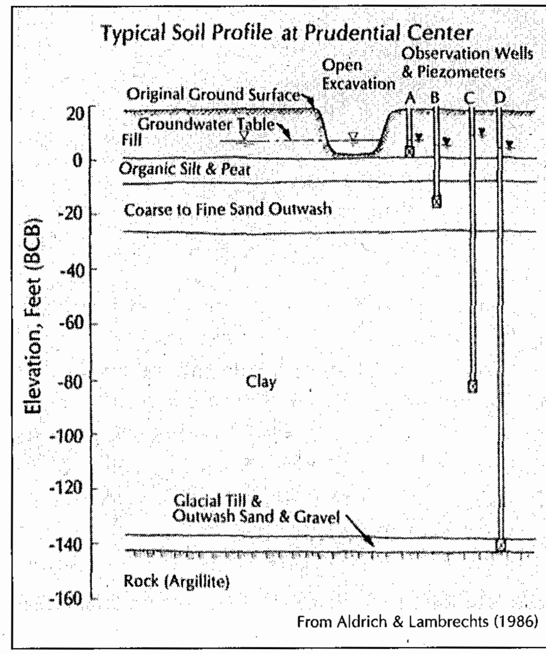


FIGURE 4-9. Profile of the surficial material below the Prudential Center showing the water monitoring wells and the static water level in Well A.

Geologic Sequence C. This sequence covers deposits within the limits of the original colonial shoreline of the Shawmut Peninsula that may be very complex, as in the area of Trimountain and its overthrust deposits, but has much less fill than in the other two sequences.

A description of the geologic units in these sequences together with their typical engineering properties were listed in Table 4-3.

Fill & Organic Sediment (I & II). The fill and the organic layers are not suitable for footings to support any significant structure.

Outwash Sand & Gravel (III & V). The upper outwash sand and gravel (Unit III) warrants consideration as a bearing stratum where it is sufficiently thick because of its density and composition. The lower outwash (Unit V) below the marine clay is too thin and often discontinuous and is not considered to be a specific bearing stratum. Light- to medium-weight structures may be supported on relatively short piles or caissons, in either Sequence A or B. Where this layer is relatively shallow, it may be feasible to use spread footings. For Sequence A, especially, estimates must be made of the post-construction settlement of the underlying marine clay. Usually, the settlements of buildings up to ten to twelve stories, with one full basement level, will be nominal. Higher buildings may be possible if more than one basement level is provided since the stress relief from deeper excavations compensates for the greater building foundation loading.

Untreated wood piles were used predominantly throughout the early years of construction in the Back Bay and pile capacities of 62 to 89 kilonewtons (7 to 10 tons) were most common when driven to bear in the upper sand and gravel layer. Problems can develop if the pile butts are alternately exposed to drying and submergence, or are continually moist. Otherwise, the use of pressure-treated timber can overcome this problem. In earlier times, pile caps were made of dry laid granite blocks set on top of wood pile tops. For certain structures, mortared granite pile caps were placed on the wood piles, such as the one that was exposed and is today on display below the Trinity Church in Copley Square. However, in some areas, rock rubble consisting of pieces of Roxbury Conglomerate have also been found.

Pressure-injected footings (PIFs) having individual capacities up to 1,070 kilonewtons (120 tons) or more are feasible where the intended support stratum has a proper grain-size distribution with less than 15 percent fine soil material (clay and/or silt), and the layer thickness is at least 3 meters (10 feet). The PIFs are a unique pile type, made by advancing a heavy steel drive tube into the sand surface and then driving one or more batches of very dry, zero slump concrete mix 0.14 cubic meters (5 cubic feet) each out of the drive tube to form an expanded concrete base within the granular soil material, which densely compacts the granular soils and increases bearing capacity. A concrete shaft is then formed above the base to complete the unit.

Belled caissons may be installed to bear on the sand and gravel only if it is practical to make undercuts in the overlying organic layer. Otherwise, straight-shaft units would be required, which are less economical. During construction, it is generally required that the base be dewatered before concrete is placed. It is sometimes necessary to dewater the bearing sand in the vicinity by installing wells, provided there are no adverse effects in the adjacent area. However, dewatering the confined sand stratum can be problematic.

Spread footings are feasible where the depth to the top of the bearing layer is only a meter or so (a few feet), and dewatering is not a serious problem. The footings are usually sized for a bearing value of 240 to 480 kilonewtons per square meter (2.5 to 5.0 tons per square foot).

Marine Clay (IV). For Sequence A, some light to medium structures are founded directly on or within the marine clay. It is important to note, however, that estimates of potential settlement must be made. Belled caissons (IV-1) are perhaps the most common foundation type in the clay stratum (see Figure 4-3). Steel casings are advanced through the upper layers and sealed into the organic deposits or clay surface. The belled portions are undercut in the overlying organic soils by rotary machine to a diameter of 1.8 to 3 meters (6 to 10 feet) or more. In the early days, this belling was done by hand labor. Usually, there is little or no dewatering required and all excavation is in the dry. The caissons are typically designed for an end-bearing capacity of 190 to 380 kilonewtons per square meter (2 to 4 tons per square foot) in the upper stiff clay zone. If that zone is fully penetrated, caissons bearing on the softer clay below would have a reduced design bearing capacity. In all cases, the strength of the clay should be verified in the field by competent geotechnical personnel as each caisson is excavated.

Friction piles are also used to provide support in the upper clay. Wood piles, of capacity up to 196 kilonewtons (22 tons), are allowed by the Massachusetts Building Code. Other pile types have also been used, based on a typical design friction value of 24 kilonewtons per square meter (500 pounds per square foot) for the portion embedded in the clay. Any such installation should be verified by on-site pile-load tests.

For structures with very dry basements (three floors), thick concrete mat foundations can be used to bear on the top of the marine clay or upper outwash sand. Basement excavation removes soil weight to counter the building weight, allowing such foundations to essentially "float" — thus, the term *floating foundation.* The behavior of the marine clay supporting the floating foundations under the MIT campus in the early part of the twentieth century gave rise to the science of soil mechanics under Karl Terzaghi.

Glaciomarine Sediment (VI-A). Light to medium structures are founded on or within glaciomarine sediment in Sequence B, especially when there is no sand layer or it is thin. Because conditions in this sequence may be very erratic, such as a combination of granular and cohesive units in discontinuous layers and lenses, each site must be carefully evaluated. Soil-bearing footings or mat foundations are usually most feasible. Occasionally, friction piles are used when the stratum is quite thick. There is one known case where PIFs have been used, but a very careful determination of the location and quality of granular deposits is required prior to PIF installation.

Footings or mats are feasible, especially where the design requires that basement excavations extend down to the glaciomarine unit. A reinforced mat and waterproofed wall system are usually required if the unit is below groundwater level. Friction piles may be considered when other foundation types are not practical in this marine deposit. A conservative design assumes that all the material is cohesive and allows for a frictional resistance of 24 kilonewtons per square meter (500 pounds per square foot) for the exposed pile surface.

Till (VI). Where suitable portions of till are close to the ground surface in geologic Sequence C, the most feasible foundation type, regardless of size of structure, would be soil-bearing footings or mats. Heavy structures extending below the groundwater surface would probably require a mat. In this case, a permanent under-drainage system may be used to relieve hydrostatic pressures if there would be no adverse effect to surrounding areas or buildings. In some places, where the upper portion of the deposit is weak, piles or belled caissons are used.

Medium to heavy structures, for which shallower foundations are not practical, may be supported on piles or caissons bearing in the glacial till in Sequences A or B. The depth to the till is usually 23 meters (75 feet) or more. In this case, it is advantageous to select the till as a bearing stratum because it has a high a load capacity.

Footings or mats are usually designed for soil bearing pressures of up to 960 kilonewtons per square meter (10 tons per square foot). Even higher values may be possible, taking into consideration that the code allows an increase of 5 percent per 0.3 meter (1 foot) of depth of penetration below the top of the till, up to two times the design value at the surface of the till.

Piles are usually designed for end bearing in the deep basal till at design values up to about 1,335 kilonewtons (150 tons). Concrete-filled steel pipe piles have been used extensively, but must take into account an allowance for corrosion if they pass through a layer of organic material. In the past several decades, pre-stressed concrete piles have been widely used. The Massachusetts Building Code had allowed capacities up to 872, 1,192 or 1,558 kilonewtons (98, 134 or 175 tons) for 30.5, 35.5 or 40.6 centimeter (12, 14 or 16 inch) square sections, respectively.

Belled caissons may be appropriate where a single caisson unit can be installed below any column. Multiple units are generally not economical because of the large cap required. They may be designed for end bearing in lodgement till at capacities of up to 960 kilonewtons per square meter (10 tons per square foot). Higher values may be used for deeper penetrations into the till. In some instances, straight-shaft caissons have been used, with support from side friction as well as end bearing.

Bedrock (VII). Normally, the bedrock is encountered 23 meters (75 feet) or more below the surface. Shallower foundations are usually more economical, unless the structure is quite heavy. The rock level is closer to the surface north of Beacon Hill in the area of the West End, Government Center and Charles River Park (where a thirty-six-story apartment structure is founded on spread footings directly on argillite).

Piles may be driven to end-bearing on, or a short depth into, the rock surface, where the overlying units do not provide adequate driving resistance. In those areas where the argillite may be weathered, the piles may penetrate 2 to 3 meters (6 to 10 feet) into the rock. Close attention must be given to the selection of an appropriate design capacity for this case, which would be coupled with selected hammer energy and necessary driving resistance.

Drilled-in caissons, as described in Section 739 of the Massachusetts Building Code, were generally limited to unusual situations where very high column loads must be accommodated and other foundation types were not feasible. Drilled shaft designs usually call for a combination of end bearing and side friction in a rock socket. However, since the early 1990s there has been substantial increase in use of such high-capacity foundations. A permanent, heavy steel, open-end casing is advanced by driving and internal cleaning to the rock surface and seated. A socket is advanced into the rock using a churn drill or other methods to a depth of 3 to 7.5 meters (10 to 25 feet). A heavy cage with rebar, or less often a heavy steel H-section column, is lowered to the bottom and set with concrete. In previous times, it was desired to dewater the bottom so the bearing surface could be inspected by a remote video camera. However, today most often the completion is done under slurry with no visual inspection prior to placing the concrete. Total capacities of 11,600 to 14,700 kilonewtons (1,300 to 1,650 tons) per unit were developed for a major tower structure in the Back Bay (Ball, 1962). Since those times, loads nearly five times those capacities have been achieved with bearing capacity on the order of 267 to 890 kilonewtons (30 to 100 tons per square foot).

More recently, drilled shafts or piles have been advanced into the rock, using temporary casing or bentonite slurry to stabilize the hole. A steel core or reinforcement is installed and the hole backfilled with cement grout to develop load in friction as well as end-bearing capacity.

Exploration & Testing Practices

Subsurface Investigations. Many of the exploration practices now in effect had their beginnings in Boston because of the work of H.A. Mohr of Gow Caisson and Raymond Concrete Pile, and Arthur Casagrande. Local exploration practice, for the most part, consists of boring and sampling methods performed in accordance with ASTM International (formerly the American Society for Testing and Materials) standards. These methods are considered to be "direct" methods, wherein borings penetrate the overburden soils and rock, and physical samples are recovered for laboratory testing and determination of the stratigraphy and geotechnical properties. Other, "indirect," principally geophysical methods such as seismic refraction, resistivity and cross-hole seismic are less likely to be used in an urban area.

Most standard borings are made using 6.3 or 7.6 centimeter (2.5 or 3.0 inch) diameter steel casing to maintain the hole through unstable soils. Larger diameter casing is used when undisturbed piston samples are required. The casing is advanced by driving and the soil within is washed out with chopping bits, roller bits and cleanout tools to the desired sampling depth. When penetrating cohesive soils, such as the clay, casing is generally not required and the hole may be stabilized by drilling mud. For deep borings that are to penetrate bouldery glacial tills, rotary drilling techniques are generally used to advance flush joint casing, using a core barrel or tricone bit. An alternate procedure is the use of hollow-stem helical flight augers, mounted on large mobile truck rigs to advance the hole and provide for soil sampling after removing a closure plate at the bottom. Only limited success is achieved in pervious materials, which are under hydrostatic pressure. Offshore drilling platforms have been used successfully in exploring for offshore bedrock tunnels for cross-harbor tunnels and outfalls for power and sewage treatment plants.

Conventional sampling procedures (SPT) are usually employed, wherein disturbed samples are obtained by driving a 5 centimeter (2 inch) outside diameter split-spoon sampler at 1.5 meter (5 foot) intervals, or at changes in sediment type, using a 63 kilogram (140 pound) hammer, dropping 76 centimeters (30 inches). Continuous sampling is sometimes used when it is important to detect frequent changes in the stratigraphy. In the clay, relatively undisturbed samples are recovered with a 7.6 centimeter (3 inch) inside diameter stationary piston tube sampler to retrieve Shelby tube samples. Sometimes 5 centimeter (2 inch) diameter tube samplers are used.

Core drilling in the rock is performed with either BX- or NX-size core barrels. In weathered or altered argillite, the best sample recovery is obtained by using a NX-size double tube barrel with a split inner liner.

Field permeability tests are performed below the casing in boreholes at selected depths. Observation wells or piezometers (or both) are often necessary to determine the long-term stabilized water levels. Seals are required where different piezometric levels may occur at various depths within the boring. Pressuremeter tests to determine properties in place are useful in measuring the stress-strain properties of the glacial till since undisturbed sampling of the till is not practical.

Boring Data Archives. A most valuable resource with regard to available subsurface information is the collection of boring data published by the Boston Society of Civil Engineers (1961, 1969, 1970 & 1971). The Society first collected about 3,900 boring records between 1923 and 1931 and listed them and their locations in the September 1931 issue of their journal and has updated them periodically. These volumes contain tabulations of the logs and locations in the Boston Peninsula as well as South Boston and Roxbury, along with some cross-sections. The data from many sources such as architects, engineers, contractors, public agencies and others were collected and processed by volunteers. A similar effort was undertaken to publish data for the Cambridge area. Although hundreds of new borings were made for the Central Artery/Tunnel Project in Boston, these have yet to be integrated with the previously collected data. Boring data are also contained in the reports of the Massachusetts Water Resources Authority (MWRA) that are kept in their library in their headquarters in Chelsea. Many others remain in private files and must be laboriously searched out. The Massachusetts Department of Transportation maintains extensive records of borings for bridge and highway work throughout the state. The recently revived Massachusetts Geological Survey is trying to record and preserve well boring data on a more regional manner in the state. Over a hundred thousand completion reports from well drillers across the state are on file with the Massachusetts Department of Conservation and Recreation.

Core & Sample Repositories. Core and sample repositories are maintained by both the Massachusetts Highway Department and the MWRA. The MWRA has over seventy thousand linear feet of core, some of which dates back to 1898, and five hundred thin sections, all of which is recorded in a digital database. These cores provide samples from the tunnels and other structures of the MWRA in the Boston area. The material is stored presently on Deer Island, where it is hoped the facility will be upgraded for their adequate preservation. Some MWRA core is also stored at the Quabbin Reservoir. The core maintained by the Massachusetts Highway Department (formerly in Wellesley) is chiefly from exploration for the interstate highways and is stored now at a facility located in Lawrence. Access to soil and rock core samples from the Central Artery/Tunnel Project is not known.

Geologic Influences on Major Building Foundations in Boston

A summary of all of the major building foundations, with notes on how their construction added to understanding Boston's geology.

DAVID WOODHOUSE

The influence of geology on building in Boston goes hand in hand with the building technologies of the day and the development of the city itself. The following review of building development incorporates information from E.G. Johnson (in Woodhouse & Barosh, 1991), along with information on the subsequent building additions of the past twenty-five years.

In the early Colonial days within the original Shawmut Peninsula, Bostonians built utilitarian structures, often of wood, with simple wood or stone foundations. Most neighborhoods were eventually leveled by major fires and only Paul Revere's house (dating from 1677) remains as an example from that era. As Boston prospered during the 1700s, more durable buildings were raised that used brick or stone. These structures include several surviving large public buildings such as the Old State House (1712), the Old South Meeting House (1729), King's Chapel (1749) and many edifices on Beacon Hill, including Bulfinch's gold-domed State House (1795). These buildings were all constructed on solid ground and probably supported on footings of granite largely supplied from quarries in Quincy. Construction also pushed toward the waterfront where Faneuil Hall (1740) and Quincy Market (1824) had to be supported on wood piles driven through the fill and underlying organic mud to firm end bearing. The original brick Custom House (1810) was constructed on Custom House Street — a small street running northeast that connects Batterymarch and India streets, just southwest of the Central Wharf — on footings and was replaced by the now existing Custom House in 1847, with its tower added between 1913 and 1915. The venerable old Custom House thus became Boston's first skyscraper — standing 151 meters (496 feet) high, with thirty-six stories (thirty-two floors in the tower alone) — even though the city had a 38 meter (125 foot) height restriction, which was waived since the Custom House was a federal government building. The new Custom House of 1847 used three thousand piles driven to the outwash or the till, which occurs at a depth of 18 to 27 meters (60 to 90 feet). It has been variously reported that the piles were driven to bedrock (Seasholes, 2003), but doing so would have been unlikely since the piles would have had to penetrate through 4.5 to 7.6 meters (15 to 25 feet) of dense outwash and till, something that would have not been possible for the pile-driving equipment of the day. Bedrock in the area is found at an elevation of –30 meters (–100 feet) MSL. The *1850 Boston Almanac* does not confirm that piles were driven to bedrock for the original new Custom House.

During the second half of the nineteenth century, Boston was ready for change and expansion since it reached the outer limit of its buildable land. Industrialization and the building of railroads greatly improved construction capabilities. The 182 hectares (450 acres) of marsh land that was once Back Bay were filled in with sand and gravel brought in by rail from Needham to the west and Dedham to the southwest (Newman & Holton, 2006). The area was laid out in a grid of streets. Fashionable brick town houses lined these streets as well as several cultural institutions (Seasholes, 2003), including the original Museum of Fine Arts (now moved to Huntington Avenue), the Museum of Natural History (currently extant on Berkeley Street between Boylston and Newbury streets — now being renovated), the original Massachusetts Institute of Technology (MIT moved to Memorial Drive in Cambridge in 1916), the Arlington Street Church, New Old South Church (now called the Old South Church), Horticultural Hall (closed), Symphony Hall and the original Boston Public Library (demolished in 1899, after completion of the new Boston Public Library, which was built between 1888 and 1895). Also present are the beautiful Trinity Church that faces the library at Copley Square and the Christian Science Mother Church and Center, which lie farther to the west. For all of these structures, the standard foundation practice was support by untreated wood piles, typically 7.5 to 12 meter (25 to 40 foot) long trees, driven to bearing in the outwash sand and gravel layer or crust of the thick marine clay deposit (Aldrich & Lambrechts, 1986) that underlie the fill and organic deposits.

Before the 1880s, wood piles were driven by dropping a heavy weight on them that was lifted between guides using animal or manpower. Later, steam power was used to raise the weight. The Arlington Street Church used 999 piles and the Trinity Church used 4,500 (2,800 under the four columns of the central tower alone) driven into the upper outwash. A similar number (more than 4,000) of wood piles was used for the new Boston Public Library in the 1880s. These piles have generally performed well, except where the pile cutoffs have been exposed to drying and decay. The Old South Church had pile failure due to poor underlying material used to support the wood piles (according to information provided by the church), and again later in 1913 through 1914 that was caused by subway construction in a deep excavation beneath Boylston Street. These problems caused the original tower to lean over 41 centimeters (16 inches) off vertical.

Relatively little new building construction took place in the early twentieth century, except for the tower added to the Custom House. Several structures were built in the 1920s and 1930s in the Back Bay, notably the John Hancock Berkeley Building, the Liberty Mutual Building and the New England Mutual Building. However, heights were generally limited due to the thick marine clay and the onset of the Great Depression. The first very tall building in Back Bay was the John Hancock Clarendon Building in 1946, which used deep steel H-piles to penetrate through the clay to bear on till and bedrock.

Boston's building renaissance began in the Back Bay in 1959 with major developments that included the first break into the skyline with the Prudential Center, a fifty-two-story office tower, with an adjacent twenty-nine-story hotel. These, and most other, tall buildings in the Back Bay built in the past fifty years have used deep foundations to support building loads below the clay on till or bedrock. This building boom took off in earnest in the 1960s, and is still continuing today. A list of buildings constructed from 1959 to the present, with available information on date of construction and foundation characteristics, is shown in Table 5-1, and the locations of ones built from 1960 to the present are shown in Figures 5-1, 5-2 & 5-3. At times, Boston's history lost out to site clearing. For example, the razing of the infamous Scollay Square and the old West End for the development of Government Center. The dramatic change in the Boston skyline during this period is easily seen in aerial views (see Figures 5-4 & 5-5). Centers of construction sprang up in the city, with each involving a need for new types of foundations and excavation support systems to accommodate the different geologies that underlay them. Because of the large size and loads of these new buildings, geologists and design engineers knew that they no longer could rely on wood pile foundations or on granite block footings, thus creating plenty of opportunity for innovation in the new science of geotechnical engineering and geo-construction.

As Boston developed, severe space restrictions added complexities to foundation design and construction in addition to the complicated geologic conditions. Where adjacent historic properties required protection during deep excavations (such as at 60 State Street), tied-back slurry walls were used. At 53 State Street, the granite facade of the existing Boston Stock Exchange Building was temporarily supported while a new glass-enclosed high-rise was built immediately behind it. Similarly, temporary facade support was undertaken at the 101 Arch Street and 125 Summer Street projects. Deeper excavations below buildings now are commonly called for to provide space for badly needed parking. Recent examples (Becker, 1991) include International Place (five levels), Rowes Wharf (five levels), 125 Summer Street (five levels), 75 State Street (five levels) and the garage below the park at Post Office Square provides seven levels for parking (see Figure 5-1). The latter utilized the "up-down" construction technique. Finally, the Central Artery/Tunnel Project required the application of recently developed equipment and techniques to make possible the installation of high-capacity foundation units and slurry walls below existing structures in low headroom conditions.

The number of new buildings constructed in downtown Boston slowed because of a recession in Boston's economy in the 1990s and again in the 2000s. Most construction in this period occurred in the South Station and Seaport area of South Boston and some farther out. Since 2012, tall building construction has resumed in the inner city with significant structures at Millennium Place and in Chinatown.

Back Bay: Public Garden to Copley Square. Copley Square in the Back Bay (which included the Prudential Center) was the site of Boston's first great development outside the downtown area and the home to many historic buildings in the city. These old buildings include the venerable nineteenth century Trinity Church (1876), New Old South Church (1875) and the Boston Public Library (built from 1888 to 1895). The library was expanded in 1972 with a four-story addition that was supported by a thick concrete mat on the stiff clay and upper outwash sand. Most if not all of the more than hundred-year-old buildings are supported on untreated wood piles, some of which have been affected by construction dewatering or a lowering of groundwater levels due to various causes.

The major development in the area, which occurred between 1968 and 1982, had begun with the sixty-story John Hancock Tower — the tallest structure in Boston and totally wrapped with reflective glass. The tower bears on a 2.6 meter (8.5 foot) thick concrete mat that is supported on 3,000 steel H-piles that extend deep into till and argillite. Bostonians remember all too well the problems with I.M. Pei's designed building that began with large movements of the excavation support system that caused substantial damage to adjacent streets, utilities and buildings. Later, during construction, the large pane double-glazed glass windows started to crack, break and fall to the pavement below. Plywood quickly replaced glass. The problem was corrected by changing the glass to a thicker single-glazed panel. It was learned that trace elements in the original double-glazed

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Downtown Boston
1	First National Bank, 100 Federal Street	1971	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
2	Shawmut Bank, 1 Federal Street	1975	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
3	State Street Bank, 225 Franklin Street	1966	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
4	Office Building, 265 Franklin Street	1983	C	IV-A-1 or VI-A-1	20-story office tower; footings on glaciomarine or moraine deposits
5	One Post Office Square	1979	B	VI-3	38-story office tower & parking structure; PIFs to glacial till
6	Office Building, 260 Franklin Street	1983	C	VI-A-2	23-story office tower; spread footings on till at depth 7.5 m (25 ft)
7	Office Building, South Milk Street	1980	B	IV-A-1	21-story office tower; footings on stiff clay
8	The Devonshire, One Devonshire Place	1980	C	VI-A-2	40-story apartment & office tower; combined footings on moraine deposits
9	Boston Co. Bldg., One Boston Place	1968	C	VI-A-2 & VII-4	41-story office tower; core on mat on moraine gravel; heavy corner loads on belled piers in argillite at 24 m (80 ft)
10	Office Building, One Beacon Street	1970	C	VI-A-2	40 story office tower; concrete mat on moraine deposits
11	Office Building, One Washington Mall	1968	B	IV-A-1	12 -story office building; spread footings at depth 6 m (20 ft)
12	Office Building, 28 State Street	1965	B	VI-A-1	40-story office tower; concrete mat bearing at depth 10.5 m (35 ft)
13	Office Building, 60 State Street	1976	C	VI-2 & VI-A-4	38-story office tower; 3-level basement; concrete mat on glacial till; belled caissons below plaza level
14	Office Building, 53 State Street	1982	B/C	VI-2, VI-3 & VI-1	40-story office tower; core on deep concrete mat on till; perimeter on concrete-filled pipe piles to till/bedrock
15	Public Parking Garage Dock Square	1978	B	VI-3	7-level parking structure; pre-stressed concrete piles to glacial till
16	Marketplace Center, State Street	1983	B	VI-3	16-story office building; pre-stressed concrete piles to till
17a	Lafayette Place, Washington Street, hotel	1980	B	VI-3	20-story hotel; concrete-filled pipe piles to till; depth 17 m (55 ft)
17b	Lafayette Place, Washington Street, office	1984	B	IV-A-1	3-story retail; 3 levels parking below; spread footings on sand
18	Office Building, 75 State Street	1986	B	VII-2	31-story office tower, 6 levels below; belled & straight-shaft caissons in argillite; slurry wall "up-down" construction
19	International Place, High Street	1985	C	VI-A-2	11 to 46 story office towers; 5 levels below; concrete mat & footings on till
20	33 Arch Street	2004	C	VII-2	33 story residence; 2.4-3.7 m (8-12 ft) diameter shafts drilled 3-10.6 m (10-35 ft) into argillite at depth 21-38 m (70-125 ft)
21	One Lincoln Street	2003		VII-2	36-story office tower, up-down construction with 5 levels; 17-20 m (55-65 ft) deep excavation; slurry wall cutoff & foundation wall keyed into till; interior column footings on till
22	W Boston Hotel & Residences, 100 Stuart St	2007/9	A	VI-A-2	25-story hotel; mat foundation on stratified sand, clay & silt
23	125 High Street	1991	B	VI-1	30-story office building on spread footings on till
					Waterfront
24	Long Wharf Hotel, Atlantic Avenue	1979	B	VI-3	9-story hotel; pre-stressed concrete piles to till
25	Harbor Towers & Garage, Atlantic Avenue	1969	B	VI-3	Two 40-story apartment towers & 6-story garage; concrete-filled pipe piles to depth 18-27 m (60-90 ft)
26	Rowes Wharf Development, Atlantic Avenue	1985	B	VI-4	15-story office/hotel, 5 levels below; belled caissons in till; slurry wall, "up-down construction"
27	Office Building, 745 Atlantic Avenue	1987	B	IV-A-1	10-story office, 3 levels below; concrete mat on sand
28	U.S. Coast Guard, EMS Bldg., Atlantic Ave.	1981	B	III-1	3-story maintenance facility; new structural mat over existing wood piles, plus additional pre-stressed concrete piles
29	Russia Wharf	2010	A	IV-2, VI-2 & VI-3	Hotel, condos, offices; load testing of existing wood piles on clay & till with ground freezing; mini-piles bearing on till; underlain by new Silver Line Tunnel
30	Intercontinental Hotel, 510 Atlantic Ave.	2006	A	VI-3 & VII-2	22-story hotel/condo wrapped around CA/T vent shaft; 2-concrete towers; perimeter slurry wall in till; drilled caissons to argillite; wharf on pre-augered, pre-stressed/pre-cast concrete piles bearing on till
					Copley Square
31	Exeter Towers, Exeter & Newbury Streets	1980	A	III-2	6-story apartment building; PIFs bearing in outwash sand
32	One Exeter Place, Exeter & Boylston Sts.	1983	A	III-2	13-story office building; pre-stressed concrete piles to depth 44 m (140 ft)
33	Boston Public Library Addition, Boylston St.	1972	A & B	IV-A-1	4-story library addition; mat foundation bearing on stiff clay & sand

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

(Table continued on next page)

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation (cont'd)

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Copley Square (con't.)
	Copley Place Project				All buildings founded on pre-stressed concrete piles driven to till or argillite at depth 30-50 m (100-165 ft)
34a	Copley Place Project, Westin Hotel	1980	A	VI-3 or VII-1	38-story hotel
34b	Copley Place Project, Central Hotel	1981	A	VI-3 or VII-1	Up to 15-story retail, office & parking
34c	Copley Place Project, Marriott Hotel	1982	A	VI-3 or VII-1	35-story hotel
35a	John Hancock Tower, St. James & Clarendon	1969	A	VI-III or VII-1	60-story office tower; steel H-piles driven to till or argillite
35b	John Hancock Parking Garage	1968	A	VII-2	8-story parking garage; H-piles & drilled-in-caissons into argillite; built on air rights above Massachusetts Turnpike Extension
36	The Clarendon, 400 Stuart Street	2006	A	VII-2	32-story offices & residences; 3 levels below grade with lowest level on mat design to resist hydrostatic uplift; foundations consist of LBEs in slurry wall shafts for internal columns & drilled shaft /caissons in argilllite
37	Mandarin-Oriental Hotel, Boylston St.	2003-8	A	V-2 & VII-1	Two 14-story towers on 220 ton high-capacity mini-piles permanently cased to argillite & doweled 0.68 m (2.3 ft) thick mat at 7.6 m (25 ft) bearing on outwash
					Prudential Center
38a	Prudential Center, Office Tower	1959	A	VII-2	52-story office tower; drilled-in-caissons, bearing in argillite at depth 66 m (200 ft)
38b	Prudential Center, Sheraton Boston Hotel	1962	A	VI-3	29-story hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38c	Prudential Center, Southeast Tower	1962	A	VI-3	29-story hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38d	Prudential Center, Apartment #5	1962	A	VI-3	26-story apartment building/hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38e	Prudential Center, Apartments #1 & #3	1963	A	VII-2	26-story apartment buildings; drilled-in-caissons to argillite at depth 55 m (180 ft)
38f	Prudential Center, Lord & Taylor	1966	A	VI-3	5-story retail store; concrete-filled pipe piles to depth 42 m (140 ft)
38g	Prudential Center, Sak's Fifth Avenue	1970	A	III-2	5-story retail store; PIFs & wood piles bearing in outwash sand
39	Colonnade Hotel, Huntington Avenue	1971	A	III-2	12-story hotel; PIFs bearing in outwash sand
40	Hilton Hotel, Dalton Street	1981	A	VI-3	20-story hotel & garage; pre-stressed concrete piles & PIFs
41	Hynes Auditorium, Boylston Street	1960	A	VI-3	Two-level municipal auditorium, basement; concrete-filled pipe piles to till or rock at depth 60 m (200 ft)
42	Hynes Convention Center	1985	A	VII-2 (mod)	Expansion area; drilled piles into argillite (250 tons)
43	111 Huntington Avenue	2001	A	VII-2 (mod)	36-story office building; 1.2-1.8 m (4-6 ft) diameter drilled shafts into argillite at 43 m (140 ft)
					Christian Science Church Center
44	Church Park Apartments	1971	A	III-2	10-story apartment building; PIFs in outwash sand
45	Church Park Garage	1971	A	III-2	6-story parking garage; PIFs in outwash sand
46	Symphony Towers, Mass Ave & Huntington	1971	A	III-2	Two 12-story apartment buildings; PIFs in outwash sand
47a	Church Center, Sunday School Bldg.	1968	A	III-2	Five-story building; PIFs in outwash sand
47b	Church Center, Colonnade Building	1968	A	III-2	Five-story building; PIFs in outwash sand
47c	Church Center, Administration Building	1968	A	VI-3	28-story office building; concrete-filled pipe piles to depth 52 m (170 ft)
48	Greenhouse Apartments, Huntington Ave	1981	A	III-2	12-story apartment building; PIFs in outwash sand
49	Ingalls Building, 855 Boylston Street	1987	A	III-2	12-story office building; PIFs in outwash sand
					Government Center
50	One, Two & Three Center Plaza	1963	C	VI-A-2	8-story office building; footings on moraine deposits
51	McCormack State Office Building	1969	C	VI-A-2	22-story office building; footings on moraine deposits
52	Saltonstall State Office Building	1963	C	VI-A-2	16-story office building; concrete-filled pipe piles into till
53	J.F. Kennedy Office Building	1966	C	VI-A-3	25-story office building; mat foundation
54	State Services Center, Staniford Street	1970	C	VII-2	8-story office building; drilled rock-socketed caissons
55	Boston City Hall	1964	B	VI-3	6-level municipal building; concrete-filled pipe piles to till
56	U.S. Government Services Building	1985	B	VI-3	10-story office; pre-stressed concrete piles to till, portion on steel H-piles

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Boston Commons & Public Area
57a	Taj Boston Addition, Arlington Street	1980	B	III-2	18-story hotel; PIFs
57b	Taj Boston Parking Garage, Newbury St.	1980	B	IV-A-2	Friction pre-stressed concrete piles in marine deposits
58	Four Seasons Hotel, Boylston Street	1982	B	III-2	13-story hotel/condominium; 2 levels with parking under; PIFs to sand layers in marine deposits
59	State Transportation Building, Park Plaza	1981	B	IV-A-1	8-story building; concrete mat foundation at depth 10.5 m (35 ft); slurry wall around perimeter
60	Tremont-on-the-Common, Tremont St.	1963	B	VI-3	25-story apartment; concrete-filled shell piles to till
61	500 Boylston Street/222 Berkeley Street	1986/9	A	IV-A-1	25- & 6-story office buildings with 3 parking levels below; mat foundation on marine clay for larger building; spread footings & tension piles for 6-story building; 29- & 23-story buildings with 3 levels parking below; slurry wall for excavation
62	Heritage on the Garden, Boylston Street	1986	B	IV-A-1	13-story condominium, 2 & 3 levels below; concrete mat on marine deposits
63	Millennium Place I, II & III	2001	C	VI-A-2	Ritz-Carlton, 36- & 38-story hotel towers; I utilized up-down construction & LBEs; II & III on mat foundation on deformed clay & sand
64	45 Province Street	2009	C	VI-2	31-story residences; slurry wall & 1.2-m (4-ft) diameter caissons in till at depth 18-23 m (60-75 ft)
96	MP-3, Hayward Place	2012	C	VI-A-2 & VII-2	15-story residential tower on split foundation consisting of mat on overthrust deposits & 1 m (3-4 ft) diameter drilled shafts in argillite to depth 24 m (80 ft)
					South End & Chinatown
65	Bradford Towers West, Stuart Street		B	IV-1	4-,6- & 9-story housing; caissons in stiff clay
66	Bradford Towers East, Tremont Street		B	IV-A-1	5- & 7-story housing; spread footings on clay, portion on deep caissons near subway
67	Elderly Housing, Washington Street		B	IV-A-1	Concrete mat on clay
68	Tufts Health, Science, Education Bldg.	1984	B	IV-A-1	9-story medical facility; concrete mat on clay
69	Wang Laboratories, Kneeland Street	1984	A	VII-1	10-story building; pre-stressed concrete piles to till or bedrock at 38 m (125 ft)
70	Tufts New England Medical Center	1978	B	VII-1	9-story medical center; pile driven to bedrock for high column
71	Boston Common/Park-Essex, 600/660 Washington Street	2003	B		28-story residential building formerly called Park Esssex; drilled caissons supporting a 1 m (3 ft) thick mat at depth 7.6m (25 ft) below street; caissons drilled to depth 33.5 m (110 ft), 3-4.5 m (10-15 ft) rock socket into argillite
					South Station & South Boston
72	Keystone Building, 225 Congress Street	1969	C	VI-A-2	17-story office tower; footings on glacial till
73	Federal Reserve Building	1973	C	VI-A-2	35-story office tower; concrete mat on till
74	Stone & Webster Building, Summer St.	1973	B	VI-3	14-story office building; concrete-filled piles to till or rock
75	South Postal Annex Addition, Dorchester Ave.	1971	B	VII-1	6-story building; concrete-filled steel pipe piles to bearing in argillite
76	Office Building,101 Federal Street	1986	B	VII-2	32-story office building with 2 levels below; straight shaft caissons socketed in bedrock, concreted under slurry
77	Office Building, 150 Federal Street	1986	B	IV-A-1	28-story office;3 levels below; spread footings on marine deposits
78	101 Arch Street	1986	C	VI-A-4	21-story office; belled caissons in till concreted under slurry
79	Office Building, 99 Summer Street	1986	C	VI-A-2	22-story office; footings on glacial till
80	Office Building, 125 Summer Street	1987	C	VI-A-2	Special 23-story office tower with 5 levels below; LBEs (barrettes) in till & rock; slurry wall "up and down" construction
81	Office Building, 100 Summer Street	1971	C	VI-A-4	33-story office tower; belled caissons bearing in till at depth 9 m (30 ft)
82	Office Building, 175 Federal Street	1973	C	VI-A-4	14-story office tower; belled caissons bearing in till at depth 12 m(40 ft)
83	One Financial Center	1979	C	VI-A-2	46-story office tower with 2 levels below grade; concrete mat on till
					Seaport & South Boston
84	Manulife US Headquarters, 601 Congress St.	2004	A	VII-2 & IV-1	14-story tower with 12 m (40 ft) deep 2.5 levels of below grade parking; southern portion on 1.2 m (4 ft) diameter shafts drilled into several feet of bedrock; remainder 1.2-1.5 m (4-5 ft) thick concrete mat floating on marine clay with slurry wall toed into clay
86	Renaissance Boston, 606 Congress St.	2008	A	VI-1 & VII-1	22-story waterfront hotel, 18 m (60 ft) pre-augered, pre-stressed/pre-cast concrete piles driven to till & bedrock at 30.5 m (100ft).

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

(Table continued on next page)

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation (cont'd)

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Seaport & South Boston (cont'd)
87	Fan Pier (including office building at One Marina Park Dr., Vertex at 50 Northern Ave & 11 Fan Pier Blvd)	2010	A	IV-A-1 & IV-1	18-story office buildings located on Fan Pier. 1.2-1.8 m (5-6 ft) thick concrete mat on clay at depth of 12 m (40 ft); in area of old boat slip channel, One Marina Park Drive also used straight-shaft caissons (friction) in clay at 21 m (70 ft) = 9 m (30 ft) below mat
88	Boston Convention & Exhibition Center/ Westin Boston Waterfront Hotel, 415/ 425 Summer Street	2006 to 2009	A	VI & VII-1; VI-2 & VII-2	Convention center & adjoining 17-story Westin Boston Waterfront Hotel; Convention Center bearing on pre-cast 35.5 x 35.5 cm (14 x 14 in.) concrete piles driven to till & argillite and 1.2-2 m (4-7 ft) diameter caissons drilled to argillite for the larger loaded columns & lateral resistance; the low-rise portion of the hotel bearing on 105 ton design capacity 32.4 x 1 cm (12.75 x 0.375 inch) wall thickness concrete filled pipe piles driven to end bearing in till & argillite; high-rise section of hotel/tower supported on a series of 1-2 m (3-6 ft) diameter rock-socketed drilled caissons
89a	World Trade Center East/Seaport Center East 2 Seaport Lane/255 Seaport Blvd	2000	A	IV-A-1	16-story office with 3-level below grade garage; concrete mat on clay
89b	World Trade Center West/Seaport Center West/155 Seaport Blvd	2002	A	IV-A-1	17-story office with 3-level below grade garage; concrete mat on clay
90	Seaport Boston Hotel, 1 Seaport Lane	1996 to 2000	A	IV-A-1	14-story hotel, 17-story west office bldg., 17-story east office bldg. with 3-level garage under; buildings on mat bearing on marine clay; garage on spread footings on clay; perimeter wall sealed into top of clay as groundwater cutoff
91	Park Lane Seaport I & II, 1 Park Drive	2004 to 2006	A	IV-A-1 & VI-1	13- & 21-story residential buildings; low-rise bearing on 1.2-1.8 m (5-6 ft) thick mat on clay at depth 12 m (40 ft); high-rise on steel H-piles bearing on till at depth 33.5-36.5 m (110-120 ft).
					Charles River Park & Longfellow Place
92a	510 Emerson Place	1960	B	VI-3	15-story apartment on concrete-filled piles
92b	10 Emerson Place	1960	B	VI-3	23-story apartment on concrete-filled piles
92c	8 Whittier Place	1962	B	III-2	23-story apartment on PIFs
92d	6 Whittier Place	1962	B	III-2	15-story apartment on PIFs
92e	Amy Lowell House	1974	B	III-2	11-story apartment on PIFs
92f	Parking Garage	1973	B/C	III-4 & VI-A-3	Spread footings & pipe piles
92g	One & Two Hawthorne Place	1973	B/C	III-4 & VI-A-3	15-story apartment; spread footings & caissons
92h	One Longfellow Place	1973	C	VII-A-1	36-story apartment; spread footings on rock
92i	Four Longfellow Place	1973	C	Vi-A-3	36-story apartment; concrete-filled pipe piles
92j	South Staniford Street	1973	C	VI-A-1	10-story apartment; spread footings on soil
93a	Massachusetts General Hospital, Charles Street, Ambulatory Care Center	1980	B	VI-3	8-story medical facility; concrete-filled pipe/steel shell (composite) piles to till at depth 21 m (70 ft)
93b	Massachusetts General Hospital, Cox Bldg.	1979	B	III-2	7-story medical facility; PIFs in sand
93c	Massachusetts General Hospital, Lunder Bldg.	2010	A	VI-VII-2	14-story medical building with up-down construction, 3 levels below grade; perimeter slurry wall; interior columns on 1.2 m (4 ft) diameter drilled caissons in till & bedrock
94	Massachusetts Eye & Ear Infirmary, Charles Street	1969	B	VI-2	13-story facility; adjacent & above original 5-story wood pile supported building;150 ton PIFs in till at 24 m (80 ft) with steel cased shafts
95	Spaulding Rehabilitation Ctr, Nashua St.	1980	B	VI-3	10/6-story nursing facility; concrete-filled pipe piles to till
96	Liberty Hotel, 215 Charles Street	2007	C	VII-1	16-story hotel on pre-stressed/pre-cast concrete piles
					Huntington Avenue & Longwood Medical Center
97	541-555 Huntington Ave, Wentworth Institute	2003	A	IV-1 & IV-2	7-story residential building; western portion of site on belled caissons in yellow clay crust; eastern portion on mini-piles in clay to avoid MWRA Muddy River sewer easement
98	West Campus, Northeastern U., Bldgs A-G	2000	A	IV-4	6 buildings, 4-11 stories, with 1-1.2 m (3.5-4 ft) thick mat foundations bearing on shallow stiff clay at depths between 2 & 6 m (7-20 ft)
99	International Village, Northeastern U.	2000	A	IV-4 & III-2	3 dormitory buildings 22-24 stories with 5-story interconnected bldg.; dormitories on 1-1.2m (3.5-4 ft) thick mats bearing on stiff clay at depth of 6 m (20 ft); 5-story building on PIFs in upper outwash

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

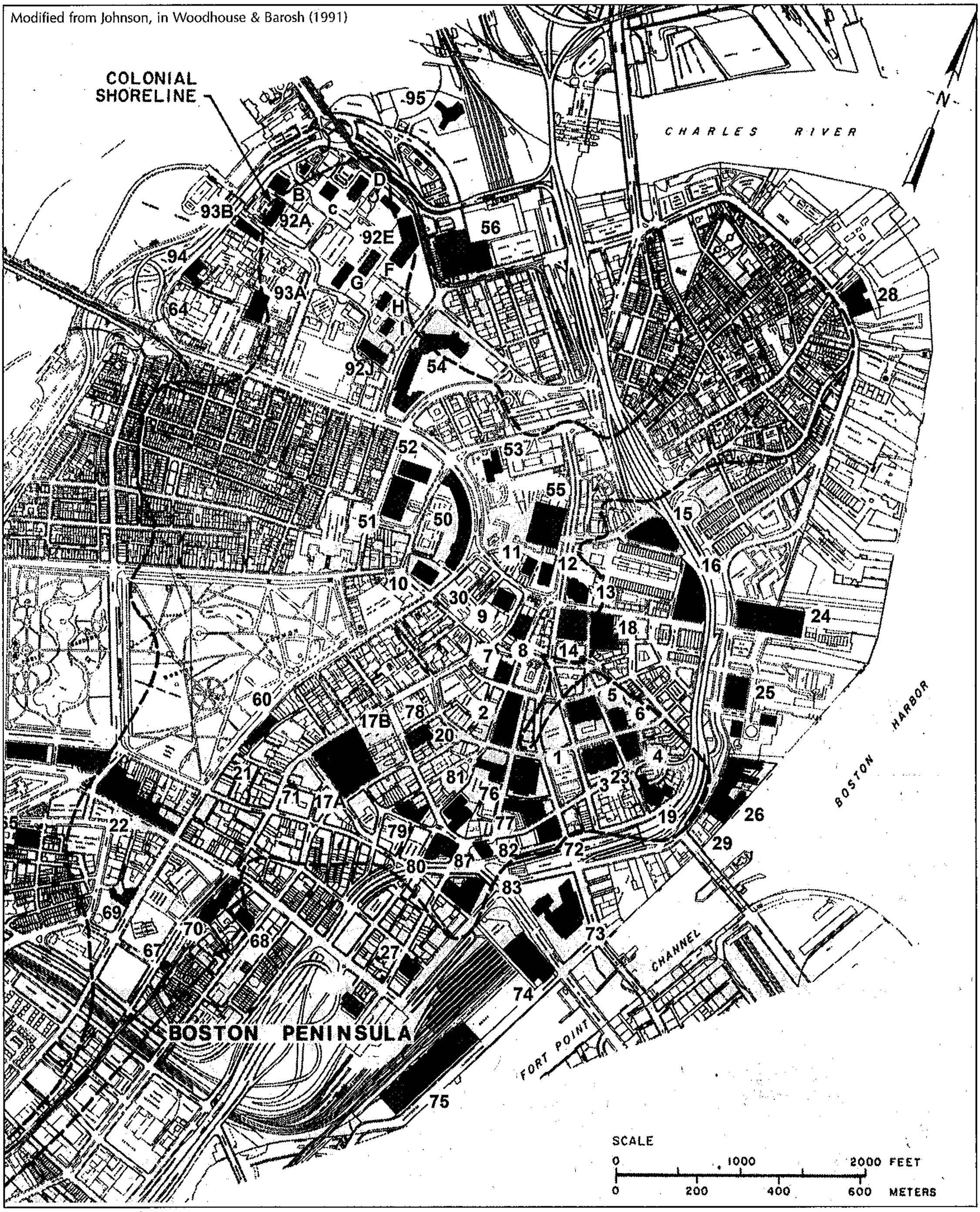


FIGURE 5-1. Map of downtown Boston showing the location of major buildings constructed since 1960.

glass were causing an inherent weakness in the windows when they experienced stress from wind load and differential thermal gradients.

The nearby John Hancock Parking Garage required the installation of 30 meter (100 foot) deep drilled-in caissons into the argillite. Some were installed within a narrow median strip

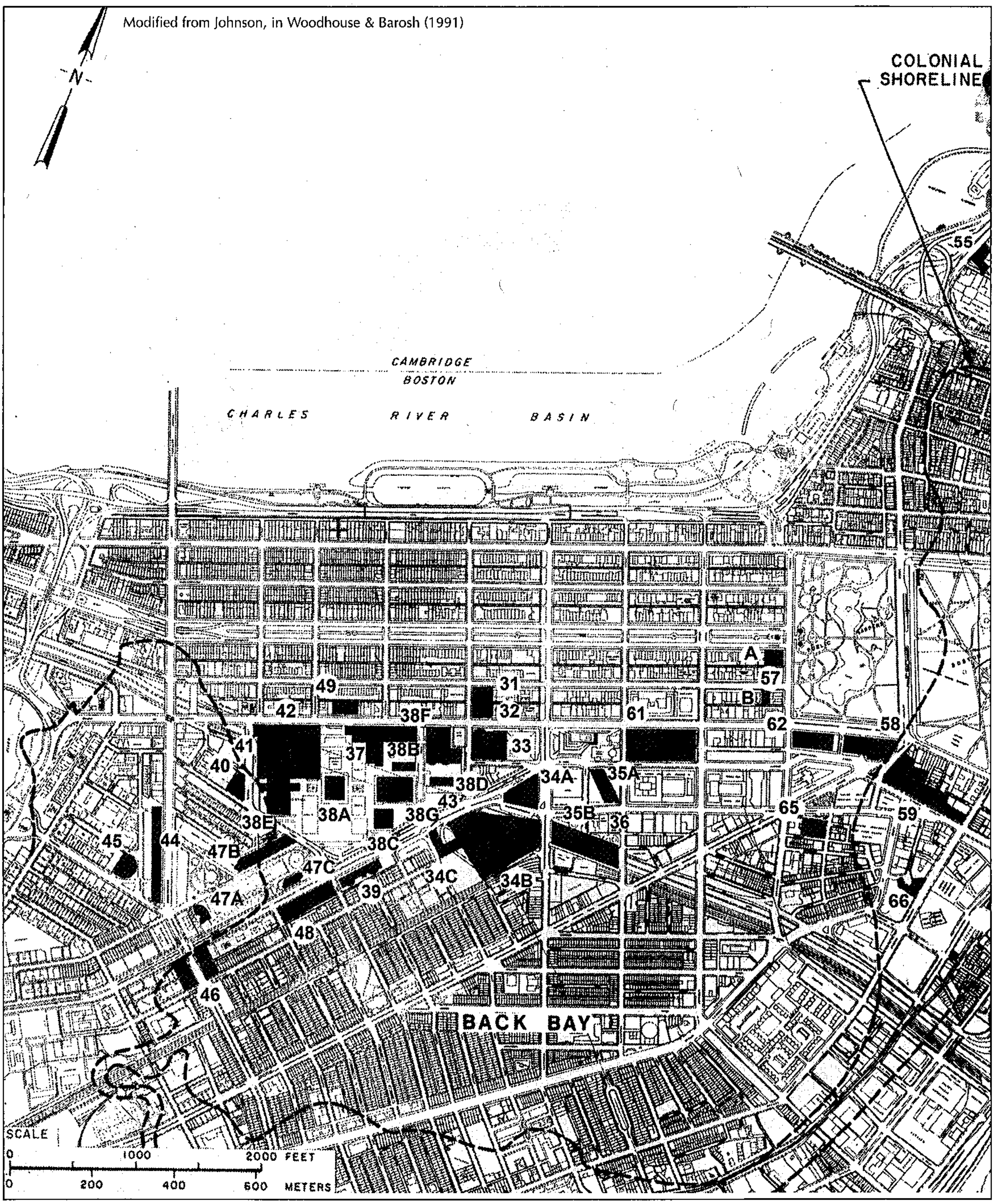


FIGURE 5-2. Map of Back Bay showing the location of major buildings constructed since 1960.

between depressed roadway sections of the Massachusetts Turnpike Extension. The Copley Place Project, built in the early 1980s on a triangular plot of land bounded by Dartmouth Street, Stuart Street and Huntington Avenue, includes two hotels (thirty-five and thirty-eight stories), plus offices and retail space. Foundations consist of pre-stressed concrete piles driven to till or bedrock at depths between 30 and 50 meters (100 and 165 feet).

Recently, the twenty-five-story Liberty Mutual Building has been constructed in 2012 at the corner of Berkeley Street and Columbus Avenue. Its foundation and structure consist of up-down construction with four levels below grade that utilize slurry walls and internal slurry panels called load-bearing elements (LBEs). Surficial materials consist of 6 meters (20 feet) of fill, a 6 meter (20 foot) layer of organic silt and a 23 meter (75 foot) layer of typical marine clay having depths of 12 to 35 meters (40 to 115 feet), below which the bedrock was found. Many old wood piles and Gow caissons hindered excavation operations. Also using a similar type of foundation is the Clarendon, a thirty-two-story office and residential tower that was constructed from 2006 to 2008 at the corner of Stuart and Clarendon streets south of the John Hancock Tower. The building consists of three levels below grade that use slurry wall construction, with the lowest level on a mat design that resists hydrostatic uplift. Foundations consist of LBEs in the slurry wall shafts for the internal columns and drilled shafts/ caissons into the argillite.

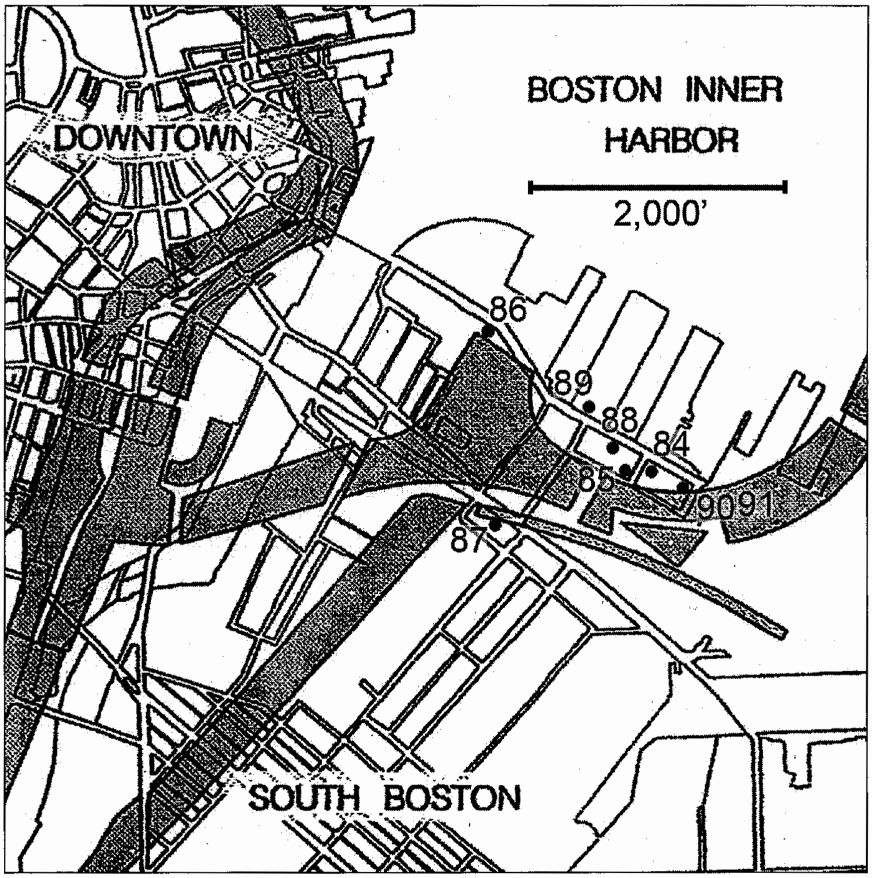


FIGURE 5-3. Map of South Boston showing the location of major buildings constructed since 1960.

One of the most historic structures in Boston is Trinity Church, which has weathered several "attacks" on its foundations. In 1872, parishioners of the first Trinity Church on Summer Street that was destroyed by a fire purchased two building lots totaling 0.367 hectares (39,487 square feet) of newly filled land in what became Copley Square (see Figure 5-6). The new church was constructed between 1872 and 1876 and consecrated in 1877. The church was designed by the renowned architect H.H. Richardson in the French Romanesque style that became known as Richardson style (see Figure 5-7). The stone used is listed by the church as Monson Granite and Longmeadow Sandstone, which is the red Triassic sandstone that was so popular at the time. However, according to Richter and Simmons (1993), Dedham Granodiorite from local quarries and Westerly Granite from Westerly, Rhode Island, also were used. The central tower weighed (Jarrett, 2012) about 8.6 million kilograms (9,500 tons).

This weight was supported by 4,500 cedar wood piles, 6 meters (30 feet) long with granite caps. The pile foundation consisted of four

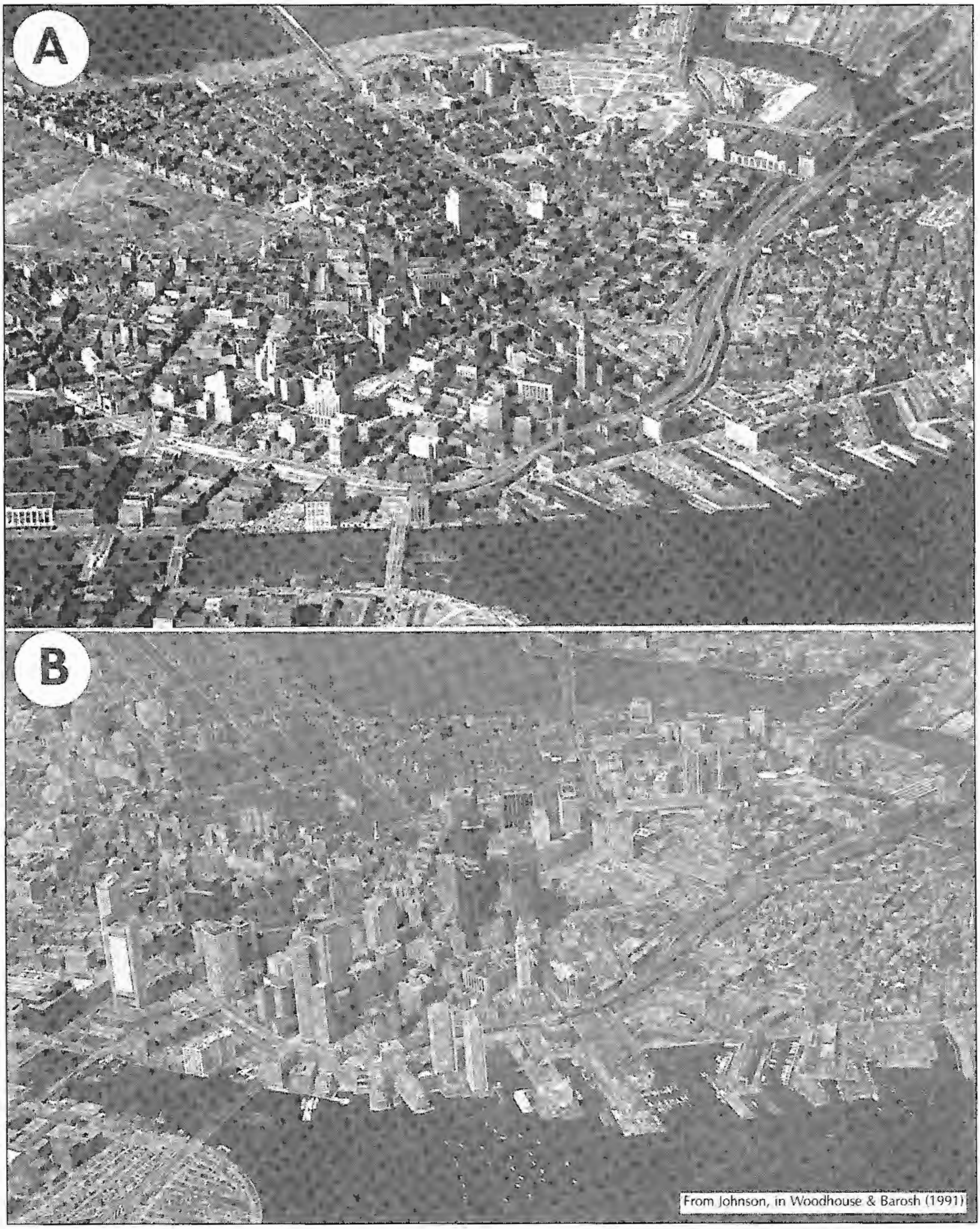


FIGURE 5-4. Aerial views of downtown Boston in (A) 1959 and (B) 1987. (Courtesy of Aerial Photos International, Inc.)

square groups, 10.7 meters (35 feet) on each side (700 piles each) that underlie pyramid-shaped granite pedestals, which serve as the bases for the four main columns of the church. (see Figure 5-8). Each 5.2 meter (17 foot) high granite pyramid is made up of granite blocks

(see color version on page 470)

FIGURE 5-5. Aerial view of Boston view on May 18, 2012. (Courtesy of lesvants.com.)

0.6 by 1.2 meters (2 by 4 feet) and 0.6 by 2.4 meters (2 by 8 feet) and is 0.65 square meters (7 square feet) at the top (see Figure 5-9). One of the granite block pile caps is exposed in the basement of Trinity Church, allowing the public to see the support for the church (see Figure 5-10).

The overburden deposits underlying the church are typical for the Back Bay. These deposits are about 6 meters (20 feet) of granular fill, organic clay and silt that extends in depth from 6 to 14 meters (20 to 45 feet), thin upper outwash sand, thick marine clay, lower outwash and till over Cambridge Argillite. The bearing stratum for the 9 meter (30 foot) long wood piles (see Figure 5-11) is either the upper outwash sand or the 1.5 meter (5 foot) thick stiff yellow clay crust of the marine clay at a depth between 13.7 to 15.2 meters (45 to 50 feet). The marine clay thickness is on the order of 24 meters (80 feet) to depths between 38 to 43 meters (125 to 140 feet); the dense strata below the clay are at a sloping surface. A 6 to 7.6 meter (20 to 25 foot) lower outwash sand and gravel underlies the clay to a depth of 44 to 50 meters (145 to 165 feet) and overlies the 3 to 4.5 meter (10 to 15 foot) thick till that extends to a depth of 44 to 55 meters (160 to 180 feet). Decomposed and weathered argillite lies at this depth.

During the time of the church's construction in the late nineteenth century, it was common practice in the Back Bay to cut off wood pile tops below the water table at an average tide level of elevation 5 feet Boston City Base (BCB). The "0" datum of BCB is set at 5.65 feet below mean sea level (MSL). Thus, the tops of the piles that were cut off at elevation 5.0 BCB or 1.5 meters (5 feet) below mean low tide have their tops at about 4 meters (13 feet) below the surrounding street grade. It was essential to keep the piles saturated in order to prevent rotting. The groundwater level in the Back Bay during the end of the nineteenth century was generally found to be at about elevation 2.4 meters (8 feet) BCB (2.48 MSL) and considered sufficient for this purpose. The pile caps at Trinity Church were originally designed with a waterway for a small boat to check water levels. A system of automatic sen-

FIGURE 5-6. Trinity Church, which was constructed from 1872 to 1876, is shown circa 1875. (Courtesy of the Boston Public Library, derived from stereograph.)

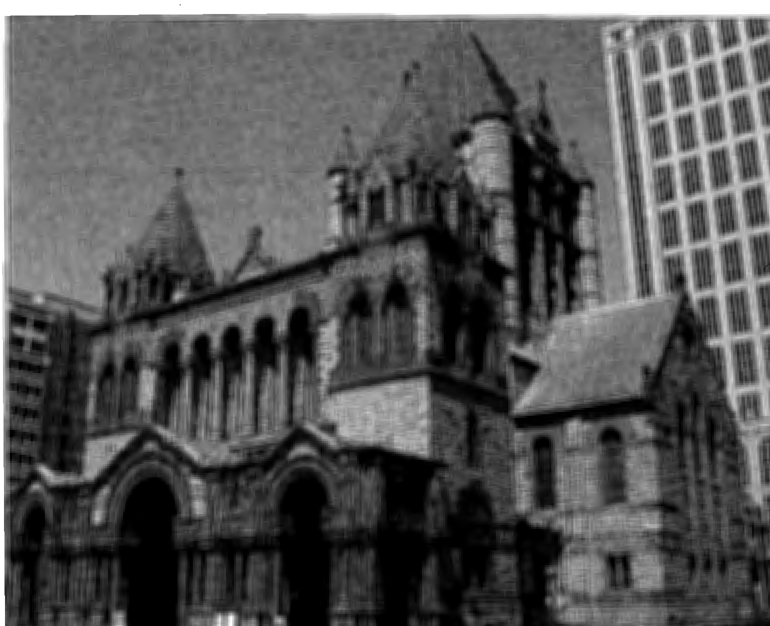


FIGURE 5-7. Trinity Church, west side of Copley Square in July 2005. (Courtesy of Mathias.)

sors now monitors the water level and water can be pumped in if it drops to a level that would affect the integrity of the piles.

The Trinity Church began to measure settlement of the central tower in the 1920s. It was found at that time that the heavy load on the wood piles had caused it to have settled about 30 centimeters (1 foot) since it was first constructed. Subsequent survey measurements found that through 1968 an additional 7.6 to 10 centimeters (3 to 4 inches) of settlement had occurred in six areas around the church. During construction of the John Hancock Tower from 1968 to 1972, differential settlement of many inches was measured along the south side closest to the tower (adjacent to St. James Avenue) and migrated horizontally toward the John Hancock excavation. This uneven settlement necessitated repairs to the church. This settlement problem also led to a lawsuit involving the John Hancock Insurance Company, for whom the tower was being built. The court found that the settlement resulted from movement of the excavation support system for the deep basement of the tower. The steel sheet pile excavation support system deflected several feet and caused considerable damage to adjacent structures, including the Trinity Church. St. James Avenue, which

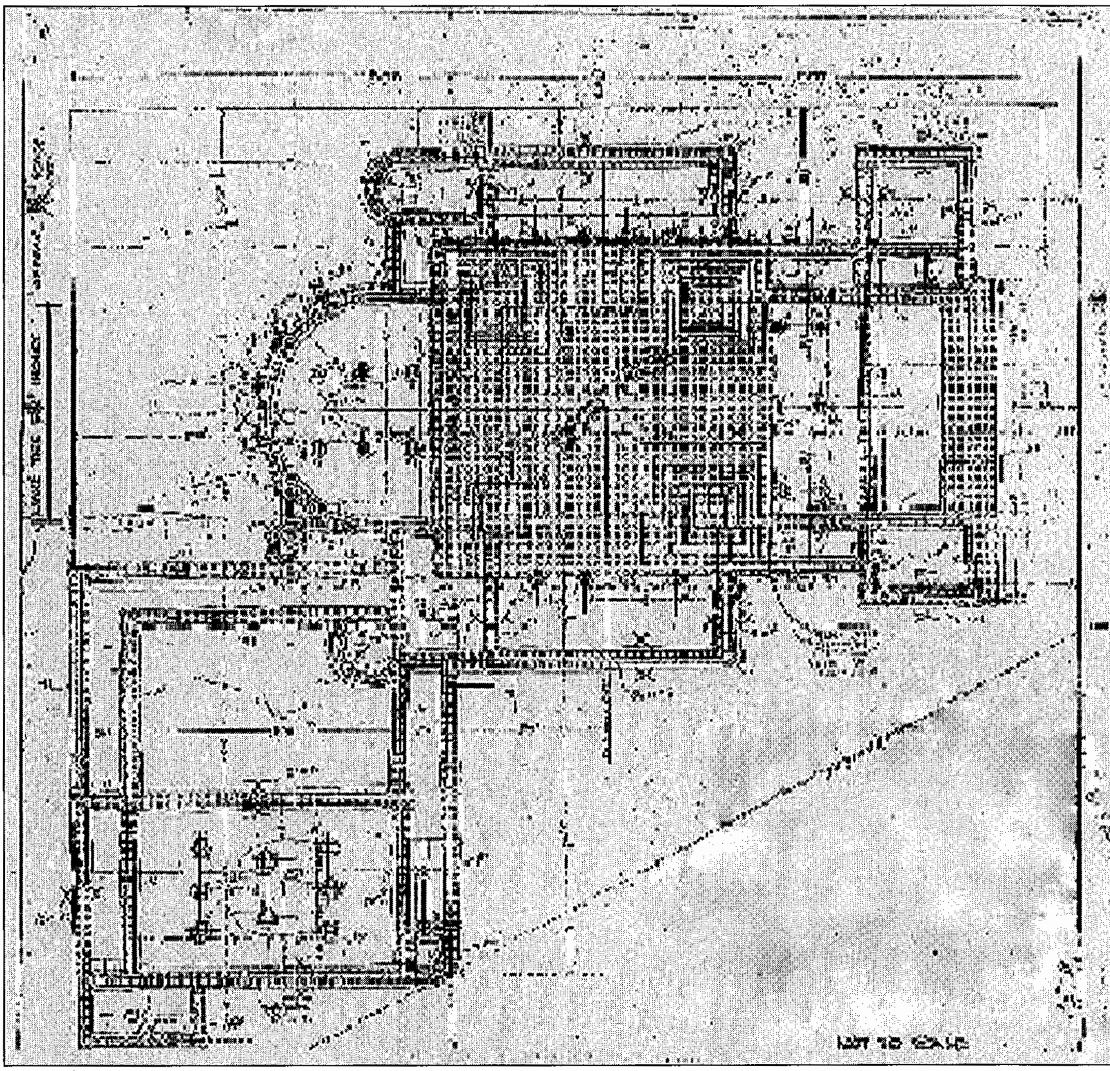


FIGURE 5-8. Trinity Church showing the plan for its pile foundation that was later augmented. (Courtesy Jean Carroon, Goody Clancy Inc.)

divides the church from the John Hancock Tower to the south, had settled more than 46 centimeters (18 inches) and lateral deflections in the tower excavation support walls were up to 110 centimeters (3 to 4 feet). Walls of the church had been pulled laterally as well and had to be knitted back together (Carroon, 2012). A list of other damage caused by the settlement were sealed by the court, as well a list of the necessary repairs effected.

Because of general concern based on the history of the church and recent issues with the John Hancock Tower, the church enacted a program from 2002 to 2005 to check the integrity and condition of the wood piles supporting the church. A number of test pits were dug to expose the condition of the piles. Wood piles that had been exposed above the groundwater level and that showed deterioration were repaired. These piles were mostly found under the church chancel. The rotted sections of the pile tops were removed and replaced by steel that was encased in concrete (see Figures 5-12 & 5-13).

Back Bay — Prudential Center. The group of buildings that comprise an area of 9.3 hectares (23 acres) generally west of Copley Square between Huntington Avenue and Boylston

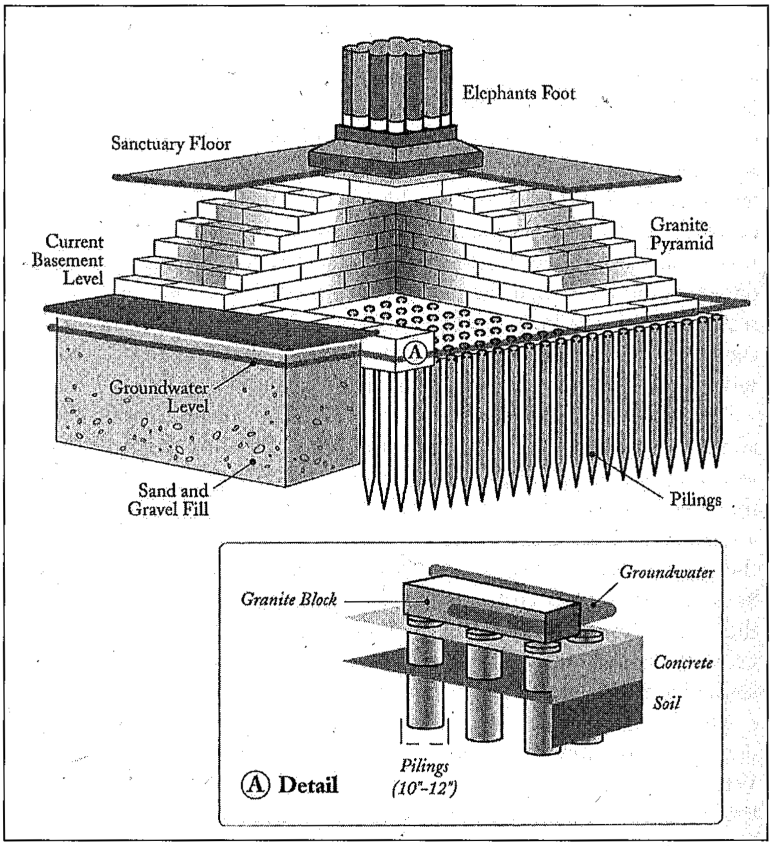


FIGURE 5-9. Trinity Church pile cap design. (Courtesy of the Globe Newspaper Company.)

FIGURE 5-10. Trinity Church basement showing the top of the pile cap approximately 2.3 m (7.5 ft) above the basement level.

Street is known as the Prudential Center (see Figure 5-2). The site was an old switchyard for the Boston and Albany Railroad from the time of original filling until the late 1950s. The complex that was constructed between 1960 and 1970 was comprised of seven buildings that included two office towers, two retail buildings, a hotel and two apartment buildings (see Table 5-1). The Prudential Center proved to be a catalyst for new development in Boston's Back Bay. The fifty-two-story Prudential Tower (built from 1960 to 1964) at 800 Boylston Street is 228 meters (749 feet) high and was the tallest building in Boston for ten years until the rival new John Hancock Tower at 241 meters (790 feet) was built. The Prudential Tower is supported by caissons drilled into the argillite. Because the bedrock was found to be weak, the caissons had to be drilled deep into the argillite, which amounted to depths from ground surface as deep as 61 meters (200 feet) (Kaye, 1982a; Ball, 1962).

The diversity of the foundation conditions in a short distance in the Prudential complex is shown by the other seven buildings in the Prudential Complex: the twenty-nine-story Sheraton Boston Hotel (built in 1962) is founded on 36 centimeter (16 inch) diameter concrete piles to till at 45 to 60 meters (150 to 200 feet); three (the Southeast Tower, Apartment 5 and the Lord & Taylor department store) are supported on concrete-filled pipe piles driven to the till or bedrock at depths up to 61 meters (200 feet); two (Apartment Buildings 1 and 3) are supported on 55 meter (180 foot) deep drilled-in caissons that penetrate into argillite; and the seventh building (originally the Sak's Fifth Avenue) is founded on a combination of Franki piles (pressure-injected footings [PIFs]) and wood piles, both bearing in the upper outwash. Other major buildings in the area of the Prudential Center include the Colonnade Hotel (built in 1971) and the Hilton Hotel (built in 1981) that were founded on deep pre-cast, pre-stressed concrete piles in concert with shallow PIFs in the outwash. Hynes Auditorium (built in 1960) used concrete-filled pipe piles driven to till or rock at a depth of 60 meters (200 feet). The Hynes Convention Center (built in 1985) expansion on Boylston Street is supported by 2,224 kilonewton (250-ton) high-capacity drilled piles into the argillite.

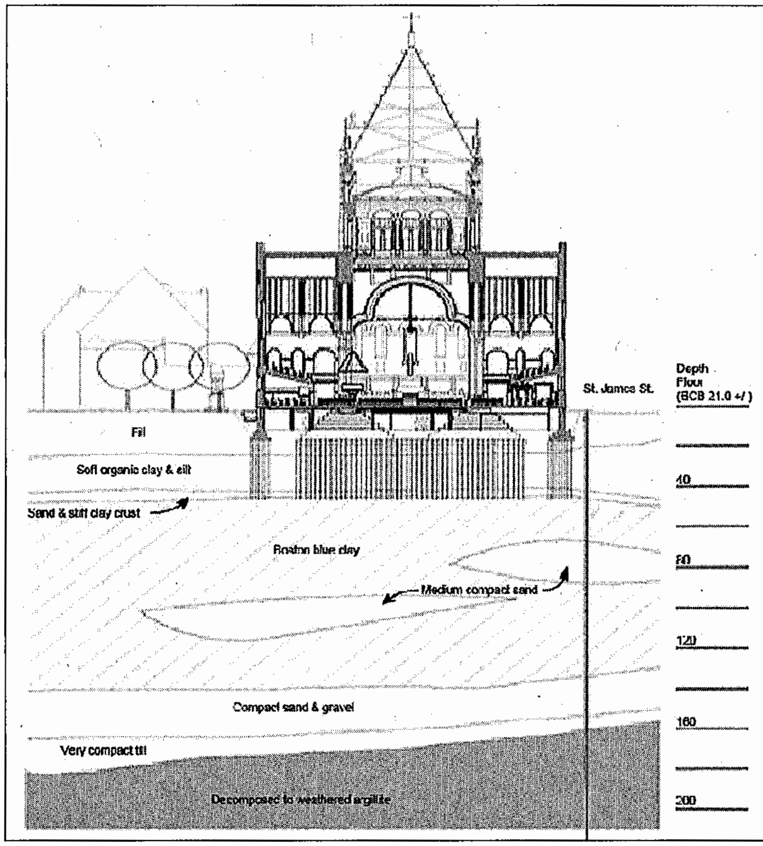


FIGURE 5-11. Section beneath the Trinity Church showing geologic units, extent of piles and geothermal well. The section consists of Cambridge Argillite, till, Lower Outwash, marine clay with weathered crust, organic deposit and fill. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

The largest structure built in the Prudential Center complex since 1987 is the thirty-six-story 111 Huntington Avenue building, affectionately called the R2-D2 building (as a reference to the Star Wars droid that it resembles), which was completed in 2002. Its foundation consists of 1.2 to 1.8 meter (4 to 6 foot) diameter shafts drilled into the underlying argillite at a depth of 43 meters (140 feet). The Mandarin-Oriental Hotel is located on Boylston Street about one block away from the Boston Public Library and was constructed during the period 2005 to 2008. The complex consists of two fourteen-story towers containing apartments and condominiums with two below-ground parking levels. The smaller of the two tower structures was the first building in Boston founded on mini-piles that have a high-capacity design load of 1,957 kilonewtons (220 tons). The mini-piles were permanently cased to the argillite bedrock. The larger building has a 68 centimeter (27 inch) mat foundation bearing on the upper outwash sand at a depth of 7.6 meters (25 feet) to accommodate the garage. The mini-pile foundation was doweled into the mat for added support.

Back Bay — Christian Science Center. The Christian Science Church owns considerable property west of the Prudential Center along Huntington Avenue and Massachusetts Ave-

FIGURE 5-12. Trinity Church rotted tops of piles beneath the cap. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

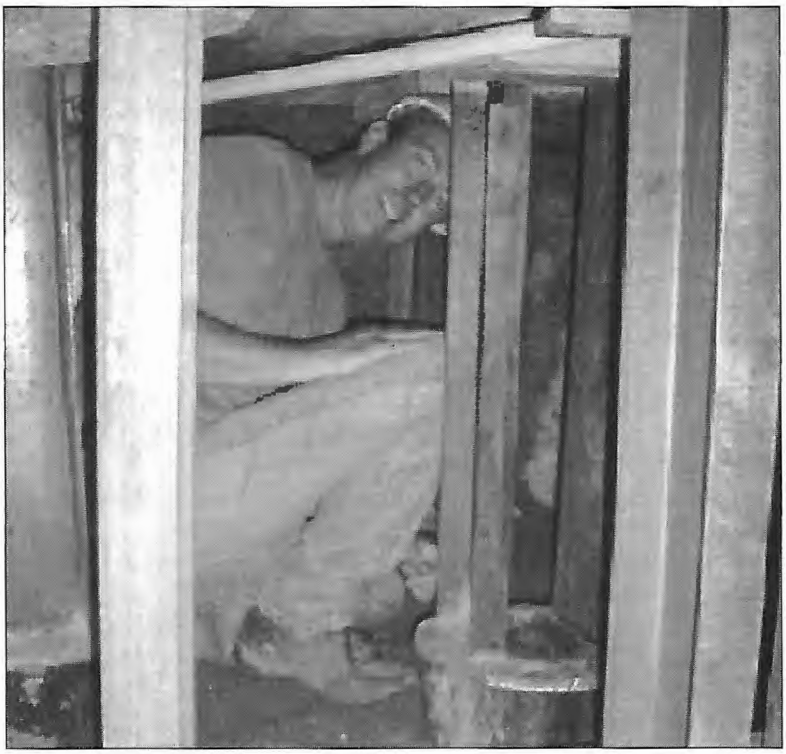


FIGURE 5-13. Trinity Church steel replacements of pile tops beneath cap. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

nue, the majority of which was developed between 1968 and 1971 (see Figure 5-2). The area is underlain by the upper and lower outwash sand and gravel. The upper outwash allowed the use of PIFs in the sand to support six of the seven buildings that were up to twelve stories in height. These buildings included the five-story Sunday School Building (built in 1968), the ten-story Church Park Apartments (built in 1971), the six-story Church Park Garage (built in 1971), the twelve-story Symphony Towers (built in 1971), the five-story Colonnade Building (built in 1968) and the twelve-story Greenhouse Apartments. Because of the size and loads of the twenty-six-story Administration Building on Huntington Avenue, the structure is supported on concrete-filled pipe piles to a depth of 52 meters (170 feet). The new Mother Church was founded on end-bearing wood piles in the same outwash. When a new facade was added, it became necessary to uncover some of these old piles in order to check on their condition. The inspection revealed that a number of the piles had been pulled out of their concrete pile cap by a soil phenomenon called negative skin friction (where the surrounding soil settles and drags the pile with it). This discovery necessitated that the old foundation (concrete pile cap) be underpinned with six new concrete footings that are founded on the outwash sand that encased the top few feet of the old wood piles. Woodhouse noted that concrete was poured to within a few centimeters (inches) of the old pile cap and dry-packed with cement. Dewatering was carried out by using well points that lowered the water table in the outwash by 2.4 and 1.7 meters (8 and 5.5 feet) at distances of 12.2 and 70 meters (40 and 230 feet) from the excavation.

Back Bay & Fenway — Huntington Avenue & Longwood Medical Area. A number of new buildings have been constructed on the western campus of Northeastern University since 2000. This area at one time was a part of the Back Bay Fens and the Fenway, and along Ruggles Street there is a deep bedrock valley that was filled with marine clay. However, deep foundations have not been needed for foundations of most buildings in the West Campus complex that includes six new buildings — A through G that vary in height from four to eleven stories (Gorczyca, 2013). There are no organic soils between the surficial fill and the upper outwash (Lexington Substage). However, the top of the stiff crust of the thick marine clay is only about 3 meters (10 feet) below the ground surface. The six buildings bear on 1 to 1.2 meter (3.5 to 4 foot) thick mats on the stiff crust of the clay at depths of 2 to 6 meters (7 to 20 feet). The weight of soil/fill that was excavated counteracted the added weight of the buildings, making these examples of "floating buildings." No relief slab drainage was necessary. On the southern side of the Massachusetts Bay Transportation Authority (MBTA) Orange Line, Northeastern University's International Village complex consists of two twenty-two- to twenty-four-story tall dormitories interconnected by a five-story building. At this location, the top of the clay is 6 to 7.5 meters (20 to 25 feet) deep. A mat foundation bearing on the crust of the thick marine clay, similar to that at the West Campus, was used for the dormitory towers. The interconnecting building is supported by PIFs bearing in the upper outwash above the clay.

The building at 541-555 Huntington Avenue is a seven-story residence hall constructed in 2003 at the Wentworth Institute of Technology. The building is founded on a combination of belled caissons and drilled mini-piles on the eastern site portion where the Metropolitan Water Resources Authority/ Metropolitan District Commission (MWRA/ MDC) Muddy River sewer easement is located (Hover, 2013). Subsurface conditions consist of up to 6 meters (20 feet) of fill overlying a 3 to 4.5 meter (10 to 15 foot) thick organic layer. The upper outwash sand and gravel with a thickness of 0.5 to 2 meters (1.5 to 7 feet) underlies the organics, which in turn overlies the marine clay. The clay was found to be up to 26 meters (85 feet) thick from a depth between 8 and 9.5 meters (26 and 31 feet), with the bottom of the layer at 34.5 meters (113 feet). At this location, the lower outwash sand was encountered, but it was not fully penetrated by the test borings. The Boston Society of Civil Engineers (BSCE) boring logs show the top of bedrock at about 33.5 meters (110 feet), but one of the borings reached 36.5 meters (120 feet) without encountering bedrock. Design engineers took advantage of the 3 to 6 meter (10 to 20 foot) thick hard crust in the yellow clay and installed belled caissons in the upper 3 meters (10 feet) with a bearing capacity of 479 kilonewtons per square meter (5 tons per square foot). The caissons were from 2.4 to 3.5 meters (8 to 11.5 feet) in diameter with shafts of 1.8 to 2.1 meters (6 to 7 feet). Drilled 25 centimeter (10 inch) diameter minipiles with a 356 kilonewton (40 ton) capacity were installed 6 to 7.5 meters (20 to 25 feet) into the clay on the eastern side. Total pile length was 13.7 to 16.8 meters (45 to 55 feet) with a skin friction of 72 kilonewtons per square meter (1,500 pounds per square foot) and 5 tons per pile were allowed for downdrag from negative skin friction.

The MassArt Tower at 621 Huntington Avenue, located about two blocks west of the Museum of Fine Arts, was built between 2010 and 2012. The foundation for the tower consists of HP 14x117 steel piles driven to a depth of 41 to 55 meters (135 to 180 feet) to the argillite. Very dense soils were encountered at a depth of 31 meters (100 feet). However, the piles were driven through these soils to bedrock for the necessary end bearing.

Farther west along Huntington Avenue is the Longwood Medical Area (LMA), a famous medical campus in Boston that forms a triangular area bounded in broad terms by the Muddy River, Huntington Avenue and the Fenway. The LMA is centered on the main thoroughfares of Longwood Avenue and Brookline Avenue as they run from Huntington Avenue to the Riverway. It is strongly associated with the Harvard Medical School and related medical facilities, such as Harvard's teaching hospitals, but prominent non-Harvard and non-medical institutions are located there as well. The Longwood area was formerly a swampy, tidal area associated with the Muddy River where it entered the Charles River in colonial times.

In the area of the Muddy River, deep sediments fill an ancient bedrock valley that reaches a bottom elevation of about –65 meters (–200 feet) MSL (Kaye, 1970 & 1982b). In this valley, the foundation investigation for the Beth Israel Feldberg Building at the corner of Longwood Avenue and Brookline Avenue (GEI, 1972) found in descending order 4.5 to 7.5 meters (15 to 25 feet) of granular materials, cinders, bricks, peat and wood; up to 1.5 meters (5 feet) of peat and organic sand below; clay and silty fine sand up to 21 meters (70 feet) thick; till 12 to 17 meters (40 to 55 feet) thick with lenses of varved, lacustrine silt and clay sediment possibly representing local ponding during original deposition. Argillite bedrock at this particular location was encountered at a depth of 45 meters (128 feet). In the Muddy River/ Fens area, deep end-bearing piles would be expected to be the foundation of choice for tall, heavy buildings.

Along the southwest area of the LMA, the topography rises onto the northern slope of the Parker Hill/Mission Hill drumlin. At this location, the shallow till offers a competent bearing material for footings and mat slabs. As the Riverway (Muddy River) is approached to the west, Woodhouse has noted that outwash sands are known to overlie the clay.

Hospital and research institutions have constructed several new buildings since the late 1990s in the LMA, where the foundation used depends on the building's location.

At the Longwood Center at Brookline and Longwood avenues, in an area of thick clay, a deep foundation was used for the eleven-story medical building for the Dana Farber Cancer Institute and the Longwood Medical Eye Center (adjacent to the Joslin Diabetes Center). The Boston Children's Hospital expansion is a ten-story facility (to be completed in 2013) located at 57 Binney Street, diagonally across from the Feldberg Building (where pile foundations were used). The Beth Israel Deaconess Medical Center is building an eighteen-story facility at Blackfan Street and Longwood Avenue, located just southeast of the Feldberg Building with the similar subsurface conditions and deep foundations. This building is scheduled to be completed in 2014.

Subsurface conditions change markedly at sites uphill from the Muddy River Valley. Brigham and Women's Hospital, at the north end of Parker Hill, which is underlain by shallow till, used shallow footings for a new clinic and laboratory building. Shallow footings were also used for the uphill Mass Eye and Ear, a six-story building at 800 Huntington Avenue, and for Harvard Medical at 25 Shattuck Street (to be occupied by Beth Israel Deaconess and the Dana Farber Cancer Institute).

Downtown Boston & Waterfront. The first wave of new development (concurrent with Back Bay — Copley Square and Prudential Center) began on the original Shawmut Peninsula in 1965 with the construction of the New England Merchants Bank Building on State Street and was soon followed in 1966 by the State Street Bank on Franklin Street (see Figure 5-2). In 1968, the innovative Boston Company Building, a forty-one-story office building located on a 0.344 hectare (37,000 square foot) plot at the southwest corner of Washington and Court streets, began construction and was completed in 1970 (see Figures 3-82 & 5-14). The site is located on the east slope of Beacon Hill and is within the limits of the original colonial shoreline of the Shawmut Peninsula. The site is underlain by deformed and faulted clay, sand and gravel, and till, representing the overthrusted Beacon Hill sediments. The central core foundation used a uniform, reinforced concrete mat bearing on the compact sand and

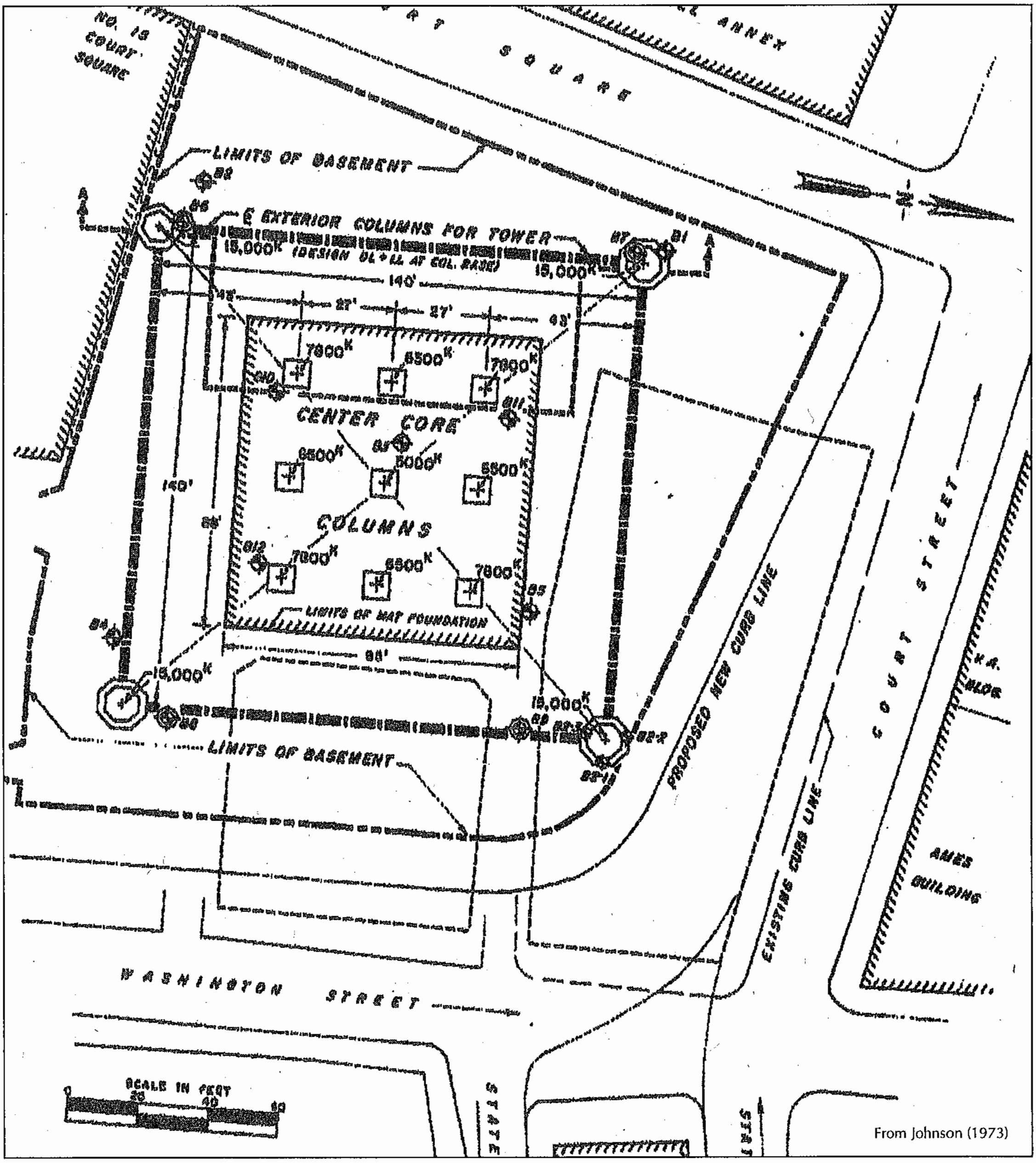
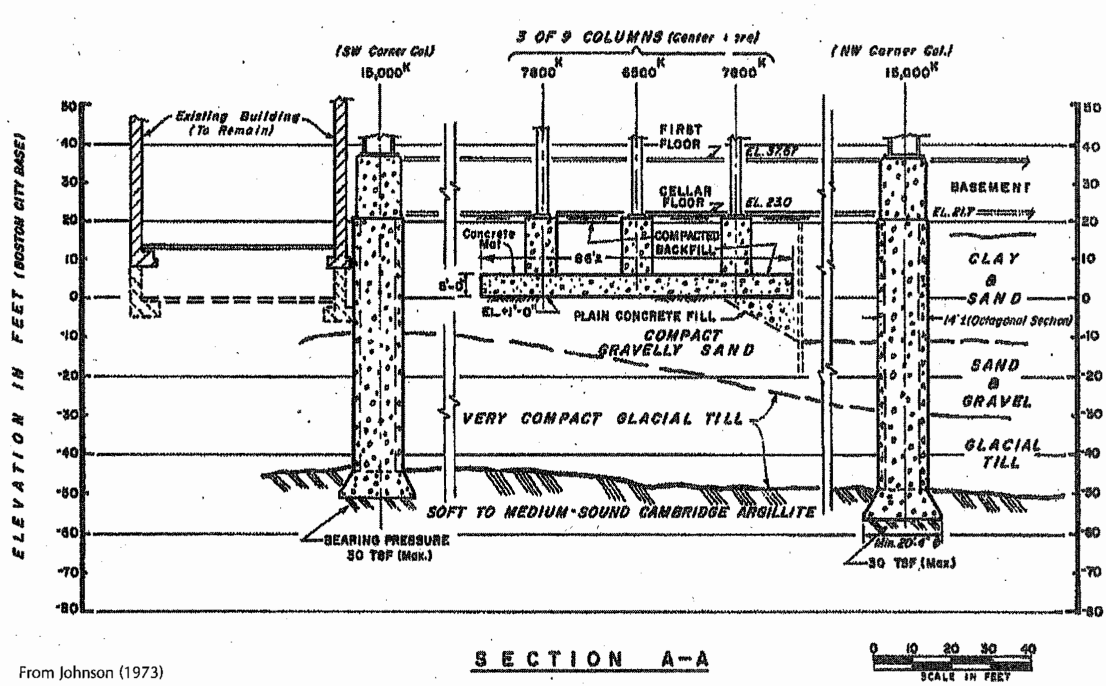


FIGURE 5-14. Foundation plan for the Boston Company Building.

gravel stratum at a maximum gross bearing pressure of 527 kilonewtons per square meter (5.5 tons per square foot). Where necessary, the marine clay overlying the sand was excavated and replaced with a mass pour of lean concrete fill to the limits specified. Each of the four very heavily loaded corner columns was founded on a large-diameter pier caisson with an enlarged bearing area supported on, or within, the argillite (see Figures 5-14, 5-15 & 5-16), some 15 meters (50 feet) below the central core mat (Johnson, 1973). The gross design end-bearing pressure on the rock surface was 2,873 kilonewtons per square meter (30 tons per square foot), with adequate provision for enlarging the bearing area and reducing the bearing intensity during construction, if necessary, to account for possible variations in rock



From Johnson (1973)

FIGURE 5-15. Typical geology and foundation geometry and column design loads for the Boston Company Building (view west).

quality (see Figure 5-17). The minimum structural pier section was based on a design compressive stress of 4,826 kilonewtons per square meter (700 pounds per square inch) for unreinforced concrete (per a 1970 Boston Building Code restriction).

In 1969, urban development moved to the waterfront along Atlantic Avenue and Commercial Street between the North End and South Station. At that time, the area was made up of old brick and granite block warehouses used primarily for refrigeration. Developers realized that young urban professionals saw these old buildings as very desirable as living spaces and converted them to condominiums. New space was also sought at the edge of the harbor, which brought challenges for the geotechnical community because the waterfront lay just beyond the old colonial shoreline and was underlain by thick deposits composed of fill, organic deposit, marine clay and glaciomarine deposit, lower outwash and till. Dealing with the fill was in itself a challenge because of the old buried granite block seawalls, which necessitated judicial use of historical maps when locating test borings. The construction in 1969 of the two forty-story-tall high-rise apartment buildings (later condominiums) known as Harbor Towers initiated redevelopment on Atlantic Avenue. The foundation consists of concrete-filled steel pipe piles driven to end bearing in the till at a depth of 18 to 27 meters (60 to 90 feet). More than a decade later, the Long Wharf Marriott on Atlantic Avenue was built between 1981 and 1985 using pre-cast, prestressed concrete piles driven to the till (which had come into common use instead of the concrete-filled pipe piles).

The Rowes Wharf Development on Atlantic Avenue, known as the Boston Harbor Hotel, is a fifteen-story office and hotel structure with five levels below and is founded on caissons belled in till. The foundation design included a slurry wall and was the first project in Boston to use the "up-down" construction technique (see Figure 5-18). The ten-story building constructed in 1987 at 745 Atlantic Avenue with its three levels below grade is founded on a concrete mat bearing on sand.

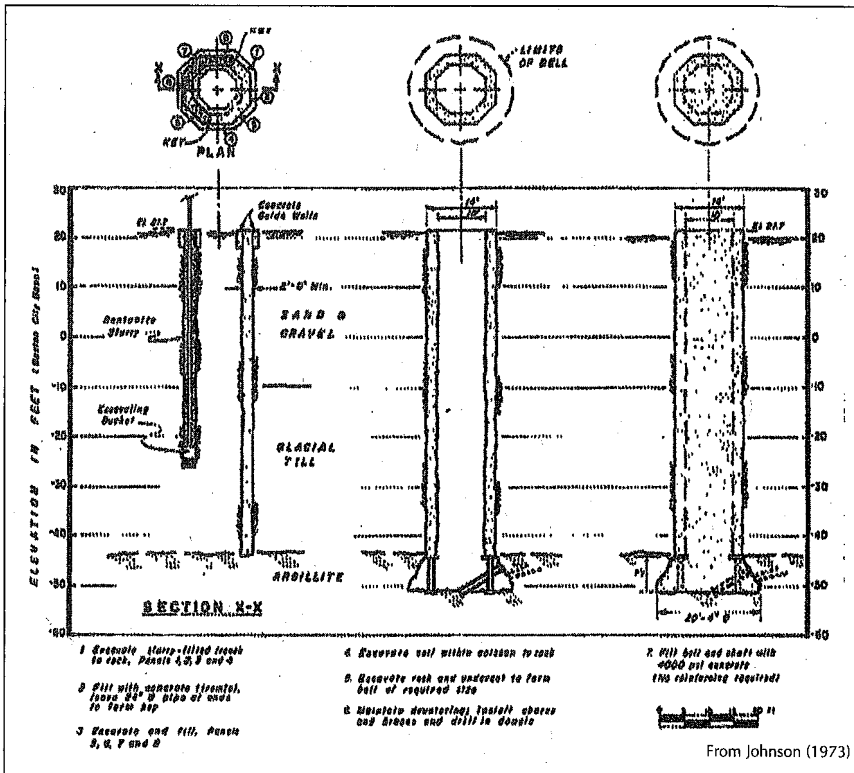


FIGURE 5-16. Construction procedures for corner piers for the Boston Company Building.

The U.S. Coast Guard EMS building located in the North End on Commercial Street (a continuation of Atlantic Avenue) is noteworthy because it has a new structural mat over existing wood piles, plus additional prestressed concrete piles driven to the till.

Geotechnical engineers took advantage of the underlying till at shallow depths on the Shawmut Peninsula that were capable of high-capacity bearing loads. Subsequently in the 1970s, the banking and insurance community further strengthened their faith in Boston by building several major high-rise office buildings in the downtown area between Tremont Street and South Station, along with considerable construction activity on the waterfront. This area incorporated the original shoreline of Boston, the remaining high ground and nearby filled land. The deposits encountered included fill, organic deposit, marine clay, lower outwash, glaciomarine and mixed overthrust deltaic and outwash deposit, and till. The argillite surface was encountered as deep as 30 meters (100 feet), between elevation –15 and –30 meters (–50 and –100 feet) MSL. Building heights varied between thirty and forty stories and most were supported by mats and footings on the till and overthrust deposits. These buildings included One Beacon Street, the First National Bank and the Shawmut Bank on Federal Street. The 60 State Street building used an innovative hybrid foundation comprised of a mat and caissons along with concrete slurry walls for excavation support. The building at One Post Office Square used PIFs in the till (see Figure 5-19).

The decade of the 1980s saw continued development along State Street and in the Financial District around Federal Street. Deep excavations for up to six levels of underground parking have been common to meet the needs of a growing city. However, there was an additional benefit to digging so deep since it brought the foundations into the high-bearing capacity till where mats and footings could safely be used. Building heights reached forty-six stories such as International Place at the end of High Street. Office buildings at 260 and 265 Franklin Street, South Milk Street, One Devonshire Place and International Place were constructed on thick concrete mats and footings bearing on the till. Certain design considerations required hybrid foundations of mats or footings in combination with concrete-filled pipe piles such as at Lafayette Place on Washing-

FIGURE 5-17. Typical condition of argillite at the base of a pier for the Boston Company Building.

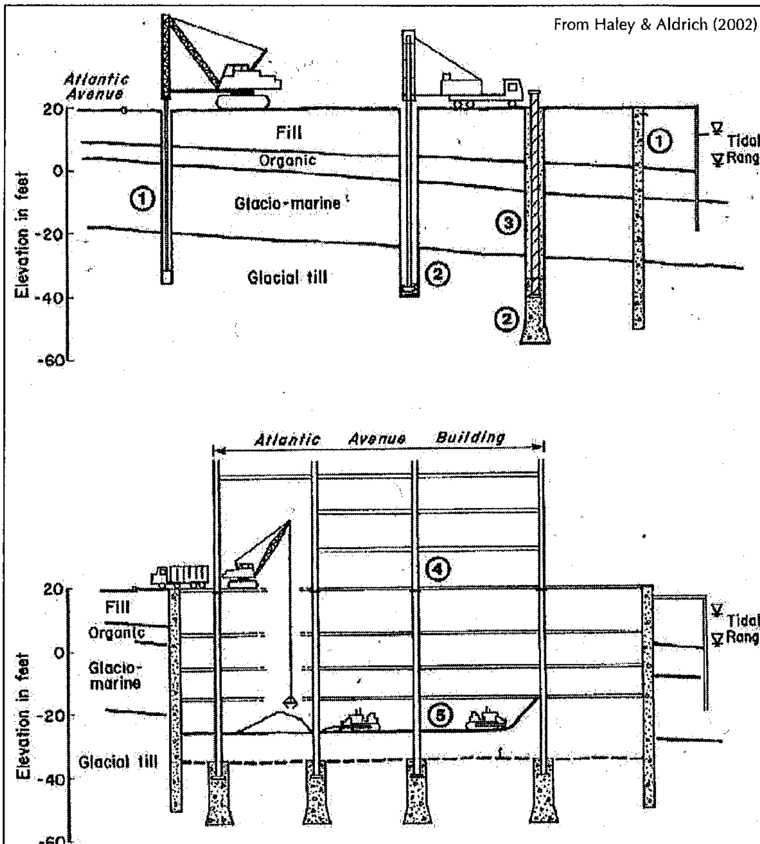
ton Street and 53 State Street. At 75 State Street, six underground levels necessitated the use of caissons in the argillite. The ten-story O'Neill Government Services Building constructed in 1985 next to North Station on Causeway Street used a foundation consisting of both pre-stressed concrete piles and steel H-piles.

The thirty-three-story office building at 33 Arch Street completed in 2004 has a foundation consisting of 2.4 to 3.7 meter (8 to 12 foot) diameter shafts drilled 3 to 10.7 meters (10 to 35 feet) into competent argillite at depths between 21 and 38 meters (70 and 125 feet). The stratigraphy encountered consists of up to 4 meters (14 feet) of fill overlying marine clay 1 to 11 meters (3.5 to 31 feet) thick that contained layers of sand and gravel with cobbles and boulders. Below the clay, a 4 to 13 meter (13.5 to 43 foot) layer of dense silt containing sand, gravel and cobbles (described as a glaciomarine deposit) overlies the bedrock. The bedrock consisted of weathered and decomposed argillite at elevations between –25 and –34 meters (–82 to –112 feet) BCB and at depths of 12 to 19 meters (38 to 63 feet). The thickness of the decomposed rock ranged from 4.5 to 14.5 meters (14.5 to 48 feet). This site exemplifies the difficulty in describing the marine clay, glaciomarine and (what may be) till deposits when they occur on a site together and have similar compositions.

The Atlantic Wharf redevelopment included the up-down construction of a thirty-one-story mixed-use tower with six levels of below-grade parking along the historic Boston Harbor waterfront (Haley & Aldrich, 2002). The site was formerly known as Russia Wharf and the construction had to address the former waterfront structures (granite block seawalls, numerous timber piles and old pier structures), weak sub-surface soil conditions, tidal groundwater levels and contaminated soils resulting from previous site usage and filling. The foundation system consisted of heavily loaded drilled shafts and a concrete diaphragm, or slurry wall. The project was required to preserve portions of the facades of former historic buildings. Below-grade construction was completed in March 2010. The overburden conditions beneath the site generally consisted of a fill layer 3 to 7.3 meters (10 to 24 feet) thick overlying organic deposit 1.8

to 4 meters (6 to 13 feet) thick, marine clay 8.5 to 18.6 meters (28 to 61 feet) thick, till 1.2 to 7 meters (4 to 23 feet) thick and bedrock 21.3 to 30 meters (70 to 98 feet) below the ground surface. The bedrock at the site consisted of the Cambridge Argillite formation that was typically highly to completely weathered.

Drilled shafts form the foundation support system, with a concrete diaphragm wall that provides permanent lateral support of the below-grade space. Design parameters of 0.10 kilopascals (5 kips per square foot) inside friction and 0.84 kilopascals (40 kips per square foot) in end bearing were chosen for the design of the drilled shafts. A total of thirty-three drilled shafts ranging from 1.2 to 2.7 meters (4 to 9 feet) in diameter were installed to support the building. The shafts supporting the concrete core were 2.7 meters (9 feet) in diameter, with approximately 20.7 to 23.5 meters (68 to 83 feet) rock sockets, while the shafts supporting the perimeter tower and low-rise columns ranged from 1.2 to 2.1 meters (4 to 7 feet) in diameter, with rock sockets ranging from approximately 2.4 to 18.3 meters (8 to 60 feet).



Top, preparation:
1 = Trenching & setting slurry walls
2 = Boring & emplacement of foundation piers
3 = Setting building columns to ground level

Bottom, construction:
4 = Set street-level slab & build up
5 = Progressively excavate & build down

FIGURE 5-18. Up-down construction for the Rowes Wharf Project showing the construction sequence.

A number of new buildings have been proposed in the downtown and South Station areas. One of potentially spectacular significance is a proposed 305 meter (1,000 foot) tall tower. For future considerations, an extensive drilling program was conducted at the proposed Trans National Place in Winthrop Square between Federal and Devonshire streets. The drilling reveals and serves as an example of the type of complex geology that may be encountered in exploring for deep foundations in Boston. Boreholes have been drilled to as deep as 65.5 meters (215 feet). These borings intersected a soft, highly to slightly weathered gray argillite with some tuffaceous and sandstone interbeds as well as quartz veins below a depth of 20.4 to 24.6 meters (67 to 81 feet) at elevation –10 to –15 meters (–33 to –49 feet) MSL that became only slightly weathered and harder with deepening (O'Hara & Haley, 2007). The very thinly layered bedding is moderately to vertically dipping. A borehole in the middle of the west side of the site intersected a breccia zone at –23 to –26 meters (–76 to –86 feet) MSL and several thin brecciated shear zones lie below indicating faults below the site. The bedrock surface shows a trough extending northeastward across the site toward the shore, as indicated by the boring data combined with those compiled by Kaye (1970). The argillite is covered by 1.5 to 6.3 meters (0.5 to 20.5 feet) of till comprised of gray gravelly silt with few cobbles and boulders. The till is overlain by 0 to 8.4 meters (0 to 27.5 feet) of glaciomarine sediment described as hard, gray clay with some amount of fine to coarse sand and gravel. Stiff yellow-brown (the weathered crust) to gray soft marine clay with scattered seams of fine sand and sandy silt 5.8 to 15.4 meters (19 to 50.5 feet) thick exists over the glaciomarine sediment. A 1.5 to 4 meter (5 to 13 foot) thickness of miscellaneous fill caps the site. The boring samples at this location demonstrate the difficulty in distinguishing till from glaciomarine sediment. The glaciomarine deposit pinches out to the north side of this site, apparently due to a later channel, which was subsequently filled by the marine clay and later acted as a guide for the formation of the tidal creek.

Up-Down Construction Technique. Increases in the value of urban sites during the building booms of the 1980s and 1990s made constructing underground space more economically attractive, particularly in congested areas. The application of the "up-down" or "top-down" construction method in Boston offered advantages for certain difficult site and subsurface conditions, as described by Haley & Aldrich, Inc. (2002). The up-down method allowed for the simultaneous construction of a project's substructure and superstructure. This approach evolved in Europe from the "Milan method" for subway construction, which has been described as "cover-then-cut" — that is, parallel slurry walls are installed and then a bridge between the slurry walls is constructed and decked over for traffic. Of note is the fact that this method was used in an early form for urban tunnel construction in several cities. In Boston, it was used for the Summer Street/ Winter Street subway construction from 1912 to 1914. For this project, the street was opened, decked and returned to surface traffic while the subway tunnel was excavated and constructed below. Slurry walls were not used then. The soil was then mined from underneath the decking to create space for the tunnel structure.

Up-down construction (see Figure 5-18, top) involves the installation of the substructure's walls, below-grade columns and foundation system from the ground surface prior to excavation (Haley & Aldrich, 2002). Concrete diaphragm walls constructed using the slurry trench methods are typically also incorporated as the perimeter basement walls. They serve the dual purpose of lateral excavation support during construction and as perimeter walls for the final structure. After the perimeter walls are completed, the structure's columns and foundation elements are installed from the existing ground surface. Then excavation begins and the substructure's floor system is installed as each level of excavation is reached. These floors also serve the function of cross-lot braces during construc-

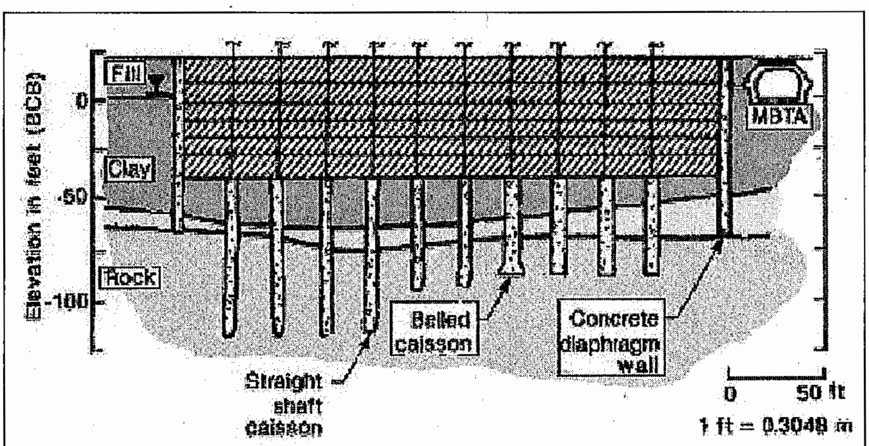


FIGURE 5-19. Section at the side of Post Office Square Garage showing lithology and slurry wall for up-down construction of seven sub-floors. (Courtesy of Deep Excavations, LLC.)

tion by providing lateral support to the diaphragm walls as the excavation proceeds downward by mining the soil below the lowest installed floor level (see Figure 5-18, bottom). At the same time the excavation proceeds downward, the superstructure is erected. The concrete diaphragm wall is typically 1 meters (3 feet) thick and provides a stiffer system than conventional steel sheeting and shoring schemes, and can result in reducing the lateral movements of the support system during construction.

The first up-down project performed on the East Coast was the Rowes Wharf Boston Harbor Hotel Project in Boston from 1985 to 1987. The $193 million Rowes Wharf Project is a mixed-use development located on a narrow strip of land adjacent to Boston Harbor with twin fifteen-story towers and five levels of below-grade parking. The challenging site and subsurface conditions dictated a creative construction procedure such as that offered by the up-down construction technique.

Since 1985, up-down developments in downtown Boston have included Millennium Place, Massachusetts General Hospital, Charles River Plaza North and South, 125 Summer Street, 75 State Street and Russia Wharf. Outside the downtown area, the technique was used for the Center for Life Sciences on Longwood Avenue, a twenty-one-story building with six levels below grade and supported by 2.4 to 3 meter (8 to 10 foot) diameter slurry caissons at a 40 meter (130 foot) depth.

The Russia Wharf building complex on Atlantic Avenue is a thirty-two-story hotel, condo and office building that was constructed between 2007 and 2010. Because of the historical nature of the site, the seven-story exterior of the building was preserved by using the slurry wall both to support and hang the facade. The new MBTA Silver Line Tunnel passes underneath the building. The foundation consists of the existing wood piles in the marine clay that were load tested in conjunction with ground freezing and underpinning with mini-piles bearing on the till.

The twenty-two-story Intercontinental Hotel at 510 Atlantic Avenue was completed in 2006 and is unique in that it is wrapped around the new vent shaft for the adjacent new Central Artery Tunnel. The building contains two 72 meter (237 foot) high concrete towers. Support for the hotel consisted of the existing vent shaft foundations, a 0.76 meter (2.5 foot) thick slurry wall keyed into the till constructed as a cutoff wall and for foundation support, drilled caissons in the argillite and pre-cast, pre-stressed concrete piles for the new wharf.

Park Square — Boston Common Area. Except for the Tremont-on-the-Common (built in 1963) and the Under Common Garage (built in the early 1960s), new projects in the Park Square and Boston Common-Public Gardens areas were developed in the 1980s. The excavation for the Boston Common Garage was 14 meters (45 feet) deep and encountered fill and deformed sediments (Kaye, 1961). Located along the original shore and adjacent tidal flats of the Shawmut Peninsula on what is now Charles Street, excavation on the west side of the garage encountered granular and cinder fill overlying peat and sediment upon which a colonial era boardwalk had been constructed. During the excavation in 1961, water-bearing sand and gravel that had been glacially folded and thrusted upward was encountered and caused excavation flooding (see Figure 3-83). A dewatering system comprising well points was installed to control the flooding. Construction of the concrete foundation slab then continued without further incident.

Shallow marine deposits were found suitable for mat foundations for the State Transportation Building (eight stories) in Park Square, 500 Boylston Street (twenty-five stories) and the Heritage on the Garden (twelve stories) on Boylston Street. Foundation conditions were expected to be variable for the projects located in the area of Beacon Hill because it was known to be underlain by glacially disturbed, heterogeneous deposits. Foundation types used have been variable. PIFs have been founded in sand that occurs in the marine deposits, which was the case of the Four Seasons Hotel (thirteen stories) on Boylston Street. PIFs and pre-cast, pre-stressed concrete piles bearing in marine deposits were used for the old Ritz Carlton Hotel and Garage (now the Taj Boston) at Arlington and Newbury streets. Concrete-filled pipe piles driven to till were used for the Tremont-on-the-Common (Johnson, in Woodhouse & Barosh, 1991).

Millennium Place Buildings I, II and III (which include the new Ritz-Carlton Hotel and two towers of thirty-six and thirty-eight stories) were constructed from 2001 to 2012 on Avery Street at the corner of Tremont and Boylston streets. The up-down construction method was used to construct Buildings I and II, and these were supported on LBEs. A mat foundation was used for Building III. All foundations bear on deformed sand and clay that are similar to those found under Beacon Hill. These soil deposits were exposed in the foundation excavation (see Figure 3-84).

The Millennium Place III project (constructed in 2012 and 2013) is a fifteen-story residential tower located on Hayward Place in the Downtown Crossing/Chinatown area of downtown Boston. The building is located on the northern edge of the original Boston Neck, an area formed of an elevated clay ridge and deformed overthrust deposits. The foundation consists of a split system due to the proximity of the Orange Line along Washington Street. The support for the excavation consisted of soldier pile and lagging with one level of internal bracing. The split building foundation includes a mat bearing on the natural glacial soils for about 75 percent of the building and along Washington Street, 0.9 and 1.2 meter (3 and 4 foot) diameter drilled shafts about 24 meters (80 feet) deep bearing in the weathered argillite.

The thirty-one-story residential building at 45 Province Street is located east of the Boston Common on what is now the southeast slope of Beacon Hill. Foundations consisted of 1.2 meter (4 foot) diameter caissons drilled through the till to a depth of 18 to 23 meters (60 to 75 feet) below grade.

Government Center Area. In the late 1950s and early 1960s, the notorious Scollay Square area and most of the historical West End were demolished to make way for new modern developments that included the original Central Artery elevated highway, Charles River Park Apartments and the Government Center complex that was built between 1963 and 1970. The modernistic Boston City Hall and several major office buildings that house federal and state agencies were constructed. Development took place on what was the east side of the old Trimountain (Beacon Hill) that was originally high ground in colonial times. The West End is unlike all other areas of central Boston in that the bedrock is shallow and locally crops out. Geologic conditions ranged from the shallow bedrock to mixed deposits of sand, marine clay, till and glaciomarine material. The variable geology presented the foundation engineer and geologist with several design options for each building and the opportunity to take advantage of the shallow nature of the bearing materials. Foundations used in this area consist of mats on the till for the twenty-five-story JFK Office Building, footings and mats on the glaciomarine deposits for the eight-story Center Plaza, concrete-filled pipe piles driven into the till to support the sixteen-story Saltonstall State Office Building and City Hall, and drilled rock-socketed caissons for the eight-story tall State Services Center on New Chardon Street.

Charles River Park & Massachusetts General Hospital Area. During the periods from 1960 to 1962 and from 1973 to 1974, the area north of Beacon Hill and south of the mouth of the Charles River that incorporated a portion of the old West End was developed. Nine apartment buildings ten to thirty-six stories tall were developed as the Charles River Park and Longfellow Place. In this area, the presence of compact and thick upper outwash sand allowed the use of PIFs and spread footings. Footings were also founded on shallow argillite. The thirty-six-story Longfellow Place at Leverett Circle sits on spread footings on the rock. Where the rock dropped off, deeper foundations consisted of concrete-filled pipe piles and drilled caissons. In the Massachusetts General Hospital (MGH) area, bounded by Charles and Cambridge streets, medical facilities were constructed between 1968 and 1969, as well as between 1979 and 1980. These buildings are founded on composite and concrete-filled pipe piles driven to the till at a depth of 24 meters (80 feet), on PIFs in the lower outwash sand and till, and on caissons belled in the marine clay.

The fourteen-story MGH Lunder Building with three levels 15 meters (50 feet) below grade was constructed at the corner of Fruit Street and North Grove Street and opened in 2011. Its construction involved the use of the up-down building method with a perimeter slurry wall. The interior columns were founded on 1.2 meter (4 foot) diameter caissons drilled into the till and the argillite bedrock.

South End/Chinatown. In this area south of Kneeland and Stuart streets, the overburden is undeformed and allows foundations for intermediate height buildings to use the stiff crust on the marine clay for bearing. The Tufts Health, Education and Science facility on Harrison Avenue is supported on a concrete mat on the marine clay. Bradford Towers on Stuart and Tremont streets consisted of five buildings four to nine stories high supported by footings and caissons on or in the marine clay. Some of the caissons were deep because of the close proximity of the Orange Line subway. Tufts' New England Medical Center expanded in the period from 1978 to 1984 with the construction of the nine-story medical facility on Stuart Street, which used pre-cast concrete piles driven to bedrock to accommodate high column loads. The ten-story Wang Laboratories on Kneeland Street is supported by deep pre-cast concrete piles to 38 meters (125 feet). The twenty-eight-story Park Essex now called the Boston Common at 600/660 Washington Street is founded on drilled-in concrete caissons to depth of 34 meters (110 feet) with 3 to 4.5 meter (10 to 15 foot) diameter sockets drilled into the argillite. A 1 meter (3 foot) thick concrete mat at a depth of 8 meters (25 feet) below the street level is supported by these caissons.

South Station-Dewey Square. From 1967 to the present, major construction has taken place in the Dewey Square-South Station area generally bounded on the north by Oliver Street and Seaport Avenue, on the northeast by Atlantic Avenue, to the south and southeast by Fort Point Channel, to the west by the surface artery street that forms the end of the downtown and to the southwest by Beach Street. A major portion of the new Central Artery Tunnel underlies this important junction. The high bearing capacity of the shallow till, representing the remnant of the excavated Fort Hill drumlin, allows the use of concrete mats and footings to support large structures. These buildings include the forty-six-story One Financial Center, thirty-five-story Federal Reserve Bank, twenty-eight-story 150 Federal Street, twenty-two-story 99 Summer Street and the thirty-two-story Keystone Building at 225 Congress Street.

The South Postal Annex and Stone and Webster buildings on Summer Street used concrete-filled pipe piles driven to till and bedrock. Caissons bearing in the till or socketed in bedrock support 101 Federal Street, 101 Arch Street, 100 Summer Street, 125 Summer Street and 175 Federal Street. One Lincoln Street is a thirty-six-story office tower built in the Dewey Square-South Station area and completed in 2003. The building used up-down construction and includes five parking levels below ground that necessitated an excavation depth of 17 to 20 meters (55 to 65 feet). The perimeter slurry wall, which is keyed into the till, is used for groundwater cutoff and became a permanent foundation wall. The interior columns have footings founded on the till.

Seaport Areas of South Boston. Development since the year 2000 (see Figure 5-3) has continued in earnest across the Fort Point Channel from downtown and South Station into the area now called the Seaport in South Boston. This area extends along Northern Avenue (now Seaport Avenue), Congress Street and Summer Street. The region was the South Cove in colonial times, which was narrowed by fill beginning in the 1830s to create the Fort Point Channel. It has remained mostly vacant land since the late 1800s when the area was developed and expanded by fill dredged from the Boston Harbor. A sea wall was created on the east side of the Fort Point Channel in a curved fan shape, creating the so-called Fan Pier. In the 1960s, the Fan Pier was planned for development, but was postponed for financial reasons until the 1990s when the John Joseph Moakley U.S. Courthouse was built in 1998. A twenty-story Grand Hyatt Fan Pier is now planned to be across the street at 28-70 Old Northern Avenue. Both of these buildings are/will be supported on pre-cast concrete piles driven deep into the till. The South Boston Seaport district is currently undergoing a remarkable transformation in spite of relatively poor soil conditions that generally consist of fill over organic soils to depths of 6 to 9 meters (20 to 30 feet), followed by local outwash sand overlying the marine clay. The clay varies from 12 to 24 meters (40 to 80 feet) thickness, and often has a stiff over-consolidated crust. Below the clay is the lower outwash, then till, with argillite below. Other new buildings recently constructed include:

- The sixteen-story World Trade Center East on Seaport Avenue constructed in 2000 with a three-level below-grade garage and founded on a concrete mat on marine clay. World Trade Center West (built in 2002) with seventeen-story offices and three-level below-grade parking on World Trade Center Avenue and built on a concrete mat bearing on clay (Siebert, 2012).
- The Manulife U.S. Headquarters at 601 Congress Street constructed in 2004 consists of a fourteen-story tower with four levels of parking covering 80 percent of the above-grade footprint, 12 meters (40 feet) below grade and 9 meters (30 feet) below the water table. The southern portion of the building near the Silver Line bears on 1.2 meter (4 foot) diameter end-bearing shafts drilled into the argillite. The remainder of the building is supported on a 1.2 to 1.5 meter (4 to 5 foot) thick concrete mat floating on the marine clay with the perimeter slurry wall toed into the clay (Siebert, 2012).
- The twenty-two-story Renaissance Boston Hotel at 606 Congress Street was built three blocks from the waterfront between 2005 and 2008. The foundation consists of pre-stressed, pre-cast concrete piles that were driven to bedrock at 30 meters (100 feet). Because of the dense sand known to exist under the site, the piles were pre-augered to 18 meters (60 feet) (Wallace, 2012).
- The Fan Pier development consists of three buildings. One Marina Park Drive, an eighteen-story office building built in 2010, is supported by a 1.5 to 1.8 meter (5 to 6 foot) thick concrete mat bearing on the marine clay at a depth of 12 meters (40 feet). A portion of the building that is constructed in the area of the old ship channel is supported by caissons drilled into the clay to a depth of 21 meters (70 feet). The Vertex Pharmaceuticals buildings at 50 Northern Avenue and 11 Fan Pier Boulevard are constructed on a mat similar to caissons used on One Marina Park Drive at Fan Pier (Martini, 2012).
- The Boston Convention and Exhibition Center Complex at 415/425 Summer Street, completed in 2004, with the adjoining seventeen-story Westin Boston Waterfront Hotel that was constructed from 2006 to 2009. In this complex, the low-rise portion of the hotel is founded on 32.4 centimeter (12.75 inch) outside diameter concrete-filled pipe piles (wall thickness 0.95 centimeter [0.375 inch], with 934 kilonewton [105 ton] capacity). The piles were driven to end bearing in the till and the argillite. The high-rise portion of the hotel or tower is supported on a series of 0.9 to 1.8 meter (3 to 6 foot) diameter rock-socketed drilled caissons. The Convention Center is supported both by 35.5 by 35.5 centimeter (14 by 14 inch) pre-cast concrete piles driven to till and argillite and 1.2 to 2.1 meter (4 to 7 foot) diameter caissons drilled to the argillite for the larger loaded columns and to provide resistance to lateral loads (Siebert, 2012).
- The Seaport Hotel at 1 Seaport Lane consists of three buildings: the seventeen-story West Office Building (built in 2000), the seventeen-story East Office Building (built in 1998) and the fourteen-story Seaport hotel and tower (built in 1996). A three-level garage exists under all three buildings. Soils found at the site consist of up to 6 meters (20 feet) of both granular fill and dredged (in 1890) clay and organic silt from Boston Harbor. A 1.5 meter (5 foot) layer of organic silt and peat underlies the fill and in turn overlies a 3 to 4.5 meter (10 to 15 foot) thick layer of the upper outwash sand. A 21 to 33.5 meter (70 to 110 foot) thick layer of overconsoli-

dated marine clay that becomes softer with depth underlies the upper outwash. An intermittent layer of the lower outwash that reaches 12 meters (40 feet) in thickness was encountered below the clay. A 4.5 meter (15 foot) thick layer of till is then found overlying argillite of varying hardness and varying degree of weathering. The perimeter walls were sealed into the top of clay as a permanent groundwater cutoff wall and foundation. All three buildings bear on the marine clay at a depth of 12 to 14 meters (40 to 45 feet), with a bearing capacity of 240 kilopascals (2.5 tons per square foot). Long-term settlement was determined to be less than 2.5 centimeters (1 inch) using the underdrained mat foundation system (Erickson, 2012).
- The Park Lane Seaport 1 and 2 Project consists of two apartment buildings of thirteen and eighteen stories. It is located at One Park Lane and the buildings were constructed between 2004 and 2006. The shorter building is founded on a 1.5 to 1.8 meter (5 to 6 foot) thick concrete mat foundation on the marine clay at a depth of 12 meters (40 feet). The taller building is founded on steel H-piles driven to the till at a depth of 33.5 to 36.5 meters (110 to 120 feet) (Martini, 2012).

Alewife Station & Condominiums — Construction Issues. Usually there is very little trouble with constructing deep foundations or balanced mat foundations for tall and medium height buildings in the Boston area. However, at the Alewife Station on the MBTA Red Line in West Cambridge, the reworked, sensitive clay was found to cause serious problems. This quite different formation proved very problematic, both during construction in the 1980s and for possible future development.

Foundation problems were also encountered more than twenty years after Alewife Station construction during the construction of a nearby condominium complex (Roma, 2012). The planned foundation design consisted of PIFs to a depth of 15 meters (50 feet), where the expected sand of the outwash deposit above the marine clay at the base of the PIFs would be compacted. At this depth, however, a loose rounded sand and gravel was encountered that could not be compacted when the PIF base was driven out and expanded. According to the contractor, it was only the second time in their experience that such a condition had been encountered. Precast concrete piles were substituted and driven to the deeper till found at a depths of around 24 meters (80 feet). As described in Chute (1959), interbedded clays and silts underlie the area. This condition with the PIFs could have been caused by confined conditions from the interbedded sand and clay, or by saturated or supersaturated "running sands." The roundness of the sand and gravel where the fines are not now present because the fines might previously have been washed out could indicate that an ancient stream bed deposit was encountered.

Conclusions

The city of Boston is underlain by a complex mixture of both deformed and undeformed soils. The historical development of Boston in the early years was influenced by the geology that limited the heights of buildings in some areas. Compounding the complexity is the fact that the bedrock, mostly argillite, can be found at very shallow depths such as in the Government Center, the West End and Charles River Place, but within a short distance of 4 kilometers (2.6 miles), the rock plunges to depths greater than 76 meters (250 feet) in the Charles River area. The geology dictated the types of foundations for buildings that have been built. Each area of Boston has its own geological and geotechnical conditions that made use of a variety of foundation types. These types included belled and straight shaft caissons, pipe piles, wood piles, H-piles, pre-stressed concrete piles, footings and mats to the point that buildings at a particular street intersection could have four foundation types. The following geologic factors determine the choice of foundation type:

- The bedrock surface is highly variable.
- The argillite, and to some degree other bedrock, can be deeply kaolinized to the consistency of clay.

- The rock is deeply weathered in certain areas.
- The till and glaciomarine deposits may behave plastically, affecting the behavior of piles. The till can contain layers and lenses of sand and gravel that are water-bearing.
- Deformed, mostly faulted clay, sand and gravel and till are found in the area of Beacon Hill.
- The marine clay is thick and can be nearly normally overconsolidated. In certain areas, some of the clay is reworked and is sensitive, with loss of strength.
- The upper and lower outwash deposits are discontinuous and sometimes absent. Where present of sufficient thickness, PIFs can be used.
- The original wood pile foundations are susceptible to deterioration when the water table is lowered.
- Overlying organic silt has softened the normally stiff yellow clay crust.

Transportation Tunnels in Greater Boston

A summary of all major transportation tunnels in the Boston area, with notes on how their construction added to understanding Boston's geology.

DAVID WOODHOUSE & PATRICK J. BAROSH

In order to accommodate Boston's growth, and to facilitate commerce, a number of public works have been designed and constructed since the late nineteenth century. Tunnels have been built for vehicular traffic as well as for mass transit. The tunnels have largely been excavated by means of open-cut excavations, with notable exceptions for the trans-harbor crossings and the Massachusetts Bay Transportation Authority (MBTA) Red Line extension through Porter Square, Cambridge. Tunnel excavations offer a unique opportunity to examine soil and rock over a long cross-section not always afforded by building excavations.

Subway Tunnels

More than a century has passed since state and local governments in Massachusetts first recognized the need for decreasing street congestion and for increasing the speed and capacity of public transportation in the Boston area. In 1888, there were more than eight thousand horses pulling streetcars in Boston. The many rapid transit facilities built since that time (Woodhouse & Barosh, 1991; Clarke & Cummings, 1997; Cheney, 2002; Cudahy, 2004; McKendry, 2005) formed the foundations of today's Red, Orange, Blue, Green and Silver subway lines of the MBTA (see Figure 6-1). This subway network, now 125 kilometers (77.4 miles) in length, carries an estimated 250 million riders annually, and has planned extensions. The system includes 50 kilometers (31 miles) of active subway tunnels. For a metropolitan area the size of Boston, its rapid transit system is large when compared to rapid transit facilities elsewhere in the United States. Boston has long been a leader in rapid transit development, starting with America's first subway — part of the Green Line, which opened in 1897, and the second undersea tunnel, the East Boston Tunnel on the Blue Line, put in service in 1904. Both lines remain in daily use and are augmented by the area's commuter rail system. The subway tunnels were largely constructed by cut-and-cover methods with three notable exceptions.

Early Subway Construction History. A three-person Board of Subway Commissioners, subject to approval of the Boston City Council and appointed by the mayor, was created in 1893 by the state legislature to report on the

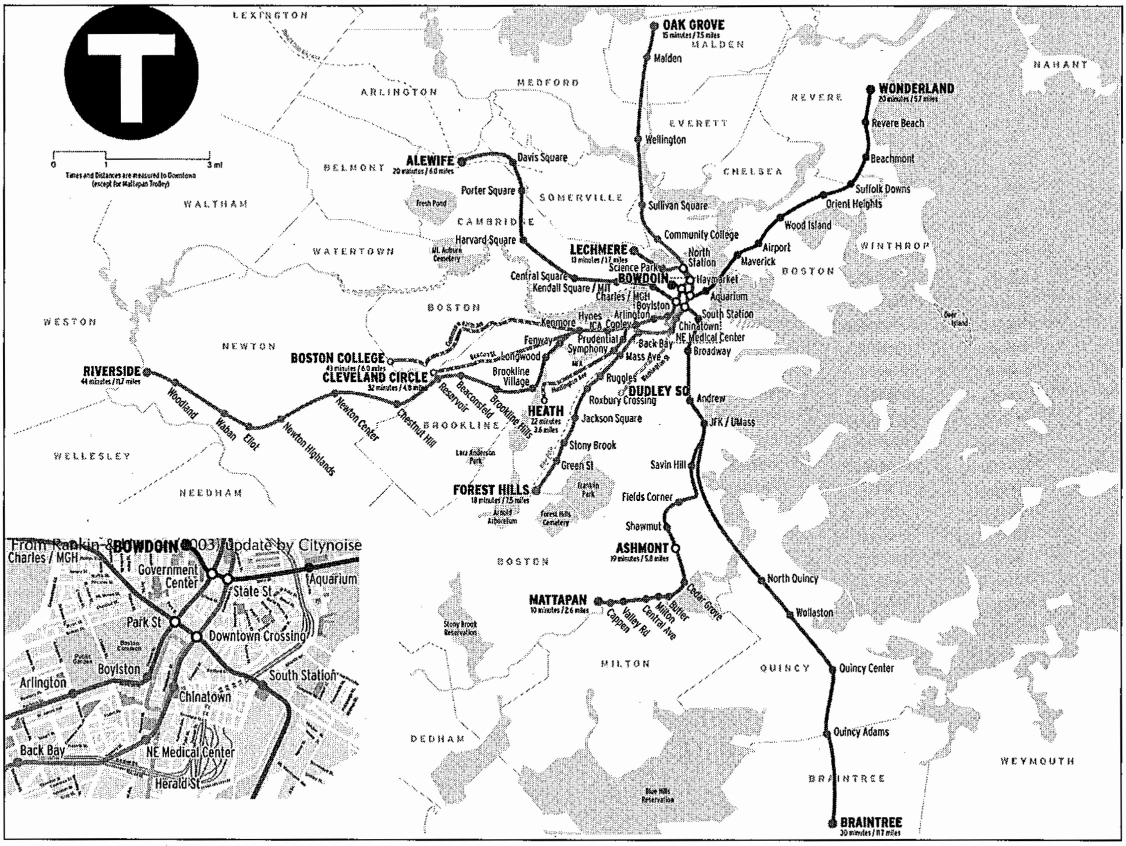


FIGURE 6-1. Map of the Boston area showing routes of the MBTA system, July 2011.

feasibility of building a subway under Boston Common for the purpose of removing streetcar traffic from Tremont Street. The council gave its consent, and the board was appointed on January 1, 1894. After hearing from critics and supporters of the subway, various technical experts in the construction, transportation and health fields, as well as from proponents of elevated railways, the legislature enacted a bill on July 2, 1894, to create the Boston Transit Commission and the Boston Elevated Railway Company. The Boston Transit Commission would be a governmental body whose primary function would be to construct the Tremont Street Subway, now part of the Green Line (see Figure 6-2). The Boston Elevated Railway Company, on the other hand, would be privately owned and charged with building elevated lines. The legislation required a local referendum, and Boston voters overwhelmingly approved the bill on July 24, 1894.

During the fall and winter of 1894-1895, the engineering staff of the Boston Transit Commission took the Tremont Street Subway from the planning phase to final design. Ground breaking took place on March 28, 1895, at a public ceremony presided over by the governor. Work progressed so rapidly that the first Tremont Street section beneath Boston Common was opened on September 1, 1897, from Park Street to a portal in the Public Garden, near Arlington and Boylston Streets. (see Figure 6-3). Two additional segments of subway were opened later. The leg under Tremont Street from Boylston Street Station to Pleasant Street (now Broadway in the Boston South End) opened on October 1, 1897, and on September 3, 1898, operations commenced on the final section to Haymarket near North Station (Whitehill, 1968) for streetcar traffic. The Haymarket end of the tunnel was connected by an elevated loop that circled to the east above Atlantic Avenue to connect South and North stations in 1901 (see Figure 6-4).

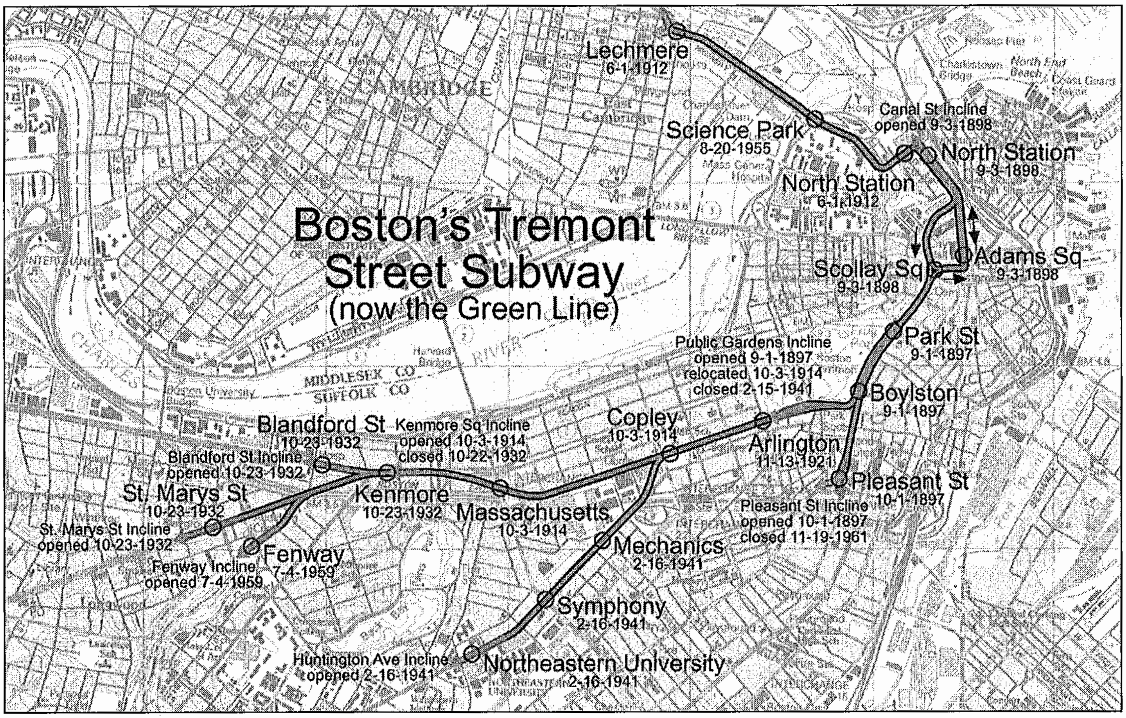


FIGURE 6-2. Map of the Tremont Street subway (Green Line) showing gradual extensions and their dates of completion. (Courtesy of spuimap.)

The original Boston Elevated Railway Act of 1894, which was amended in 1897, provided for a transit tunnel under Boston Harbor to East Boston and the Boston segment of a subway to Cambridge. The East Boston Tunnel, the first underwater transit tunnel in North America, opened for streetcar traffic in 1904. The tunnel, now part of the Blue Line, extended from Maverick Square, East Boston, to Court Street Station, near Scollay Square (now Government Center) in downtown Boston and allowed passenger transfer to the elevated train at a midway station at Atlantic Avenue and State Street.

A 2 kilometer (1.23 mile) long subway tunnel was then dug under Washington Street between 1905 and 1908 for the Sullivan-Dudley line and replaced the use of the Tremont Street Tunnel for service to Dudley Square. The Washington Street Tunnel, which follows the old Boston Neck, was opened for public use on November 30, 1908. Removal of high-platform and third-rail equipment (the third rail was never used) from the Tremont Street Subway began at once, and on December 4, 1908, streetcar service fully resumed through all parts of the subway that were formerly used by the high-platform trains of the elevated system.

The Boston Elevated Railway and the Boston Transit Commission shared joint responsibility for constructing a line to connect Park Street in Boston with Harvard Square in Cambridge. This line consists of a cut-and-cover Cambridge Tunnel from Harvard that rises on the Longfellow Bridge, crosses over the Charles River and then runs through a shield-driven, hand-mined tunnel under Beacon Hill and under the Park Street Station. This segment is now part of the Red Line (see Figure 6-1). The Cambridge section was built by the Boston Elevated Railway, but all sections in Boston were built by the Boston Transit Commission. Construction in Cambridge started July 12, 1909, on the first segment and the subway began operation on March 23, 1912. An extension to South Station, known as the Dorchester Tunnel, opened on December 3, 1916. A further extension, which opened on June 29, 1918, continued southward through a

FIGURE 6-3. Construction trench for Tremont Street subway circa 1896. (Courtesy of the Society for the Preservation of New England Antiquities.)

tunnel under Fort Point Channel to reach Andrew Square in South Boston.

The need for rapid transit service in the congested Back Bay area led to a proposal to construct a new subway line, which was approved by the state legislature in 1907. The bill specified that the facility be built under the Charles River Embankment and be known as the Riverbank Subway, with stations located at Charles Street, Dartmouth Street and Massachusetts Avenue. The Boston Elevated Railway strongly opposed the location of the Riverbank Subway, and abutting property owners, who were worried about the effects that the construction of the subway would have on sewers and other underground utilities, joined together and protested to the legislature. The protest succeeded and in 1911 the lawmakers abandoned the Riverbank Subway in favor of a line beneath Boylston Street. The Boylston Street Subway, now the Green Line, began construction in March 1912 for a two-track cut-and-cover tunnel, which would eventually run from a connection with the Tremont Street Subway near the Public Garden Incline to a portal in Governor Square, now Kenmore Square (see Figure 6-2). As part of the subway construction, the incline itself would be shifted to the middle of Boylston Street, parallel to its old location. The subway opened on October 3, 1914.

A short extension of the East Boston, streetcar based subway system took place between 1912 and 1916. The East Boston Tunnel, when originally opened, ran downtown to Court Street Station, which was a stub-end single-track terminal. Traffic volume through the tunnel increased tremendously over the years, and this single-track turn-back became an operational nuisance. The answer was a short 796 meter (2,610 foot) extension to Bowdoin Square. The tunnel runs through the deformed Pleistocene soil deposits of Beacon Hill (Boston Transit Commission, 1913; Kaye, 1976b), where an underground station, a loop and a surface incline to Cambridge Street were built. The loop allowed a quick turnaround for streetcars from East Boston, while the incline permitted cars to come to the surface and travel all the way through from Cambridge to East Boston. Streetcar tracks were laid across the Longfellow Bridge along with the subway in the center. The East Boston Tunnel Extension was opened on March 8, 1916. The Boston Transit Commission had by this time opened the East Boston Tunnel and its extension to Bowdoin, the Washington Street Tunnel, the Boylston Street Subway and the Tremont Street Subway.

In the late 1930s, the Boston Transit Department (which succeeded the Boston Transit Commission in 1918) began the Huntington Avenue Subway (see Figure 6-2), now a branch of the Green Line, through a variety of deposits (Aldrich & Lambrechts, 1986). This subway was a Work Projects Administration (WPA) program and was one of the first examples of major federal funding for local mass transit construction. Prior to the subway, the Huntington Avenue streetcar line ran from Forest Hills, past Northeastern University on Huntington Avenue to Copley Square and then on Boylston Street as far as the block between Arlington and Charles streets. At that point, the streetcars entered the portal to the Boylston Street Subway. The Huntington Avenue line was the last major surface streetcar route to run through this heavily congested section of the Back Bay, and its diversion into the new subway portal south of Massachusetts Avenue on February 16, 1941, shortened the running time considerably.

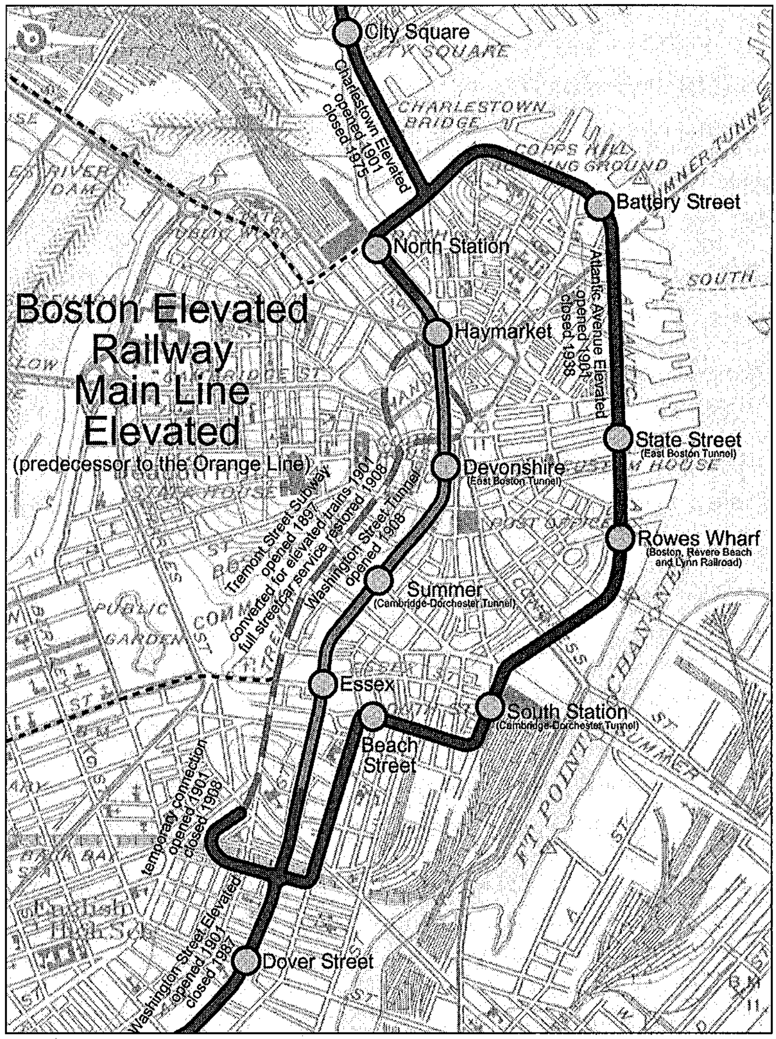


FIGURE 6-4. Map of how the Boston Elevated Railway tied into the Tremont Street subway between Haymarket and south of Essex stations to make a transit loop through Boston. (Courtesy of spuimap.)

The Public Control Act of 1918 was extended in 1931 under new terms, which reduced the rate of payment to the private owners of the Boston Elevated Railway and, among other things, provided for the eventual purchase of the company by the Commonwealth of Massachusetts. Popular sentiment grew over the years against publicly assisted payments to private shareholders for the use of a facility that was providing an essential public service and for which a fare was also demanded. The state purchased the Boston Elevated Railway in 1947 and reorganized it as the

Metropolitan Transit Authority (MTA). Two years later, on July 2, 1949, the functions, powers and personnel of the Boston Transit Department were transferred to the MTA, along with the title to the subways and other transit properties formerly held by the city of Boston. The MTA was an effective agency for the area it served, but its activities were limited to fourteen cities and towns. To form a mass transit operation with metropolitan responsibilities, the state legislature created the Massachusetts Bay Transportation Authority (MBTA), which superseded the MTA on August 3, 1964. The MBTA has much broader powers than its predecessor and greatly expanded responsibility, and it now serves seventy-nine cities and towns.

Recent History of Subway Construction. The Orange Line subway was extended from the end of the Washington Street Tunnel at Haymarket northward through a new immersed tunnel under the Charles River to Charlestown to replace the old Charlestown Elevated Railway, which had been in operation since June 10, 1901. The new tunnel, the Haymarket North Extension, opened April 7, 1975, and the elevated line through the center of Charlestown in Thompson Square to Sullivan Square was torn down the same year. Once through the tunnel under the Charles River, the Orange Line runs at grade along an existing railroad right-of-way to Oak Grove in Melrose. A major expansion of the MBTA took place between 1981 and 1987, with the construction of the Northwest Extension of the Red Line in Cambridge and Somerville and the Southwest Corridor for the Orange Line through Back Bay and Roxbury. A new subway station at Tufts New England Medical Center and a southwest relocation of the Orange Line (from the old 1908 Washington Tunnel at Kneeland Street and the Washington Street elevated line to Forest Hills in Jamaica Plain [see Figure 6-4) to the old Boston and Providence [Penn Central] railroad embankment) was part of a plan to redevelop the South Cove area (the area surrounding Back Bay Station) for urban renewal. The plan made use of land previously intended for the Interstate 95 highway extension into Jamaica Plain and Roxbury that was abandoned in 1972. The first part of the corridor was the South Cove Tunnel to carry the line beneath the Massachusetts Turnpike without interrupting the traffic flow during construction. The idea for the Southwest Corridor was conceived in 1964, the planning done in the period 1972 to 1979, the construction started in 1979 and the relocated Orange Line opened on May 4, 1987.

A Northwest Extension of the Red Line from Harvard Square was planned to go underground to the west edge of Cambridge and from there rise up to travel along an abandoned commuter rail line through Arlington to Lexington. Objections in Lexington and Arlington about concerns for increased traffic congestion succeeded in limiting the extension to present terminus at Alewife Brook at the western edge of Cambridge. The opening of the last segment of this extension took place on March 30, 1985.

The most recent tunnel construction was for bus and rapid transit travel between South Station and Logan Airport via the South Boston Seaport area, by passing under Russia Wharf, the Fort Point Channel and part of the South Boston flats. The Silver Line Bus Rapid Transit System was planned as part of improvements and expansion of the MBTA to link the Roxbury section of Boston with the downtown and the South Boston Convention Center area. The further link from Logan Airport to transport passengers to the Red Line subway at South Station uses the roadway of the Ted Williams Tunnel of the Central Artery/Tunnel Project. The surface section of the Silver Line from Roxbury was constructed as Phase I and uses buses along Washington Street. It was followed by the Phase II tunnel section from South Station to South Boston. Phase II originally was planned as the South Boston Piers Transitway and part of environmental mitigation for the Central Artery/ Tunnel Project (see Figure 6-1). It opened in December 2004, with a new name — the Silver Line, Waterfront Phase. The final route of a planned Phase III tunnel section to connect South Station with Boylston Station of the Green Line is controversial and yet unfunded. Ambitious plans have been in the works for two decades to extend the Blue Line from Bowdoin Station to connect with the Red Line at Charles/MGH Station.

During the Central Artery/Tunnel Project, the elevated Green Line near North Station was placed underground and the Canal Street incline and elevated railway along Causeway Street were demolished. This project principally consisted of a joint North Station Superstation for both the Green and Orange lines, as well as re-routing the Green Line beneath the new TD Garden arena to a new portal near the Zakim Bunker Hill Bridge.

Geology & Construction Methods of Subway Tunnels

The subways were constructed chiefly in a variety of soft ground conditions that vary from marine clay to lodgement till as they passed under the Shawmut Peninsula and the filled areas of the Back Bay and the Boston Neck. Only rarely were subways dug through bedrock.

Tremont Street Tunnel of the Green Line. A surface excavation method was chosen for the Tremont Street Tunnel rather than a deep tunnel as used for the London subway. The innovative building of a tunnel in a ditch, dug by pick and shovel, established what is now called the cut-and-cover method (see Figure 6-3), which has since been widely used. A framework of steel beams and concrete was constructed in the excavation, and covered by an arched roof of brick and concrete and then buried. The 2.4 kilometer (1.5 mile) long tunnel between Boylston and Haymarket skirts the edge of Beacon Hill and is through deformed till, clay and outwash (Kaye, 1961). It encountered some difficulty with sand flowing into the trench, but this problem was solved by bulkheads. Another quite unusual problem developed in the discovery of 910 bodies in unmarked colonial graves off the edge of the Granary, or Old Common, Burial Ground (Cudahy, 2004). At the other end near Haymarket, the tunnel is through a filled tidal flat area. It took three and a half years to complete the entire tunnel between 1895 and 1898.

East Boston Tunnel of the Blue Line. Construction on the East Boston Tunnel, which passes under Boston Harbor to connect Boston with East Boston, began in 1900 and was completed on December 30, 1904 (see Figure 6-1). The original tunnel was 1,600 meters (5,280 feet) in length, of which 823 meters (2,700 feet) are under water. It was originally used for streetcars, but it was converted over one weekend to rapid transit subway cars in 1924. One end of the tunnel was located in Maverick Square in East Boston, where a portal (now closed) allowed the streetcars to run as a surface line. From East Boston, the tunnel runs under Boston Harbor to Long Wharf and up State Street and ended at what was then called Court Street Station (also now closed). The streetcars could exit onto Cambridge Street near Russell Street in Bowdoin Square through a portal (closed in 1924, and abandoned and filled in 1952), and then travel to and across the Longfellow Bridge. The tunnel was dug using a tunnel shield under pressure. The shield rolled forward on concrete footings laid down ahead in two small pilot tunnels. The tunnel was the first to be built entirely of concrete with no steel framing (Cheney, 2002). The tunnel leaked and had to be grouted nightly for many years following construction.

The tunnel was constructed in mainly Pleistocene glacial sediments varying from marine clay under the harbor and the glaciomarine deposit along both waterfronts, to the deformed clay and sand around Beacon Hill (Crosby, 1903; Kaye, 1976b). From Bowdoin (including the Cambridge Street portal) to State and Court streets, the tunnel encountered a till consisting of mostly silty sand; stratified sand; deformed and mixed deposits made up of pervious outwash and deltaic sand, marine clay and till; and argillite in the West End, which included Bowdoin Square, where the bedrock is close to the surface. From State Street easterly to the Aquarium Station (formerly the Atlantic Avenue Station) on the waterfront, the tunnel was constructed through the till on the east side of Beacon Hill to Court Street and a variety of deposits found under the original shoreline of Boston. These deposits consist of fill, organic sediment, marine clay, outwash sand, glaciomarine sediment and till. The Central Artery/Tunnel Project cross-sections show these complex deposits well. The tunnel from the filled-in waterfront was constructed under the Boston Harbor through the marine clay and entered Maverick Square Station in East Boston. In this area, the underlying material is similar to the west side since Maverick Square is also located on filled land just northwest of the Camp Hill drumlin. The Blue Line was extended under the north end of the Camp Hill drumlin in 1952 to provide a station for the expanding Logan Airport (see Figure 3-92). The Blue Line tunnel was connected (from 1952 to 1954) to the old narrow-gauge Boston-Revere Beach-Lynn Railroad.

Beacon Hill & Cambridge Tunnels of the Red Line. The 5,183 meter (17,000 foot) long subway system between Park Street Station and Harvard Square had tunnel construction on either side of the Charles River (see Figure 6-1). In order to connect the recently built Tremont Street subway to the new Cambridge subway, the Boston Transit Commission constructed a tunnel through Beacon Hill as the Cambridge Connector, during the period 1909 to 1911. The Longfellow Bridge had previously been built in 1907 over the Charles River from Charles Circle in Boston to the Cambridge side just east of Kendall Square. The bridge was intended to convey trains, in addition to vehicular and pedestrian traffic. The Cambridge trains entered the subway just before Kendall Square and traveled westerly underground past the Central Square Station to terminate at Harvard Square.

The Beacon Hill tunnel extended from the Park Street Station to Phillips and Grove streets, a distance of 762 meters (2,500 feet) along a 1,453 meter (4,000 foot) radius arc. The tunnel passed diagonally from the southeast to the northwest under the remnants of the original Mount Vernon and Beacon hills. Historical records reported that "it was constructed through a very hard mixture of sandy clay containing numerous small stones, and occasionally boulders" (Colby, 1912). This description best fits the slices of lower till found in Beacon Hill. The tunnel intercepted "artesian" wells dating back to colonial times that necessitated the use of a 578 kilonewton (65 ton) thrust hydraulic roof shield pushing a 9.8 meter (32 foot) diameter bore. Two tubes 6 meters (16 feet) high and 7.5 meters (25 feet) wide were constructed with an arched roof of concrete. The deepest point of the tunnel was 30 meters (100 feet) below the ground surface where it passed beneath the hill.

A 90 meter (300 foot) long open cut was dug where the tunnel exited what was once the northern slope of Mount Vernon. The deposits encountered would be expected to be similar to both the organic silt and marine clay associated with the original shoreline of Boston found in the area of the Massachusetts General Hospital and the northern edge of Mount Vernon, and the sand and till found under Strong Place and the nearby Holiday Inn. The tunnel would then have been bored through the lower till, deformed lower outwash sand and clay under Trimountain and the Boston Common to Park Street Station. Pictures of the excavations at the State House and at Park Street, as well as observations of the deposits encountered during excavations to construct the Under Common Garage on Charles Street, support this conclusion (see Figures 3-81 & 3-83). The artesian wells encountered also indicate that pervious sand and gravel is present under Trimountain.

The tunnel between Kendall and Harvard squares on the Cambridge side of the river (for the Cambridge Main Street Subway) was built by the cut-and-cover technique developed fifteen years earlier. The work force averaged 2,500, but up to 4,000 workers at a time were employed. Near Harvard, the finished tunnel consisted of two stacked tunnel boxes, each 4.9 meters (16 feet) high by 7.6 meters (25 feet) broad, with the outbound track the higher one (Anon., 1911). The Cambridge tunnel crosses an area consisting primarily of marine clay, with varying amounts of upper outwash sand and gravel. The subway to Harvard Square opened March 23, 1912.

Boylston Street Tunnel of the Green Line. The Boylston Street Subway crosses Back Bay from the south end of the Tremont Street Tunnel to Governor (now Kenmore) Square several blocks west of Massachusetts Avenue (see Figures 6-3 & 6-5). The excavation became well known because of the discovery of fishweirs near Dartmouth Street (Boston Transit Commission, 1913) and its depiction in the novel *Back Bay* by William Martin (1979). The invert of the subway varies from approximately an elevation 0.9 meters (3 feet) Boston City Base (BCB) at Massachusetts Avenue, to its lowest point at elevation –5 meters (–19 feet) BCB between Arlington Street and Hadassah Way, thence to elevation –3 meters (–10 feet) BCB at Charles Street (Aldrich & Lambrechts, 1986) (see Figure 6-5). Ground surface along Boylston Street is generally elevation 17 BCB from Charles Street to Gloucester Street.

The structure is underlain by a wide variety of deposits including the fill, organic silt and upper sand and gravel outwash (see Figures 4-5 & 6-5, & Table 6-1). Peat encountered between approximately Hadassah Way and Charles Street — a distance of 140 meters (460 feet) — necessitated wood piles to support the structure (Aldrich & Lambrechts, 1986). Aldrich and Lambrechts (1986) researched the engineering geology and reported on the geologic conditions as described by L.B. Manley, Assistant Engineer for the Transit Commission:

"As is well known, the land reclaimed from the Back Bay consists of sand and gravel filling resting on a bed of silt whose upper surface lies at about grade 0, Boston City Base, or grade 100, Boston Transit Commission Base. This layer of silt is continuous throughout the length of the subway, and attains a thickness of about 5.2 meters (17 feet) at Dartmouth Street, and over 6.1 meters (20 feet) in the Fens. Between Exeter Street and Charlesgate East and between Clarendon Street and Charles Street, where it finally disappears, it averages about 2.4 meters (8 feet) in thickness. Below the silt between Massachusetts Avenue and Hereford Street, and at Exeter Street, are pockets of peat from 0.6 to 1.2 meters (2 to 4 feet) in thickness. Another extensive body of peat occurs between Arlington and Charles streets, where it attains a great depth.

"Below the silt and peat is a stratum of sand and gravel which also extends throughout the length of the subway excavation except for a length of about 488 meters (1,600 feet) between Exeter and Clarendon streets. This sand and gravel carries large quantities of water laden with sulphurated hydrogen, which has been offensive to passersby and injurious to the health of those working in it. This gas, as it leaves the surface of the water, is particularly destructive to metal, and copper floats in several of the temporary pump wells have been corroded through at the surface of the water in a few weeks' time by the action of this gas. It is supposed that this layer of gravel is the same as that which appears in the bed of the Charles River and affords an underground water course which tends to equalize the level of the ground water in the Back Bay."

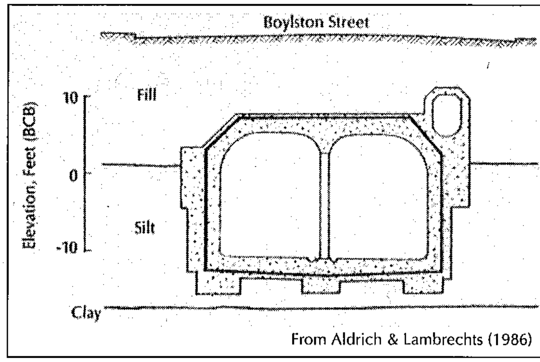


FIGURE 6-5. A section of the Boylston Street Subway between Berkeley and Clarendon streets at Station 58+00.

The sand and gravel layer is part of the same Lexington Outwash found at the nearby Gravelly Point on Massachusetts Avenue. A temporary drawdown of water levels both in the fill and in the lower sand and gravel stratum would have occurred during construction (Aldrich & Lambrechts, 1986). The drawdown in the sand stratum is estimated to have reached elevation –3 meters (–10 feet) BCB where the subway route passed opposite to what is now the Prudential Center.

Special care was needed alongside the Old South Church to prevent a further tilt of its tower, which was taken apart and rebuilt due to excessive settlement (Boston Transit Commission, 1913). Problems with its foundations had caused the tower to lean soon after it was built from 1872 to 1873.

Dorchester-Fort Point Channel Tunnel of the Red Line. The Boston Transit Commission completed the Dorchester Tunnel in 1915 from

TABLE 6-1.
Geologic Material Along the Boylston Street Subway

Location	Approximate Station	Elevation Top of Rail (ft, BCB)	Soil Conditions at Bottom of Subway
Kenmore Street (at Commonwealth)	0+00	16.2	Sand & gravel fill underlain by silt
Charlesgate West (at Commonwealth)	6+00	–8.7	Silt underlain by sand and gravel
Charlesgate East (at Commonwealth)	10+00	–18.9	Sand & gravel, short section of clay
Massachusetts Avenue (at Newbury Street)	19+32	7.5	Sand & gravel fill underlain by silt
Hereford Street	27+15	7.7	Silt over sand & gravel
Gloucester Street	31+55	1.9	Sand & gravel
Fairfield Street	37+15	4.8	Sand & gravel
Exeter Street	43+75	–6.4	Silt over sand & gravel
Dartmouth Street	49+80	–6.5	Silt over thin peat over thin sand & gravel
Clarendon Street	56+05	–8.8	Silt over thin peat
Berkeley Street	62+25	–13.0	Sand & gravel
Arlington Street	69+10	–14.5	Clay
Hadassah Way	73+35	N –14.0 S –11.2	Fairly hard blue clay Peat between Hadassah Way & Charles Street
Charles Street	78+00	N –4.2 S –5.0	Blue clay & gravel

Notes: From Aldrich & Lambrechts (1986). All elevations BCB. Information was obtained from Boston Transit Commission Plans Nos. 10219, 10386, 10091, 10418,11157, 11159, 11161 & 11162 of the "Boylston Street Subway." The bottom of subway structure varies from 1.2 to 1.7 meters (4 to 5.5 feet) below top of rail. The subway is supported on wood piles from Station 71+82 to 76+41.

Park Street Station to South Station (then called Dewey Square) and from there beneath the Fort Point Channel to the Broadway Station in South Boston (Boston Transit Commission, 1914), with service on the surface initially from Broadway to Ashmont. The tunnel was later extended to Andrew Station (see Figure 6-1). The Dorchester Tunnel, which intersected the Washington Street Tunnel at Summer Street, is 3.6 kilometers (2.3 miles) long and was constructed as a cut-and-cover tunnel on land, with shield-driven segment under the Fort Point Channel for 0.5 kilometers (0.3 miles). New subway stations were constructed at Chauncey Street (now Downtown Crossing) and Dewey Square (now South Station). The materials removed from the tunnels were used to fill in South Boston or were dumped at sea.

The cut-and-cover tunnel encountered clay with sand and what was called hardpan consisting of sand, gravel and clay. These findings are consistent both with the glaciomarine deposits found in the South Station area in the Central Artery/Tunnel Project borings and the hard clayey till observed by Woodhouse in the caissons for the 100 Summer Street (the Blue Cross-Blue Shield Building). The tunnel under Fort Point Channel was driven using a 7.3 meter (24 foot) shield, hydraulic jacks and compressed air pressure (Cohill, 1916). The depth of the tunnel is approximately 6 meters

TABLE 6-2.
Geologic Material Along the Huntington Avenue Subway

Location	Approximate Station	Elevation Top of Rail (ft, BCB)	Soil Conditions at Bottom of Subway
Massachusetts Avenue	13+85	–6.0	12 ft hard packed coarse sand
Cumberland Street	21+50	–10.9	11 ft hard packed coarse sand & gravel
West Newton Street	26+65	–13.0	7 ft hard packed sand & gravel
Garrison Street	32+00	–13.1	4 ft hard packed coarse sand
B&A Railroad Tracks (Massachusetts Turnpike Extension)	37+50	–13.6	Hard yellow clay (sand pinches out at Station 37+50)
Blagden Street (& Exeter Street)	41+30	–10.7	4 ft silt over medium blue clay & sand
Boylston Street (& Exeter Street)	44+50	–6.9	4 ft peat over 8 ft fine sand over stiff blue clay

Notes: From Aldrich & Lambrechts (1986). All elevations BCB. Information was obtained from Boston Transit Commission Plans Nos. 17947, 17943, 17936, 17933 & 17914 of the "Huntington Avenue Subway, Plan & Profile." The bottom of subway structure varies from 1 to 1.8 meters (3.5 to 6 feet) below top of rail. Footings, pedestrian passageway (Massachusetts Avenue) and bottoms of catch basins are deeper.

(20 feet) below the bottom of the channel at an elevation –15.2 meters (–50 feet) BCB, according to the Boston Transit Commission report of 1916. Soil under the Fort Point Channel consists of fill and harbor mud overlying stiff blue marine clay and the hard sandy clay till (Cohill, 1916). The tunnel excavation was primarily through the clay.

Huntington Avenue Tunnel of the Green Line. The Huntington Avenue Subway, which is now a branch of the Green Line, was constructed between 1937 and 1940 (see Figure 6-2). The surface Green Line enters the subway at Northeastern University just west of Massachusetts Avenue, crosses under Massachusetts Avenue as it enters Back Bay, and joins the Boylston Street subway at Exeter Street in Copley Square (see Figure 6-1). Within this area, the invert of the subway structure varies from elevation –3 meters (–10 feet) BCB at Massachusetts Avenue down to elevation –5.8 meters (–19 feet) BCB where the structure passes below the railroad tracks and under the Massachusetts Turnpike Extension (Aldrich & Lambrechts, 1986).

Aldrich and Lambrechts (1986) described the surficial deposits along the subway (see Table 6-2). The upper outwash sand and gravel, which is the Lexington Outwash, extends from 1.5 to 3.7 meters (5 to 12 feet) below the bottom of concrete from Massachusetts Avenue to the Massachusetts Turnpike. North of the turnpike to Boylston Street, the structure bears without piling on the organic deposit and the marine clay typically found in the Back Bay. During construction, it was necessary to dewater the highly permeable outwash for the entire length of the subway along Huntington Avenue to elevations as low as, or even below, –6.1 meters (–20 feet) BCB. It was noted that a very significant drawdown of the water level for a period of two to three years occurred over a wide area. The level in an observation well at Massachusetts and Commonwealth Avenues 0.6 kilometers (0.4 miles) away was reported to have dropped from elevation 2.1 meters (7 feet) to elevation 0 BCB in 1939. In fact, construction for the Huntington Avenue Subway required extensive and prolonged dewatering to levels below any known construction before or since (Aldrich & Lambrechts, 1986), which is significant because major construction around Copley Square has occurred since the subway was built, including the Prudential Building and Center, the Christian Science Complex, the John Hancock Building, and the Westin Hotel and Copley Place Development. Only one major additional building in the Prudential Center on Huntington Avenue has been constructed after 1986 and it had no significant impact on water levels. In addition, drains installed in the tunnels of both subway lines have undoubtedly collected groundwater that leaks into the structure, but data on groundwater levels reported in the section on the Boston Groundwater Trust information website (www.bostongroundwater.org) have not shown notable lowering in the period 2000 to 2012.

Haymarket North Extension Tunnel of the Orange Line, Green Line Tunnel & North Station "Superstation." With the construction of the Washington Street Tunnel, completed in 1908, the end of the MBTA Orange Line exited the subway tunnel at Friend-Union Station and climbed the Canal Street incline subway alongside the Green Line to the elevated portion over Causeway Street at North Station. The elevated Orange Line then proceeded across the Charles River over the North Washington Street Bridge (see Figure 6-4) toward Charlestown and followed above Main Street and Thompson Square to the terminal at Sullivan Square. The Green Line used the same incline from Haymarket Square Station to North Station, where it continued northwestward by another elevated viaduct to Cambridge.

The expansion and modernization of the Orange Line included the construction and expansion of the line to Melrose along with construction of a "superstation" at North Station. The first phase, the Orange Line Extension, was carried out between 1966 and 1977, which at that time was considered to be the most complex transit engineering project ever undertaken in the country. The expansion of the Orange Line was called the Haymarket-North Extension Project and it had a total length of 9.5 kilometers (5.9 miles) from Haymarket Square to the Malden-Melrose line. The first construction phase of the Orange Line ran underground through a two-track tunnel built in two sections for a total length of 1,380 meters (4,520 feet). It consisted of a cut-and-cover tunnel that followed Haverhill Street from Haymarket north to Causeway Street where the original complex for the future North Station "Superstation" was built. The cut-and-cover tunnel then continued down Accolon Way until it reached the Charles River. This area from Haymarket to Causeway Street was once a part of the old Mill Cove and Mill Dam that was filled in the early 1800s with the city's street sweepings, shells and till excavated from the top 12 meters (40 feet) of the west and north sides of Beacon Hill. Soils encountered in the tunnel consisted of the fill, organic silt and clay, which locally appeared to be glaciomarine in origin. The Orange Line was constructed under Accolon Way to Charlestown and then on the surface to Melrose. Problems developed with the open cut along Accolon Way that resulted from the use of steel sheet piling for excavation support. The Empire Carpet building that was next to the cut, and to the rear of the Railway Express building on Accolon Way, settled. Lateral movement of the Empire Carpet sheeting was 13 centimeters (0.5 feet) and settlement was 27 centimeters (0.9 feet). The structure was on timber piles and the first floor slab was an asphalt on grade. The silts washed out under the slab and the carpets that had been stacked on end collapsed and fell through the masonry wall.

H. Russell recollected in 2012 that the sheeting had numerous holes, and Lambe (1970) considered the role of groundwater to be most important. Lambe also found that significant movement occurred below the bottom of the excavation, and he attributed these movements to clay consolidation. In addition, Lambe showed that:

- The thrust from water pressure and the effective soil stress were significant.
- Groundwater flow analysis was complicated by the soil layering that caused differing permeabilities, and that there was leakage of water through the sheeting.
- The measured pore pressure was far below the static values, but that steady state seepage analysis gave reasonable prediction of water pressure.
- Groundwater levels affected key factors in excavation support design such as pore

pressure, soil stress, strut loads and wall movement.

Because the 12 to 18 meter (40 to 60 foot) deep Orange Line Tunnel excavation through Accolon Way was in close proximity to the foundations of the old Boston Garden and the Anelex Building, these structures had to be underpinned using one-hundred and fifty-five 890 kilonewton (100 short ton) piles driven to a depth of refusal at 14 to 20 meters (45 to 65 feet) where they penetrated into the glacial till. Uncovering and examining the old Simplex piles supporting the buildings, Woodhouse found that some of these original cast-in-place piles showed "necking" and, hence, had provided little or no foundation support to the original building.

The Charles River crossing was accomplished by the use of twin prefabricated steel tunnels lined with reinforced concrete and separated by concrete. Construction took place between October 1971 and July 1973. Dimensions of the tunnel sections were 9.8 meters (32 feet) in length, 11.4 meters (37.5 feet) wide and 6.9 meters (22.5 feet) high. Their tops were submerged 5.5 meters (18 feet) below low tide. Dredging for the immersed tubes was through river muck and clay. The tunnel exited to the surface at the Prison Point Bridge and Community College Station in Charlestown. Since it was in close proximity to footings for what was then the elevated Central Artery, these foundations had to be underpinned using caissons drilled 3.7 meters (12 feet) into the bedrock. The Charles River Tunnel was opened to subway traffic on April 7, 1975. The seventy-four-year-old elevated Orange Line structure was considered a "black serpent of blight" on the landscape through Charlestown and was demolished between 1975 and 1976.

The second major part of the work was making a better connection with the existing underground station of the Orange Line by building the so-called "superstation" adjacent to North Station. This superstation, which was constructed in stages between 1991 and 2005, involved the demolition of the old Boston Garden arena, the removal of the east Cambridge viaduct on Causeway Street and the enlargement of the underground station at North Station to include a common station for the Orange Line and the Green Line. The Green Line connection to the Lechmere Viaduct was placed underground around North Station as part of the Central Artery/Tunnel Project. The old Canal Street incline from the Haymarket Station and the remaining 0.8 kilometers (0.5 mile) of elevated railway along Causeway Street that was built in 1912 were taken down. As part of the project, a six-story underground garage was constructed under the arena with the use of slurry walls and load bearing elements for the future Boston Garden (now called the TD Garden).

The two lines were built adjacent and parallel through the station in order to allow cross-platform transfers and access to North Station and the sports arena. The station was excavated more than 15 meters (50 feet) deep through mainly old fills north of Haymarket. A Green Line tunnel was excavated farther north before swinging west under the new TD Garden arena and rising to cross over the viaduct. Caissons drilled 3 meters (10 feet) into the argillite bedrock for TD Garden, and the Green Line below it, encountered hard diabase dikes within the argillite bedrock that were reported to have slowed drilling from as much as 8 meters per day to less than 1 meter per day (25 feet per day to 3 feet per day) (Haley, 2013; Cardoza, 2013).

Southwest Corridor Tunnel of the Orange Line. A proposed extension of Interstate 95 into Boston was abandoned in 1972 due to public opposition and a moratorium imposed by then-Governor Sargent on further highway construction in Boston. This change left the acquired right-of-way, from which many structures had been cleared, unused. Money set aside for this cancelled Southwest Expressway Highway Project then was redirected by the Massachusetts Legislature for the construction of a relocation of the Orange Line from the elevated structure over Washington Street to this right-of-way (see Figure 6-6). Construction began in 1979 and the Southwest Corridor opened to much fanfare in 1987. This project finally allowed the elevated Orange Line and the remaining old Washington Street Elevated railway (which ran from Forest Hills

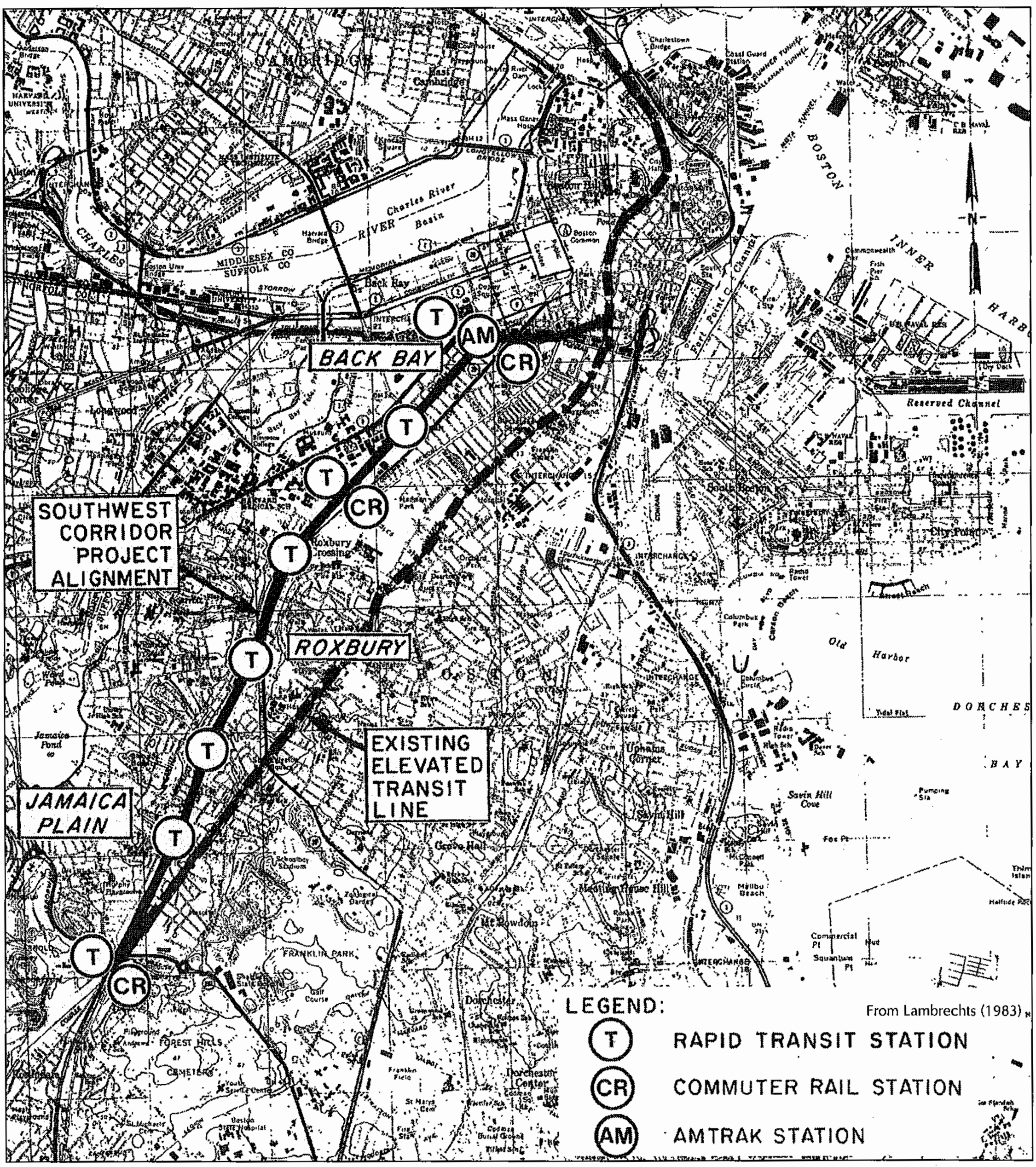


FIGURE 6-6. Location of the Southwest Corridor Project of the Orange Line Subway. The Amtrak station is the Back Bay Station.

through Roxbury to downtown Boston) to be demolished. The old Washington Street Tunnel was re-routed into the new corridor in May 1987 via the South Cove Tunnel. The corridor is a shared route with two tracks for the relocated Orange Line subway and three tracks for MBTA commuter rail and Amtrak service. The alignment through Back Bay follows parts of two original railroad embankments that were constructed across the Receiving Basin in the mid-1830s. From Massachusetts Avenue to Dartmouth Street (Back Bay Station), the new concrete structure was built below ground (see Figure 6-7) in a 915 meter (3,000 foot) long cut-and-cover tunnel that required excavations as deep as 11.6

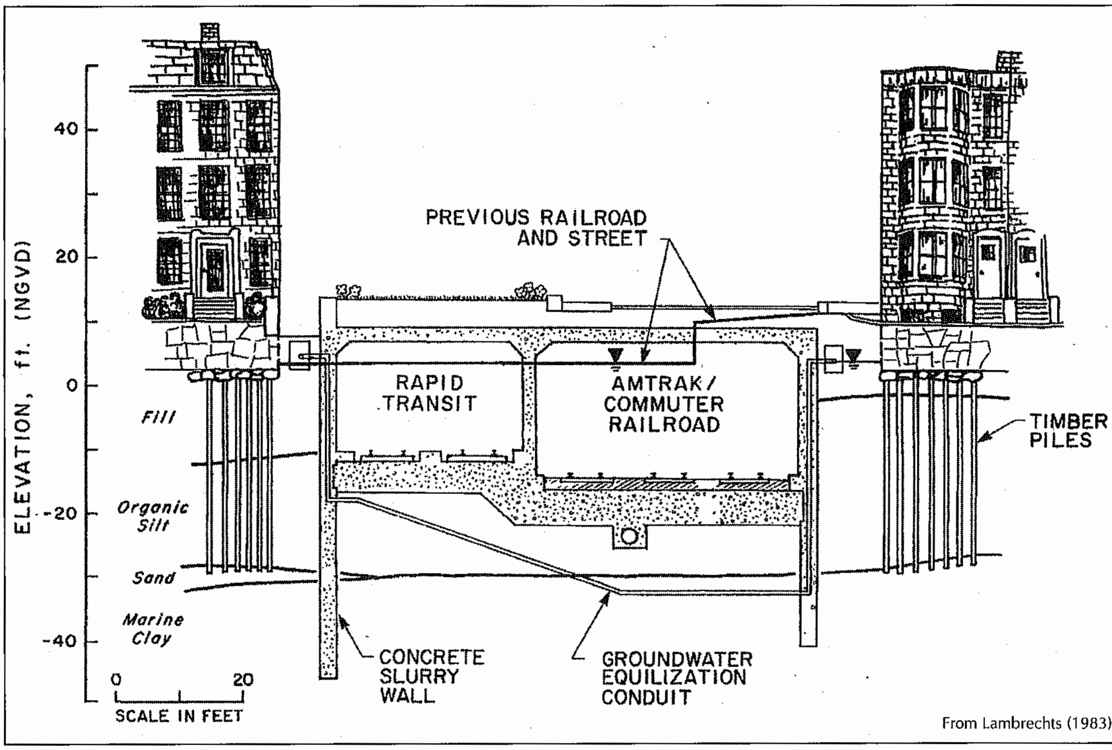


FIGURE 6-7. Typical section of the Southwest Corridor Project of the Orange Line through the Back Bay.

meters (38 feet). East of Dartmouth Street, the structure extended about 3 meters (10 feet) below the former grade. The 7.25 kilometer (4.5 mile) long project is 24 to 30 meters (80 to 100 feet) wide. About 30 percent of the corridor is roofed over and buried, and the rest of it has been designed to accommodate a future deck.

The corridor tunnel traverses the Boston Pleistocene sequence in the Back Bay (see Figure 6-8) and into the inland glacial sequence in Roxbury and Jamaica Plain (Lambrechts, 1983). The soft marine clay and organic deposit of the Back Bay were particular concerns in the project and layers of very peaty silt up to 1.5 meters (5 feet) were encountered in the latter.

Reinforced concrete slurry walls were used for lateral support for about 640 meters (2,100 feet) of the tunnel excavation (see Figure 6-7). The 1 meter (3 foot) thick concrete walls penetrated 2.4 to 4.6 meters (8 to 15 feet) into the clay stratum of the Back Bay and serve as the tunnel's permanent walls. Depth of slurry wall penetration was established depending on strength of the crust of the marine clay that was determined by test borings made for each of the 6 meter (20 foot) long slurry wall panels. The crust has superior end-bearing support properties (see Figure 6-9), where present. Some minor amounts of water leakage occurred through a few of the vertical joints between wall panels. This leakage is common and has been observed on other construction projects in Boston with similar excavation support walls, but there was no appreciable lowering of groundwater levels in adjacent areas. In other deep excavation areas where adjacent structures were farther away from the excavation or absent, steel sheet-piling was used for temporary lateral support of the excavation. East of Dartmouth Street, excavations were shallower and soldier piles with wood lagging were used. Water seepage into these excavations temporarily lowered groundwater levels (Aldrich & Lambrechts, 1986) in adjacent areas as much as 3.7 meters (12 feet).

According to Aldrich and Lambrechts (1986), where concrete slurry walls were used,

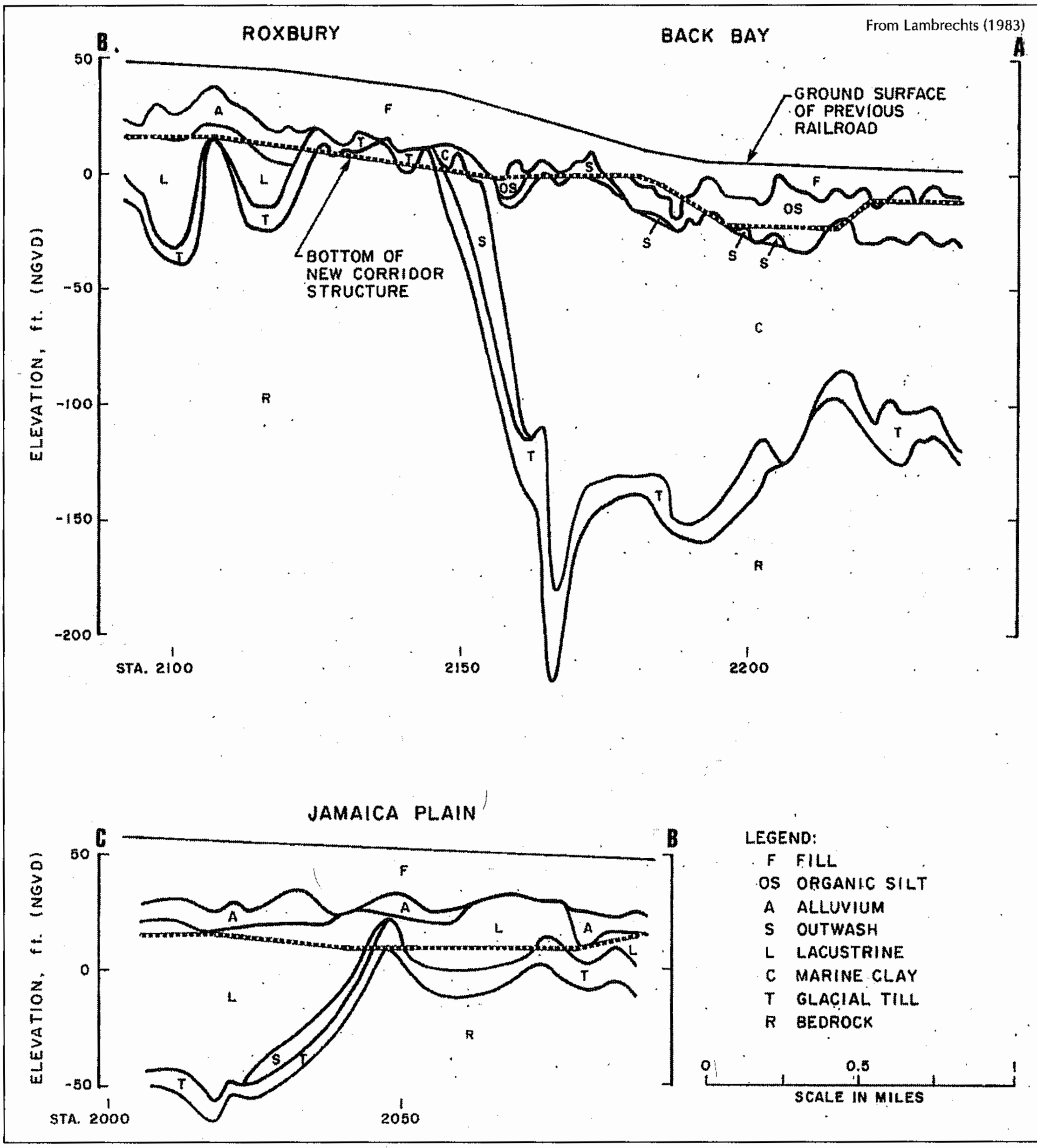


FIGURE 6-8. Section along the Southwest Corridor from the Back Bay to Jamaica Plain showing geologic units and tunnel depth. The Back Bay portion shows the Pleistocene sequence of Boston: undivided upper and lower till (T), local lower outwash (S), marine clay (C), patchy upper outwash (S) and organic deposit (OS). The Roxbury to Jamaica Plain portion shows inland sequence of till (T), lacustrine silt and fine-grained sand and minor clay (L) and alluvium (A). The lacustrine deposit is approximately the same age as the lower outwash.

the tunnel is supported on a thick concrete invert slab bearing on compacted sand and gravel fill, which was used to replace compressible and unsuitable organic soils (see Figure 6-9). East of this portion of the tunnel, the structure was supported on pre-cast, prestressed concrete piles driven through the clay to end bearing on till or bedrock.

In order to allow the natural groundwater flow across the corridor structure (which

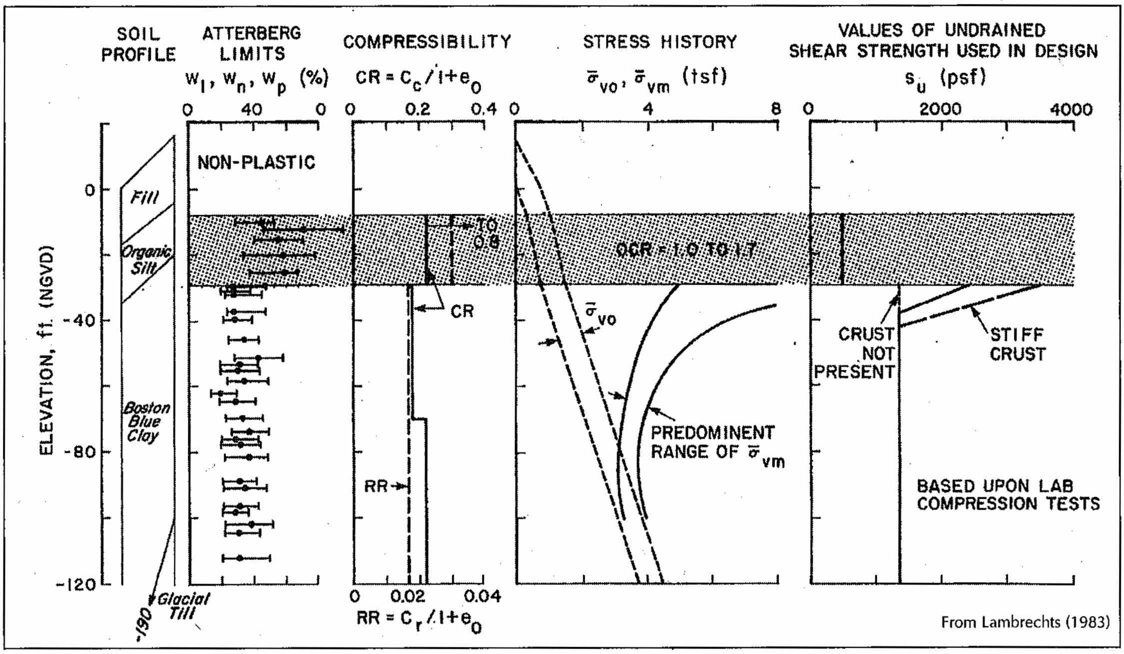


FIGURE 6-9. Engineering characteristics of the surficial deposits along the Southwest Corridor.

would form a hydraulic barrier), a groundwater equalization under-drain system was installed (see Figure 6-7). This system consisted of longitudinal drains placed 0.6 to 1.2 meters (2 to 4 feet) below the pre-construction groundwater level along either side of the structure. Where slurry walls formed the tunnel walls, 20 centimeter (8 inch) diameter header pipes surrounded by crushed stone were connected to 20 centimeter (8 inch) galvanized steel pipes cast into the walls and connected beneath the invert slab. In other areas, rectangular drains of crushed stone wrapped in filter fabric were constructed beneath the invert slab and up the outside of each wall in order to allow water to flow between longitudinal drains on either side (Aldrich & Lambrechts, 1986).

The Southwest Corridor Project includes the large Back Bay Station, which extends from Clarendon Street to Dartmouth Street, for combined Amtrak, commuter and subway train service. The station construction extended under part of an eight-story building (see Figure 6-10) and replaced some caisson support of the building by a "C"-shaped load transfer (Lambrechts, 1983).

South Cove Tunnel of the Orange Line. The Orange Line beneath Washington Street connects to the new Southwest Corridor (see Figure 6-11) by way of the South Cove Tunnel and the previously constructed South Cove Station (now called the Tufts New England Medical Center). The tunnel is approximately 0.77 kilometers (0.5 mile) long and consists of 444 meters (1,450 feet) of cut-and-cover on the north end, 107 meters (350 feet) of twin tunnels under the Massachusetts Turnpike and 221 meters (725 feet) of cut-and-cover on the south end (Stacho, 1968). Because of the concern for settlement of the overlying roadway, the top of the 4 meter (12 foot, 11 inch) high tunnel box (inside height) was to be no less than 0.46 meters (1.5 feet) from the underside of the roadway. The tunnel under the turnpike was a twin-bore that used both a roof shield driven by hydraulic jacks and a 7.3 meter (24 foot) diameter compressed air shield.

Construction of the northern part of the tunnel passed very close to existing buildings and had to preserve their structural integrity. Two designs to protect the foundations from settlement included underpinning with piles driven to bedrock and the construction of a 1 meter (3

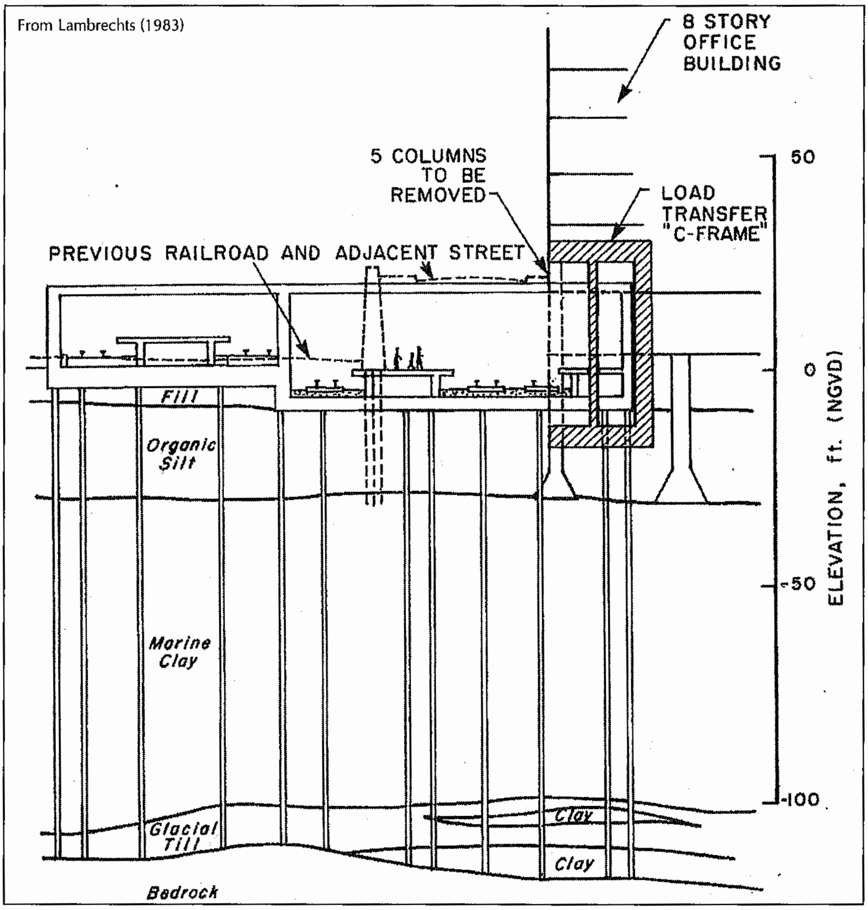


FIGURE 6-10. Section through the Back Bay Station showing the underpinning and the load transfer "C"-frame building support.

by the Boston Redevelopment Authority to be built above the tunnel north of the Massachusetts Turnpike. Also, the groundwater levels in the area had to be maintained and recharged if deemed necessary.

The geology along this 805 meter (2,640 foot) tunnel is highly variable (see Figure 6-12), as described by Stacho (1968). The underlying material consists of 1.5 to 3 meters (5 to 10 feet) of miscellaneous fill originally brought in from Roxbury, Dorchester and Brighton about one hundred years ago when the South Cove was filled and developed. Beneath the fill under the former tidal flats of the cove is a layer of peat and organic silt, which ranges in thickness from a feather edge to as much as 6 meters (20 feet). Marine clay with a thickness of 18 to 30 meters (60 to 100 feet) underlies the organic deposit and consists of an upper approximately 1.4 meter (5 foot) thick soft blue clay (the hard crust is reduced and softened by the overlying organics) and a lower stiff pre-consolidated weathered yellow clay crust that is normally soft and gray at depth. Identified as "gray clay" on the profile, a thin till layer about 1.5 meters (5 feet) thick and made up of clay, sand, gravel and argillite fragments was found on top of the bedrock. The argillite was encountered at depths approaching 35 meters (115 feet), at elevation –35 meters (–115 feet) MSL, at the south end of the tunnel and rising to a bedrock

foot) thick reinforced concrete wall. The wall was constructed using a bentonite slurry cutoff wall that was then filled by tremie concrete. The concrete slurry wall was successful in minimizing settlement. A study by Lambe (1970) compared the performance of the excavation for the South Cove Tunnel using steel sheet piling and concrete slurry wall. The Don Bosco School was protected from the South Cove Tunnel excavation by a concrete slurry wall, which reverted to steel sheet piling just past the school. The concrete slurry wall moved inward 2.5 centimeters (1 inch) and settled as much as 1.5 centimeters (0.6 inches), which was very much less than the ground moved behind the adjacent steel sheet piling section that moved laterally 15 centimeters (6 inches). In addition, it was required that the tunnel be designed to support the new buildings that were planned high at a depth of 20 meters (65 feet), at elevation –20 meters (–40 feet) MSL or less, under the Washington Street portion of the Orange Line Tunnel at Kneeland Street.

Northwest Extension Tunnel of the Red Line. The 5.0 kilometer (3.1 mile) Northwest Extension of the MBTA Red Line beyond Harvard Square to Alewife Station (see Figure 6-1) was constructed between 1979 and 1985, and consists of two deep rock tunnel sections and shallower cut-and-cover sections in the overburden. The first section, which is 1,342 meters (4,400 feet) long, connects the new cut-and-cover Harvard Square Station to the 46 meter (150 foot) deep Porter Square Station (Dill, 1986). The five-level deep station and approach tunnels were built into the argillite because of the high cost of constructing a shallow tunnel in clay and the consequent surface disruption it would have created according to the MBTA. The Porter Square Station is, in turn, linked to the cut-and-cover Davis Square Station by the second deep bedrock tunnel section, which is 884 meters (2,900 feet) long (Cullen *et al.*, 1982). Beyond the Davis Square Station, the Northwest Extension continues as cut-and-cover tunnel along a railroad right-of-way to the Alewife Brook Station, which is its present terminus. Considerable exploration was done for the project and a thorough evaluation of the results of the exploration was made for design (Stimpson & Thompson, 1981; Keville & Sutcliffe, 1983; Waggoner, 1984).

From Lambe (1970)

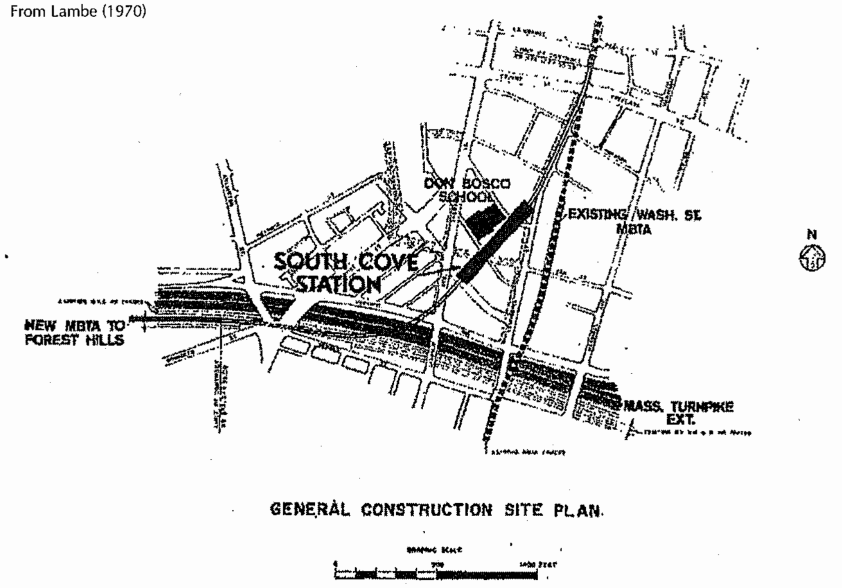


FIGURE 6-11. Map of the Southwest Corridor Tunnel and the South Cove Station.

The deep tunnels are twin bores, with each excavated to 6.7 meters (22 feet) in diameter. The construction access shafts now serve as ventilation and emergency egress shafts at intervals along the alignment. A variety of excavation and support techniques was utilized during the construction of the shafts and tunnels. The minimum support requirements originally specified for lengths of the tunnels, based on the expected subsurface conditions, were as follows: circular steel ribs and wood lagging for soft ground and mixed-face conditions — 1,479 meters (4,850 feet); steel sets for moderately sound rock conditions — 1,085 meters (3,560 feet); and rock bolt support or other appropriate support at the contractor's option in sound rock — 1,866 meters (6,120 feet).

The primary rock type along the tunnel alignment is the Cambridge Argillite, with lesser amounts of intrusive rock. The engineering properties of the bedrock and that of the overburden were determined (see Tables 4-4 & 4-5) for the project (Hatheway & Paris, 1979; Cullen *et al.*, 1982). The argillite is not uniform in appearance, but it does not show any significant variations from a geotechnical standpoint, except where it is significantly faulted or sheared and degraded by groundwater. The bedding characteristics in the argillite are extremely variable (Cullen *et al.*, 1982), although the bedding generally dips gently to moderately (20 to 45 degrees) to the south and repre-

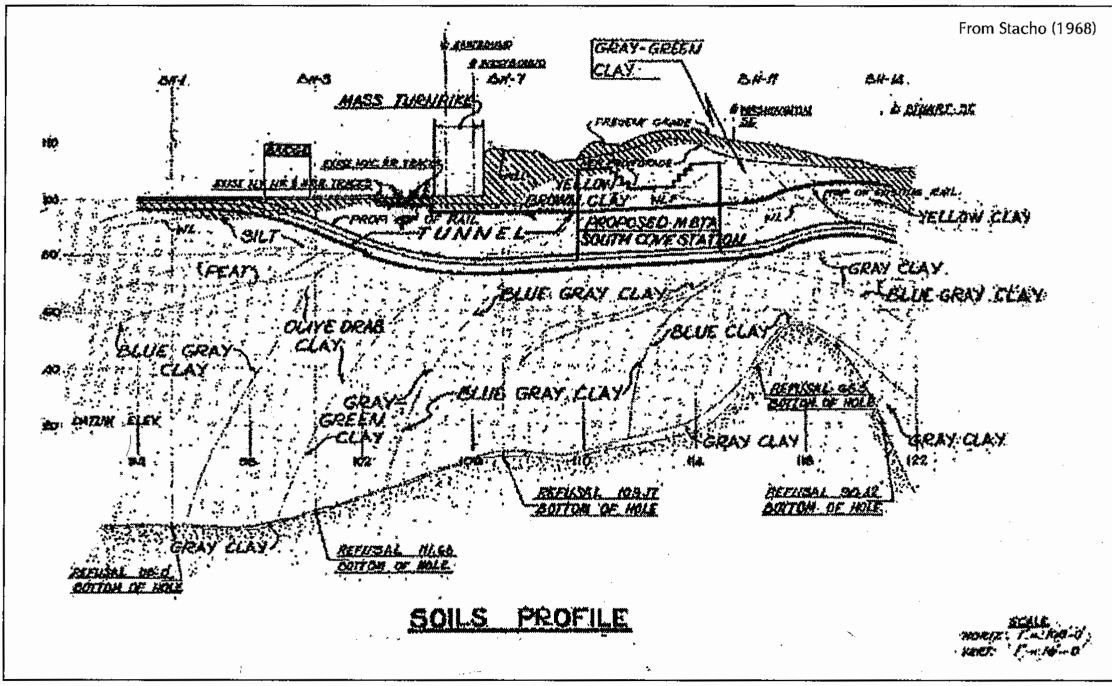


FIGURE 6-12. Section of the Southwest Corridor Tunnel near the South Cove Station at Follen Street.

sents the tilted fault block north of the Charles River. The bedrock varies from a massive dark to medium-gray, fine-grained argillite to one exhibiting rhythmic bands of light-gray layers alternating with medium- to dark-gray layers. The coarser-grained and generally lighter colored layers display well developed bedding structures such as graded sequences, cross-bedding and ripple marks. Mafic to felsic intrusive bodies are not uncommon and the characteristics of each occurrence vary greatly. They differ in composition, texture, orientation and contact relations.

The tunnel alignment is obliquely down or up-dip, depending on the direction of its orientation. On the curved tunnel section from Porter Square Station to the Davis Square Station, the alignment swings around almost parallel to the strike of the beds (Cullen *et al.*, 1982). This gradual change resulted in a varying response by the bedrock to the boring of the tunnel, which translated into a differently shaped tunnel opening (Hathaway & Paris, 1979). Joints are usually spaced 30 to 50 centimeters (12 to 20 inches) apart along bedding planes and their presence or absence did not normally affect the stability of the tunnel opening. The exception exists near faults, or the top of the rock, where very closely spaced joints, usually 10 to 25 centimeters (4 to 10 inches), developed parallel to the bedding surfaces. Three major joint sets were encountered during construction. The major joint sets, other than bedding plane joints, along the alignment generally strike north-northeast. In addition, the joints have nearly vertical dips (angle measured from the horizontal surface at right angle to the strike of the rock). Jointing parallel to bedding is also commonly developed and strikes nearly east-west with gentle to moderate dips, either north or south. A well-developed set of joints was found nearly parallel to shear zones, which are usually oriented more east-northeast. These joints tend to decrease to become non-existent with increasing distance from a shear zone and did not contribute to major support problems because most were oriented nearly normal to the tunnel alignment. Locally, overbreak occurred if these joints were parallel to the alignment (Cullen *et al.*, 1982). Shear or fault zones without associated clay gouge did not have much effect on tunnel construction. Where gouge is present, however, the stability is affected owing to the reduction of the frictional forces binding blocks of rock together around the tunnel opening. The integrity of the tunnel opening was further affected where these zones nearly parallel the alignment (Cullen *et al.*, 1982).

The Pleistocene section along the alignment west of (but not including) the Davis Square Station contains moderately thick and variable deposits. The units and their thicknesses are, in ascending order from the bedrock (Bechtel, 1978): till 0 to 21 meters (0 to 70 feet), marine clay 0 to 18 meters (0 to 60 feet), upper outwash sand and gravel 0 to 15 meters (0 to 50 feet), and miscellaneous fill 0 to 4.5 meters (0 to 15 feet). It is noted that, at Davis Square, the slurry wall encountered problems when it was discovered that a portion of the wall was not keyed into the argillite, but was bearing on a boulder in the till. Woodhouse observed that a thick slab of the argillite about 1.5 meters (5 feet) thick had been dislodged by the glacier and deposited in the till. This case points out the need to core no less than 3 meters (10 feet), but preferably 6 meters (20 feet), of the bedrock to confirm that the top of the rock has been encountered.

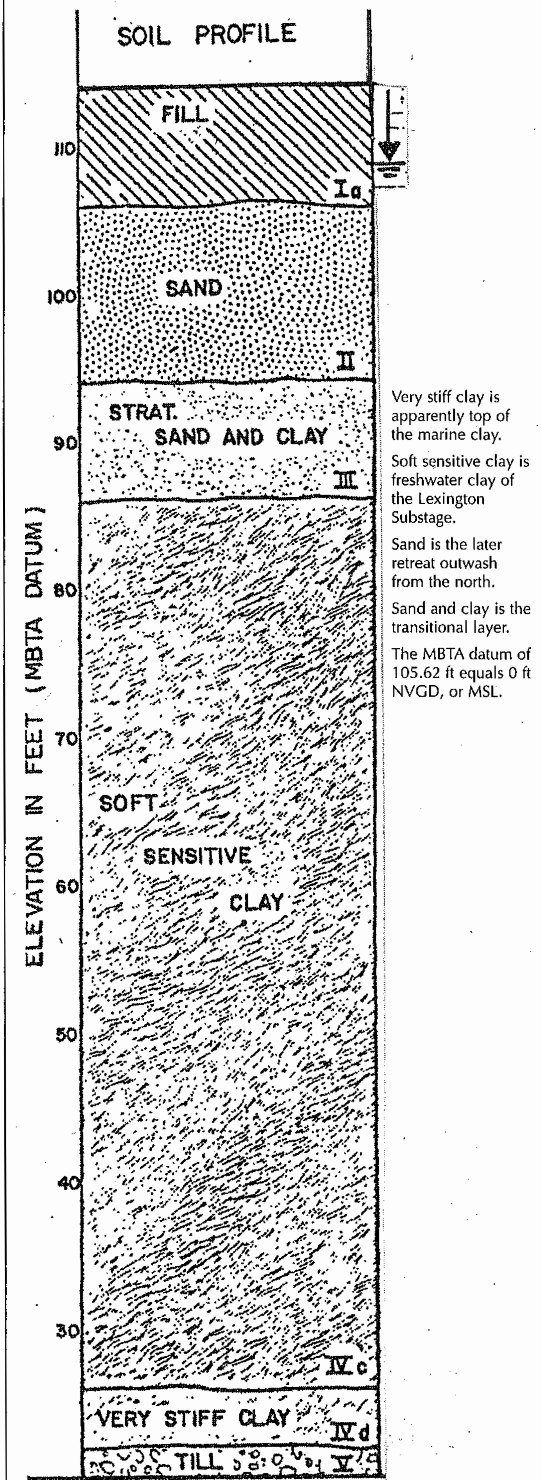
Excavation for the Alewife Station, which is the location of the station garage complex at the end of the Red Line, encountered an anomalous deposit of soft sensitive clay that caused several problems. The unusual complexities posed by this clay were thoroughly considered in design. The station design consisted of an 18 meter (60 foot) wide by 11 meter (37 foot) deep excavation with cast-in-place slurry walls used for cofferdam construction and permanent walls for the station. The presence of the sensitive clay caused problems with the slurry wall. The test borings found about 2.4 meters (8 feet) of miscellaneous fill overlying stratified sand and clay to 6 meters (20 feet). At this depth, soft sensitive clay was encountered to a depth of 24.4 meters (80 feet) where very stiff yellow clay from 24 to 27 meters (80 to 90 feet) was found overlying the till layer of only limited thickness, less than 3 meters (10 feet) The top of bedrock is generally about 30 meters (100 feet) deep (see Figure 6-13).

The following discussion is adapted from Goldberg-Zoino Associates's *Slurry Wall Test Panel Report, MBTA Red Line Extension Davis Square to Alewife*, and from personal communication (Barvenik, 2012).

The sensitive-like clay at the Alewife Station area in West Cambridge was recognized to be somewhat different that the "usual" Boston Blue Clay. The Alewife blue clay had lower than normal strength relative to the Boston Blue Clay, sensitivity greater than 20 versus 4 to 8, a lower plasticity index and liquid limit, and a higher liquidity index with natural water content greater than the liquid limit. The possibility of large strength loss with disturbance during excavation resulted in the selection of cast-in-place diaphragm walls (slurry walls) for cofferdam construction. This method provided rigid walls extending below the bottom of the excavation to prevent excessive lateral displacements and improve base stability. The slurry wall also provided a permanent wall for the station platform excavation area and the tunnels leading into the Alewife Station from Davis Square.

Because of the unusual character of the soft sensitive-like clay, a test section was undertaken to reveal inherent potential construction problems, resolve uncertainties and reduce contingencies in the bid prices. The test section results showed that the sensitive clay deposit appears to be over-consolidated by at least 71 kilopascals (1.0 kips per square foot) throughout its entire depth. The deposit did not exhibit any consistent trends of increasing or decreasing strength with depth but a high degree of strength variability actually exists throughout the deposit. Based on field and lab testing, average undrained strength for the clay is 43 kilonewtons (900 pounds per square foot). The clay anisotropy is as much as 175 percent. Wick/sand drains were used both to speed up drainage for rebound and to foster more drained-strength conditions during excavation. The excavation was made in sequential benched steps, thereby providing some drainage time.

The station wall bottoms rotated inward during excavation, resulting in the top of the walls moving away from the excavation and, thus, leaving a gap between the top struts and



From Goldberg, Zoino, Dunnicliff & Associates (1978)

FIGURE 6-13. Columnar section in Alewife Station area of the Red Line.

the wale. This rotation indicated that the clay inside the excavation was not providing sufficient resistance to withstand the soil pressures outside the walls prior to the installation of the lower struts in the station excavation area.

Problems also developed with the installation of piles to support the parking garage and station mezzanine areas (see Figure 6-14). All the inclinometers and piezometers installed indicated that the slurry walls were moved by the pile driving. The piles were to be pre-augered through the sensitive clay to limit disturbance. Sufficient water was required to flush out the cuttings during augering so that only clear water remained in the hole before pile insertion. If this operation were not done, it was feared that the clay would remain in the pre-auger hole and would turn into a thick liquid because of its high sensitivity and not rise up to the ground surface, escaping through the small space between the hole wall and the pile when the pile was placed in the pre-augered hole. The contractor apparently did not figure in the cost of dealing with all the water and a settling pond that would be required to meet the specification. Instead, only a small volume of water was used during drilling, which did not flush out the cuttings. The result was that very little soil/clay cuttings came out of the hole when the pile was inserted, and a spike in pore pressure in the clay surrounding the pre-auger hole developed, leading to disturbance.

Alterations to the auger allowed more water to be pumped in temporarily, which cured this problem. The problem redeveloped, however, when the contractor again resumed the practice of using very little water. Each time a pile went in, it acted like a piston and displaced the viscous clay remaining in the lower portions of the hole out into the formation as a volume change. The end result was that the pile installation outside the already placed concrete diaphragm walls pushed the walls laterally about 15 centimeters (6 inches). This displacement was enough to cause the two cast-in-place slurry walls (which were to be the permanent tunnel walls) to move toward each other, thereby impinging on lateral train clearances. The contractor was then allowed to drive the internal piles between the two slurry

FIGURE 6-14. Aerial view (from west) of the Alewife Station of the Red Line during construction. (Courtesy of M. Barvenik, Goldberg-Zoino Associates.)

walls in the same manner to push the walls back out. That, plus requiring removal of all the imperfections (bulges) in the concrete walls, provided just barely enough clearance for the trains not to "rub the walls" on their way through the station.

Further problems with the 35.5 centimeter (14 inch) square, 42.5 meter (140 foot) long precast concrete piles developed when the hammer was found to be delivering less energy, resulting in a pile load test failing. However, the new hammer broke and the contractor again used the flawed hammer to drive a large number of piles with insufficient energy. The pile driver was unable to get back into the area to re-strike or further advance the piles to required design capacity due to all the piles already being in place. Subsequent calculations concluded that there was reduced pile load capacity but that the resulting factor of safety less than the specified standard 2 would be sufficient. Monitoring of the garage as it was being constructed found that it did not settle an unacceptable amount because of lower ultimate pile capacity. Another consideration was that only five stories of the garage were constructed, although it was designed to take seven stories, which is problematic for any future proposed addition to the original constructed height of the garage at Alewife (which would require adding piles similar to that done at Central Parking Garage at Logan Airport).

The Route 2 Bridge (which originally crossed the previous railroad alignment) now crosses over the subway storage tunnel that is beyond the Alewife Station. The bottom of the clay was very deep in this area. Bridge abutments on either side of the tunnel roof slab were underpinned with top-down construction. The tunnel roof is supported on the slurry walls, which then had to be deep (more than 24 meters [80 feet]) to pick up sufficient load-carrying capacity through side friction. Given the stiffness of the walls, the calculations showed that the long walls extending far below the bottom excavation support strut (which was a meter [several feet] above the thick tunnel invert slab) would impose very large loads on the bottom strut due to the rigidity of the support system relative to the strain required in the clay to develop its shear strength and the passive resistance between the walls. A "hinge" was therefore formed in the slurry walls below the bottom strut by crossing the inside and out-

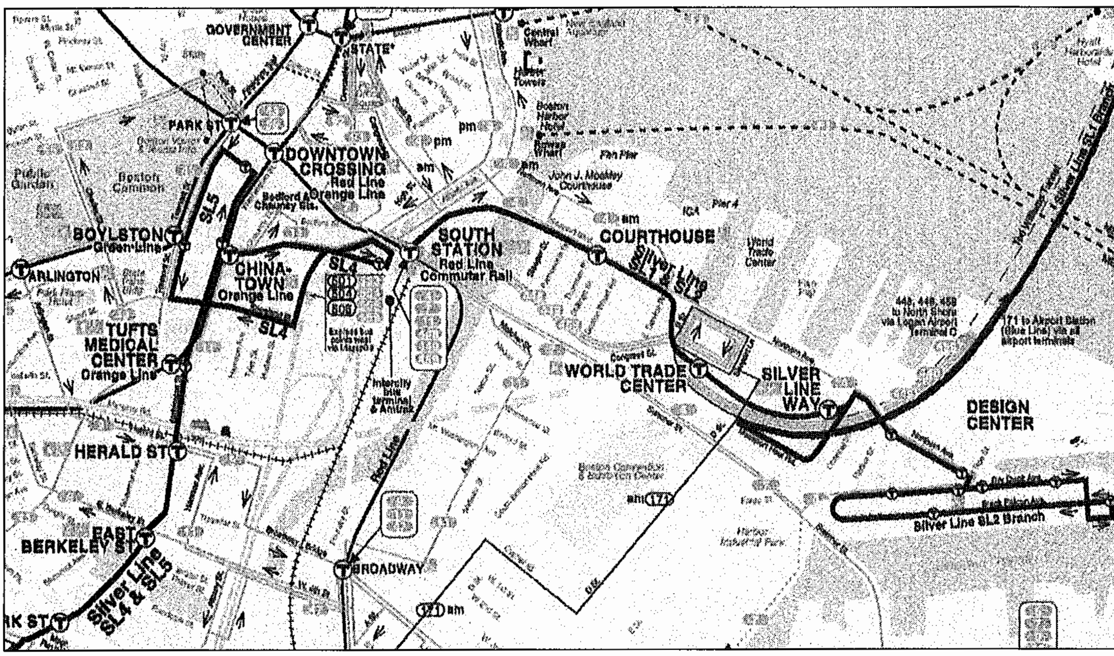


FIGURE 6-15. Map of the Silver Line through central Boston and South Boston. (Courtesy of the MBTA.)

side reinforcing bars to opposite sides of the wall, thus reducing the moment-carrying ability of that point in the wall. This solution maintained the vertical load carrying capacity needed for the underpinning, while eliminating the moment in the wall and, thus, the otherwise high lateral loads on the bottom strut.

The high sulfate and low pH (as low as 1) in the soils and groundwater that originated from the Grace Chemical sludge lagoon affected the concrete and steel. There were health claims by MBTA transit workers alleging that the Grace Chemical groundwater contamination was causing headaches, etc. However, an investigation discovered a small leak in an elevator hydraulic hose that was atomizing the hydraulic oil and dispersing it into the air. The issue disappeared once the leak was found and repaired. However, this investigation uncovered the fact that the contractor never installed the cutoff slurry wall that was supposed to be installed below the floor slab between the tunnel slurry walls. This wall would have separated the boat slab section through the stratified sand deposits in the Grace Chemical area to the east of Alewife Brook Parkway from the relieved slab in the clay deposits of the station area to the west of Alewife Brook Parkway. The lack of this wall resulted in far more groundwater coming into the relieved slab drainage system, which was contaminated by the groundwater from the boat slab section through Grace being pumped from the station area.

Silver Line Tunnel. The Silver Line was originally planned as a subway in 1948, but ended up as a hybrid rapid bus line that provides service at street grade from Dudley Square Station in Roxbury to South Station, and then with transfer to a tunnel, continues on to South Boston Seaport and Logan Airport. Although it has a normal subway line designation, the Silver Line is largely a bus on city streets (see Figure 6-15). The line runs on the surface from Dudley via Downtown Crossing Station or Chinatown to South Station. At South Station, a second segment has its terminus below ground and it runs in a tunnel that passes above the Central Artery northbound from Essex Street to Congress Street and goes under Fort Point Channel to emerge just east of the World Trade Center in the South Boston Seaport area, where the line splits at the Silver Line Way Station. One route continues on the surface northeastward through the Ted Williams Tunnel to the airport and another eastwards to the Boston Design Center. Plans to extend the tunnel from South Station westward to the Boylston Station on the Green Line are currently on hold. The construction of the existing Silver Line Tunnel section, which opened December 17, 2004, demonstrated some excellent innovative engineering techniques in both its onshore and sub-channel portions.

The tunnel passes through an area of old docks and mostly nineteenth century infilling that encroached on Fort Point Channel. The line extends through the Russia Wharf area at Atlantic Avenue and Congress Street (which is near the original Boston shoreline) and is underlain by 3 to 5 meters (10 to 16 feet) of granular fill and debris from old harbor-front structures that had been dumped on organic sediment that ranges in thickness from 1.5 to 3 meters (5 to 10 feet) thick (Boscardin *et al.*, 2005). The tunnel is built mainly within the underlying 3 to 15 meter (10 to 49 foot) thick layer of marine clay that overlaps a 1.5 to 10.5 meter (5 to 12 foot) thick dense upper till, which forms part of the east base of the Fort Point drumlin (see Figure 6-16). Very soft to medium hard argillite occurs below at depths of 19.5 to 24 meters (64 to 79 feet). Particular care was needed to seal off groundwater because the porous fill had many open voids. This goal was accomplished using a slurry cutoff wall. The groundwater level is that of the nearby Fort Point Channel and fluctuates between 0.3 to 1.0 meters (1.0 to 3.3 feet) with the tide.

Special design considerations had to be made in constructing the tunnel below Russia Wharf, which contains historical buildings dating back to the late 1800s that remained occupied during construction (Lacy *et al.*, 2004; Boscardin *et al.*, 2005). The buildings have steel frames and masonry facades supported by granite caps and wood piles, and the tunnel had to pass through the piles, fill and abandoned wharf structures (see Figures 6-16 & 6-17). A 13 meter (43 foot) wide by 8.5 meter (28 foot) high tunnel 100 meters (328 feet) long was constructed using the New Austrian tunneling method and the sequential excavation method. These methods were selected to protect and preserve the buildings of Russia Wharf and mitigate any ground and building movements (see Figure 6-17). These efforts included soil freeze cycling, raising and lowering the buildings, the installation of temporary and permanent underpinning, and the installation of mini-piles supported by the underlying argillite bedrock. There was full geotechnical instrumentation of the buildings and the tunnel to monitor movements before, during and after the tunnel construction. The wood piles that were cut out for construction of the tunnel were supported by the tunnel walls designed to carry the loads.

The Fort Point Channel portion was constructed as an immersed tube with cut-and-cover tunnel sections on the sides of the channel (Leifer, 2006). The tunnel in this location remains mostly in the marine clay, except for a small part in the middle that reached downward into the upper till. During dredging for the immersed tube placement, a 6 by 6 by 2.4 meter (20 by 20 by 8 foot) glacial erratic boulder was found at the clay-till contact and had to be broken up in place before dredging could be completed. The deeper parts of the dredged trench penetrated sand and clay, and the shallow ends were located in granular fill or cohesive fill consisting of dredged clay and harbor sediments. The tunnel tubes were prefabricated nearby and floated into place, lowered into the trench and then assembled, connected and backfilled.

The South Boston section was constructed as a cut-and-cover tunnel that begins at a depth of about 11.6 meters (38 feet) deep at the Fort Point Channel and ramps up to the ground surface east of the World Trade Center. The deeper part lies in outwash sand and marine clay, and the shallower part in granular fill or cohesive fill, which consists of dredged marine clay and harbor sediment (Leifer, 2006).

Red Line/Blue Line Connector Tunnel (Proposed). A new extension of the Blue Line subway, designated as the Red Line/Blue Line Connector, has been proposed to run from Bowdoin Station, currently the end of the Blue Line, to the Charles/MGH Station located at Charles Circle on the south side of the Charles

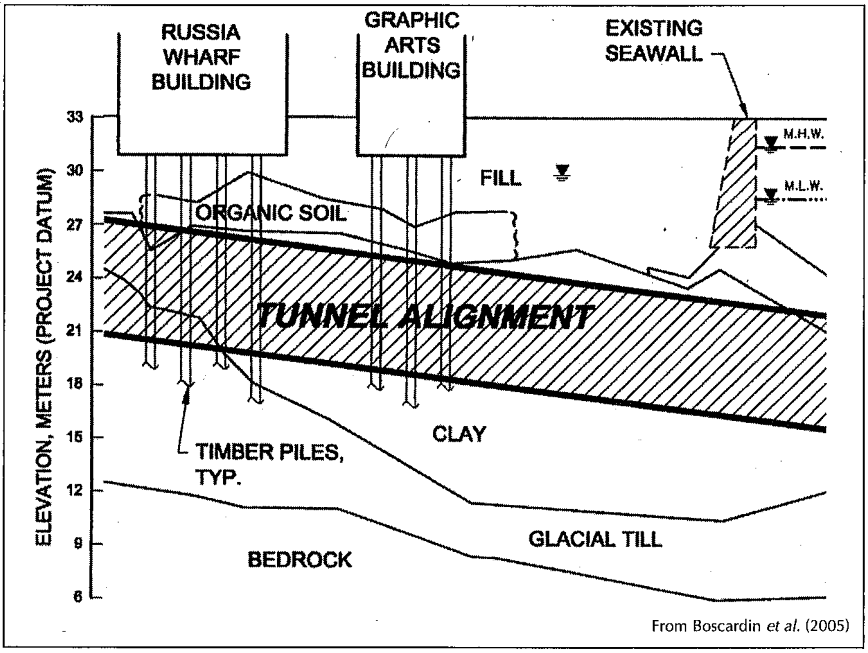


FIGURE 6-16. Section along the Silver Line Tunnel between the corner of Atlantic Avenue and Congress Street and the edge of Fort Point Channel passing beneath the Russia Wharf Building (view north).

River (see Figure 3-95). It would be an east-west tunnel lying beneath Cambridge Street. The MBTA Blue Line, which is the only subway line that does not connect to the Red Line, currently terminates at the Bowdoin Station located on Cambridge Street in the West End at the base of Beacon Hill. The preliminary plans and explorations for the proposed construction would have the connector extend a distance of approximately 990 meters (3,250 feet) in twin 6.4 meter (21 foot) diameter north and south tunnels with invert depths between 15 and 18 meters (50 and 60 feet). These tunnels would be cut-and-cover or mined and have a tunnel invert at elevation 19.2 meters (63 feet) at Charles/MGH Station and elevation 25.9 meters (85 feet), based on MBTA datum of 32.2 meters (105.62 feet) equals 0.0 MSL, at the Bowdoin Station. Surface elevations based on test boring data (MBTA datum) are about 43.6 meters (143 feet) at Bowdoin Station and 32.6 meters (107 feet) at Charles/MGH Station. Design Alternative 1 would eliminate the existing Bowdoin Square Station and Alternative 2 includes the construction of a new Bowdoin Station. The tunnel design incorporates vent shafts, station connections and egress stairways.

The tunnels are proposed to be constructed by a combination of technologies: the sequential excavation method for the two tail track tunnels at Charles/MGH Station; and, earth pressure balance tunnel boring machine for the running tunnels from near the Charles/MGH Station to the shaft near Bowdoin Station at Cambridge Street. Cut-and-cover construction would be used from this point to the nearby Blue Line/Green Line Government Center Station. The tunnels will run from the Charles River to the Beacon Hill and West End area. To avoid settlement of old brick homes and other shallow foundation buildings that bear on the till and glaciomarine deposits under the higher Bowdoin Square area of Cambridge Street, special attention would be placed on pre-construction underpinning. In addition, several buildings are supported by wood piles and dewatering close to the tops of the piles would need to be addressed to protect the piles.

Previous foundation investigations and exposures in construction excavations from the Charles River to Bowdoin Station encountered stratified sands on Strong Place on the south side of Cambridge Street at the base of Beacon Hill. North of this location on Cambridge Street at the Massachusetts General Hospital, fill, organic silt and marine clay were found. However, stratified and faulted sand and gravel were exposed in the excavation for the Holiday Inn 152 meters (500 feet) east of this location. Farther east up Cambridge Street is an area dominated by till and glaciomarine deposits. Shallow argillite was found to underlie the till at the Saltonstall Building across Cambridge Street from Bowdoin Station.

The north and south tunnel profiles (Haley & Aldrich, 2010) were constructed from extensive drilling in the area (see Figures 3-85, 3-91 & 3-95). These profiles show that the surface is underlain by 3 to 4.6 meters (10 to 15 feet) of granular fill mixed with cinders, ash, bricks and other miscellaneous materials. In the low-lying area of Charles Circle and running east up to Massachusetts General Hospital, from 3 to 7.6 meters (10 to 25 feet) of compressible organic silt, delineating the previous tidal flats of the Charles River, were found. A thin discontinuous layer of upper outwash sand up to 2.4 meters (8 feet) thick underlies the organic silt in the area of Charles Circle. This sand, which overlies the marine clay, represents the upper outwash. A layer of marine clay was encountered at a depth of 6 to 15 meters (20 to 50 feet) and has a thickness from 3 to 18 meters (10 to 60 feet). The clay thickens and thins, pinching out in the higher elevations of Bowdoin Square. The thin clay is shown to be underlain in some areas by what appears to be the glaciomarine deposit. The tunnels run mostly through marine clay, with lower sections in the glaciomarine deposit and into a short section of till on the south side of Cambridge Street near the Massachusetts General Hospital. Discontinuous sand, which lies at the base of the clay, reaches a thickness of 9 meters (30 feet) in a channel in the till north of Cambridge and Grove streets. This sand is called *marine sand*, but it apparently represents the lower outwash. The deposition may have continued as marine waters rose. The till overlying the argillite and sandstone bedrock reaches a thickness on the order of 18 meters (60 feet) southward on the flanks of the Beacon Hill drumlin and thins down to less than 1.5 meters (5 feet thick) to the north (see Figure 3-85). The till merges with the glaciomarine deposit that is up to 21 meters (70 feet) thick. This finding again demonstrates that the glaciomarine deposit is difficult to distinguish and classify. Elevation of the top of the bedrock varies from 1.5 meters (5 feet) MSL near the Charles River to –14 meters (–45 feet) MSL as Bowdoin Square is approached. The rock is severely to moderately weathered Cambridge Argillite.

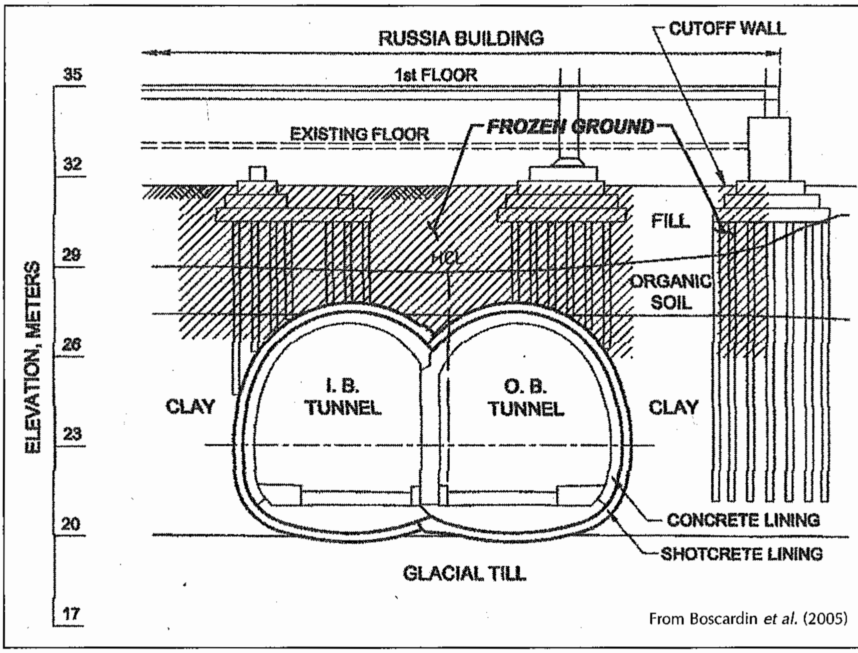


FIGURE 6-17. Section through the Silver Line tunnel beneath the Russia Wharf Building (view west).

Trans-Harbor Highway Tunnels

Three major subaqueous highway tunnels, as well as the East Boston Tunnel on the Blue Line subway, connect downtown Boston with the communities northeast of the harbor, exiting in East Boston (formerly Noddle's Island). The highway tunnels were constructed in three phases since the need to accommodate

FIGURE 6-18. The shield at the Boston vent shaft of the Sumner Tunnel on June 20, 1932. (Courtesy of the University Archives & Special Collections Department, Joseph P. Healey Library, University of Massachusetts–Boston.)

increased traffic grew, and eventually they became incorporated into the Central Artery/Tunnel Project.

Sumner Tunnel. The Sumner Tunnel was constructed under Boston Harbor between 1931 and 1934 at a cost of 19 million dollars in order to access East Boston and Logan Airport other than by ferry or a circuitous land route. The deep bore tunnel has a base elevation inside the tunnel of –37 meters (–120 feet) MSL and is 9.1 meters (30 feet) in diameter with a length of 1,723 meters (5,651 feet). It was constructed by using a conventional pressurized shield through the marine clay and mud under Boston Harbor, with the muck being removed by hand (see Figure 6-18) and shipped to Logan Airport for fill (Loveland, 1932). The tunnel crosses over a 100 meter (328 foot) deep bedrock valley that underlies Boston Harbor. Circular steel rings were pushed 80 centimeters (32 inches) at a time by the shield, which circled the edge of the rings. Electricity and gasoline instead of steam were used in the pressurized air in order to advance the tunnel — a major advancement for its time.

Two concrete box sections 125 and 132.7 meters (410 and 435 feet) long were constructed at the two ends of the tunnel using open cut-and-cover methods. On the East Boston side, materials encountered consisted of the harbor fill and the till associated with the Camp Hill drumlin; on the North End side, harbor fill, organic sediment and marine clay were encountered. The tunnel lay chiefly in the marine clay. Repairs of tunnel deterioration were made in the 1960s. Other work in the 1990s found that the original contractor had skimped on steel supports, but the tunnel by then had lasted over fifty years. Recent major repairs to the ceiling tiles and their supports occurred in 2007.

Callahan Tunnel. The State Highway Master Plan of 1948 declared the Sumner Tunnel "overtaxed." Ten years later in 1958, the Massachusetts Legislature authorized the parallel Callahan Tunnel be built to alleviate traffic to and from Logan Airport in East Boston. The tunnel is 1,545 meters (5,068 feet) long and 9.1 meters (30 feet) in diameter, and was constructed at the end of the 1950s and opened in 1961. Its construction covered a period of only nineteen months. It was of similar construction to the Sumner Tunnel and was deep bored at the same depth through the harbor sediment using the shield method (see Figure 6-19). A full-sized shield started from the Boston side and a pilot bore started from the north to eventually meet beneath the channel. The tunnel was lined with bolted steel rings that were covered by a concrete liner. The ends of the tunnel were constructed of 18.3 to 24.4 meter (60 to 80 foot) concrete box sections using open cut-and-cover methods. Similar deposits as at the Sumner Tunnel were encountered. In the 1990s, repairs were made primarily to the ceiling panels and tiles that had been deteriorating. Repairs made in 2006 included the replacement of 418 loose ceiling bolts and the installation of diagonal steel beams in the ceiling to meet current seismic code requirements.

FIGURE 6-19. Callahan Tunnel showing front end of the tunnel shield on March 23, 1961. (Courtesy of the *Boston Globe.*)

Ted Williams Tunnel. Soon after the Callahan Tunnel was opened, the state recognized that a third harbor crossing would be necessary. It was not until 1968 that plans were drawn up for the new third tunnel to connect the Massachusetts Turnpike to Logan Airport, which was then estimated to cost 144 million dollars. In the early 1980s, the design of a tunnel to East Boston at Route 1A near the terminus of the other two tunnels was advanced by then-Governor King's administration. However, the location and function of the third tunnel eventually constructed as part of the Central Artery/Tunnel Project expanded greatly in the 1980s under Governor Dukakis's administration. The third tunnel was constructed from September 1991 to March 1994 from the far easterly end of the South Boston flats to the area of Bird Island flats at Logan Airport, and forms part of the Interstate 90 extension. The tunnel initially opened to commercial traffic on December 15, 1995, and was named the Ted Williams Tunnel. The tunnel was opened fully to all traffic in 2003.

The Ted Williams Tunnel has a total length of 2,575 meters (8,448 feet), including approaches. It is a twin-tube tunnel, with two lanes in each tube, which are each 12.2 meters (40 feet) in diameter. Length of the twelve immersed tubes totaled 1,207 meters (3,960 feet) under water. Requirements for the tunnel were that it had to pass under the elevation –10 meters (–30 feet) MSL deep boat anchorage in East Boston and the elevation –12 meters (–39 feet) MSL deep anchorage for the container shipping channel in South Boston. The existing two navigation channels were to be deepened by up to elevation –12 meters (–39 feet) MSL. Two bores were originally considered in preliminary design, but the chosen tunnel design consisted of twelve sections of double full circle, "binocular" steel sections or immersed tube tunnels sunk into a 1.2 kilometer long by 15.2 meters deep by 30.4 meters

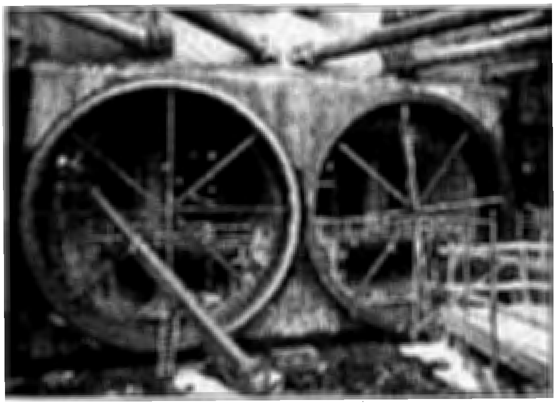


FIGURE 6-20. Connection of the south end of the Ted Williams Tunnel to the covered roadway leading to Logan Airport. (Courtesy of the Massachusetts DOT.)

wide (0.75 miles by 50 feet by 100 feet) trench excavated into bedrock, glacial till, clay and harbor sediments (see Figure 6-20). The trench was excavated by the "super scoop" clamshell excavator on a barge. About 1,000 meters (3,280 feet) of hard rock were encountered that required drilling and blasting to prepare the rock for excavation. Special environmental precautions were necessary to drive fish and lobsters away prior to each blast. Each of the 12 by 24 by 100 meter (39 by 79 by 328 foot) immersed tube elements were coupled together and made watertight by special gaskets. The tunnel was designed to meet a seismic design of a horizontal ground acceleration of 0.15 g operating design event (ODE), 0.3 g maximum design event (MDE) and an accidental load from a sinking ship or dragging anchor.

Eleven test borings in the water had shown that the top of the bedrock was just 1.5 to 2 meters (5 to 7 feet) below the harbor bottom for about two-thirds of the immersed tube tunnel. The top of the argillite is at about elevation –14 meters (–45 feet) MSL at the South Boston end. A soft to stiff clay comprised the rest of the harbor bottom. Sixty additional borings and a bathymetric survey confirmed the original findings. Chemical analysis of the harbor sediments found that the top 1.5 to 2.1 meters (5 to 7 feet) were contaminated and did not meet the criteria for disposal twenty miles at sea in the designated and regulated area. These contaminated sediments were dredged and disposed of at a newly designed and regulated facility at Logan Airport. Some of the approach excavations in South Boston encountered hazardous waste, which was excavated and dumped at the Spectacle Island disposal facility after being treated. The East Boston cofferdam constructed for the Logan Airport approach was the largest in North America, being 216.5 meters long by 25.9 meters deep (710 by 85 feet). In South Boston, the junction excavation was free-standing circular cofferdam using slurry wall and continuous ring beams (Kirmani & Highfill, 1996).

Utility Tunnels

Shallow utility tunnels have been constructed around Boston for more than a century, especially for river and short bay crossings. These tunnels are mostly in the marine clay and organic sediment, and generally use a shield method under compressed air. For example, in 1898 and 1899, the Massachusetts Pipeline Gas Company excavated three tunnels: under the Mystic River at Malden Bridge in Charlestown near Everett, under the Charles River at the then new bridge on Washington Street between Charlestown and Boston, and under the Charles River at the River Street Bridge between Cambridge and Brighton (Cummings, 1901). These 122 to 137 centimeter (48 to 54 inch) diameter steel-lined pipes were advanced from riverside shafts under a minimum safe cover of only 2.4 meters (8 feet) and flooding occurred on occasion. A similar 2.7 meter (9 foot) diameter tunnel was driven under the channel between Chelsea and Charlestown by the Metropolitan Water Board from 20 meter (65 foot) deep shafts 43 meters (140 feet) apart, also at this time in the early 1900s.

Mystic Cable Tunnel. In 1941, the Boston Edison Company constructed a cable tunnel through soft ground from the Mystic Generating Station at Alford Street in Everett under the Mystic River to the Charlestown side at depth of about 20 meters (65 feet) (Bray, 1945). On each side of the river a 4.6 meter (15 foot) square shaft with 5.5 by 9 meter (18 by 30 foot) underground splicing chambers mounted on top were sunk and a 335 meter (1,100 foot) long circular tunnel driven between them. The tunnel is lined with 35 centimeter (15 inch) thick cast-in-place concrete with an inside diameter of 2.4 meters (8 feet). The invert of the tunnel on the Everett side is elevation –14.2 m (–46.5 feet) MSL and slopes down to elevation –15.8 meters (–51 feet) MSL on the Charlestown side. The shafts were constructed under compressed air because of the potential for heavy water inflow from saturated silty sand and the concern that this inflow could lead to loss of ground and settlement of nearby structures. The tunnel was excavated by hand methods and air spades under 172 kilonewtons per square meter (25 pounds per square inch) of compressed air.

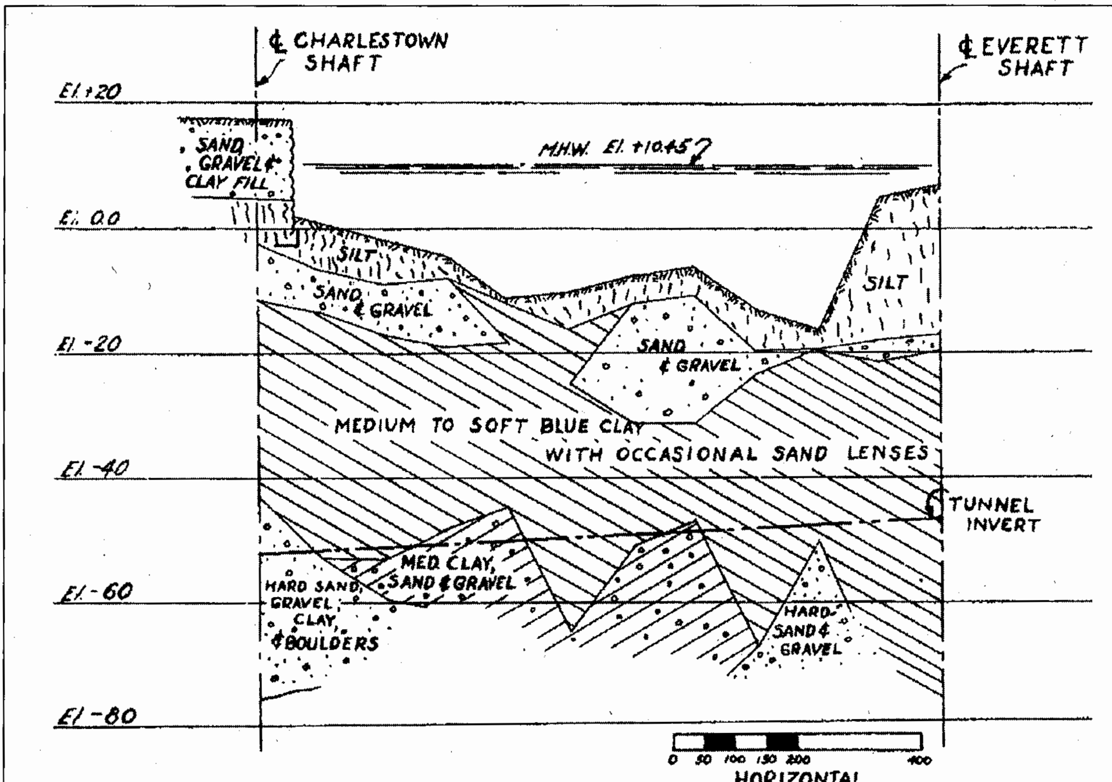
Twelve exploratory test borings were drilled, one at each shaft and every 30 meters (100 feet) near the alignment (see Figure 6-21). The 30 meter (100 foot) long borings reached an elevation of approximately –24 meters (–80 feet) MSL, and were terminated in till or an overlying clay with some sand and gravel on the Charlestown side. The borings there encountered about a 10 meter (30 foot) thick till. Above this till is the marine clay with scattered sand layers that have a soft to medium stiff consistency. The bottom elevation of the clay ranges from between elevation –12 meters (–40 feet) MSL to over elevation –24 meters (–80 feet) MSL and the top is between elevation –3 and –6 meters (–10 and –20 feet) MSL, yielding thicknesses between 10 and greater than 18 meters (35 to more than 60 feet). The tunnel alternates between the till and marine clay on the south to all clay on the Everett side. A 6 meter (20 foot) thick (but discontinuous layer of sand and gravel) corresponding to the Lexington Outwash fills channels cut into the top of the clay. Capping this deposit is an irregular layer up to 6 meters (20 feet) thick of organic silt and river alluvium. Test borings for a wind turbine generator testing facility located about one-half mile downstream on the Little Mystic Channel in Charlestown (Miller, 2009) found the bedrock at a depth of 43 meters (140 feet), at an elevation of –39 meters (–127 feet) MSL. Upson and Spencer (1964) thought that the Mystic River in this area represented the ancestral buried Malden River with the bedrock found at elevation –37 meters (–120 feet) MSL at the nearby Tobin Bridge and as deep as elevation –73 meters (–240 feet) MSL at Deer Island.

The Central Artery/Tunnel Project: The Big Dig

The original Central Artery (Tsipis, 2001), also known as the John F. Fitzgerald Expressway, ran from Andrew Square in South Boston to the Mystic River Bridge (later renamed the Tobin Bridge) access, a distance of 5.12 kilometers (3.18 mi). It consisted of a surface roadway, a tunnel and an elevated section. The entire highway actually comprised about 12.6 kilometers (7.8 miles) of roadway surface, ramp and tunnel construction, and connected at its middle to the Callahan and Sumner tunnels, which run under Boston Harbor to East Boston. The elevated six-lane section from High and Broad streets to the Tobin Bridge was constructed during the period 1951 to 1954 and opened in Boston in 1954 with much political fanfare. Because of the public outcry concerning the unsightliness of the steel structure, called the "Green Monster," the southern half-mile was constructed underground as the Dewey Square Tunnel or the South Station Tunnel and opened in 1959. This tunnel was the first major interstate highway tunnel beneath an inner city area in the United States.

The highway was designed to alleviate downtown Boston's traffic for several decades to come. However, within a decade of its opening, the Central Artery reached its designed capacity of 75,000 vehicles daily, which increased to 200,000 daily by the late 1970s. This growth, coupled with some major flaws in the pre-interstate exit/entrance ramp design and positioning, resulted in considerable traffic congestion.

The chosen solution to alleviate the congestion and to remove the aging and deteriorating elevated freeway, originally called the Central Artery/Tunnel (CA/T) Project, was to construct a new depressed eight- to ten-lane expressway in a tunnel by cut-and-cover methods under the existing elevated road while not disrupting the economic viability of the city (see Figure 6-22). The project was widely referred to as the Big Dig (Vanderwarker, 2001). The project's centerpiece is the



From Bray (1945)

FIGURE 6-21. Section along the Mystic Cable Crossing Tunnel.

Thomas P. O'Neill, Jr., Tunnel, which extends 2.4 kilometers (1.5 miles) between Kneeland Street and Causeway Street, and opened in 2003. Other major components of the CA/T Project include the new Seaport Access and Ted Williams tunnels beneath South Boston and Boston Harbor to link the extension of the Massachusetts Turnpike (I-90) to Logan International Airport and Route 1A, and connecting the downtown elements to Interstate 93 north to a two-bridge crossing of the Charles River at the expressway's northern limit (see Figure 6-23). The larger of the two Charles River bridges, the Leonard P. Zakim Bunker Hill Bridge, is a ten-lane, cable-stayed hybrid bridge, the widest ever built and the first to use an asymmetrical design. The CA/T Project started construction in 1991 and was declared complete at the end of 2007.

The initial concepts for depressing the Central Artery were formed in the late 1970s. Preliminary designs began in 1980 when a working paper was produced that evaluated the geological and geotechnical conditions of the Leverett Circle Connector. The connector was a part of the "trumpet interchange" — a series of tunnels, surface roads and bridges linking Storrow Drive, Interstate 93, the Route 1 Tobin Bridge, the Craigie Bridge over the Charles River and a new underground Central Artery. The initial Environmental Impact Report for the Third Harbor Tunnel from downtown Boston to the Bremen Street area of East Boston was developed in 1982. The Central Artery depression was added in 1983, with the new Seaport Access South Boston location for the Third Harbor Tunnel. So, the CA/T Project started in 1982 and the Environmental Impact Statement process was underway in 1983. The CA/T Project was authorized by U.S. Congress in 1988. The joint venture of Bechtel and Parsons Brinckerhoff was assigned to be project design and construction management consultant. The final design began in 1989.

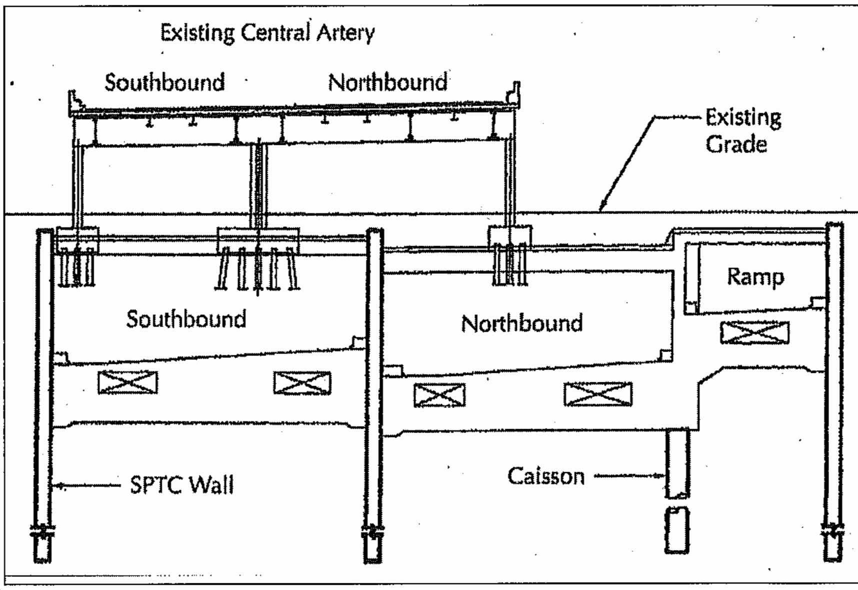


FIGURE 6-22. Relation between the pre-existing Southeast Expressway viaduct and the new Central Artery Tunnel. (Courtesy of the Massachusetts Department of Public Works.)

The first part of the CA/T Project to be designed and constructed was the new Third Harbor Tunnel. A South Boston by-pass road from the Southeast Expressway to the South Boston portal of the Ted Williams Tunnel opened in 1993. The tunnel itself opened in 1995. A bridge (then known as "the little bridge") across the Charles River connecting Interstate 93 and Leverett Circle/Storrow Drive was opened in 1999. The Zakim Bridge, which carries Interstate 93 over the Charles River and into the new Central Artery Tunnel, opened in 2003. The underground artery partially opened in 2003, and the Massachusetts Turnpike extension to the Logan Airport and Route 1A opened in 2004.

Overview of Project Requirements & Constraints. The design engineers were faced with formidable challenges of:

- building a new highway through the heart of Boston beneath the existing elevated highway (see Figure 6-22);
- keeping the existing highway operating to maintain traffic flow;
- avoiding disruption of a very old infrastructure, some dating from the 1600s, but expanded and updated in the 1800s when Boston experienced significant growth; and,
- not causing any damage to or disturbing historic buildings.

The underground route of the road and its ramps were crisscrossed with numerous century old utility lines (whose locations were sometimes unknown), ninety-year-old subway tunnels and several generations of old seawalls, piers and foundations (see Figure 6-24). In addition, the highway had to pass under a major confluence of rail lines that lead to the railhead at South Station, and cross beneath the Fort Point Channel.

A cut-and-cover tunnel was selected for the 30 meter (100 foot) wide highway. Preliminary work consisted of utility relocation, an ongoing rodent control program necessitated by the disturbance of their habitat, underpinning of the existing 1,128 meter (3,700 foot) long end-bearing, pile-supported elevated highway and an on-going archeological survey. In order to control the groundwater and tidal flow (and at the same time provide support for the tunnel), 7,927 linear meters (26,000 feet) of steel-reinforced concrete slurry wall were constructed along the downtown Central Artery route as combined excavation support wall, underpinning supports and final tunnel structure wall. Concrete immersed tunnels were used in the crossing of the Fort Point Channel because of shallow water depths and low clearance of existing bridges, and because of the existing transit tunnels that had to be crossed. These concrete segments were made on-site in a casting basin at the edge of Fort

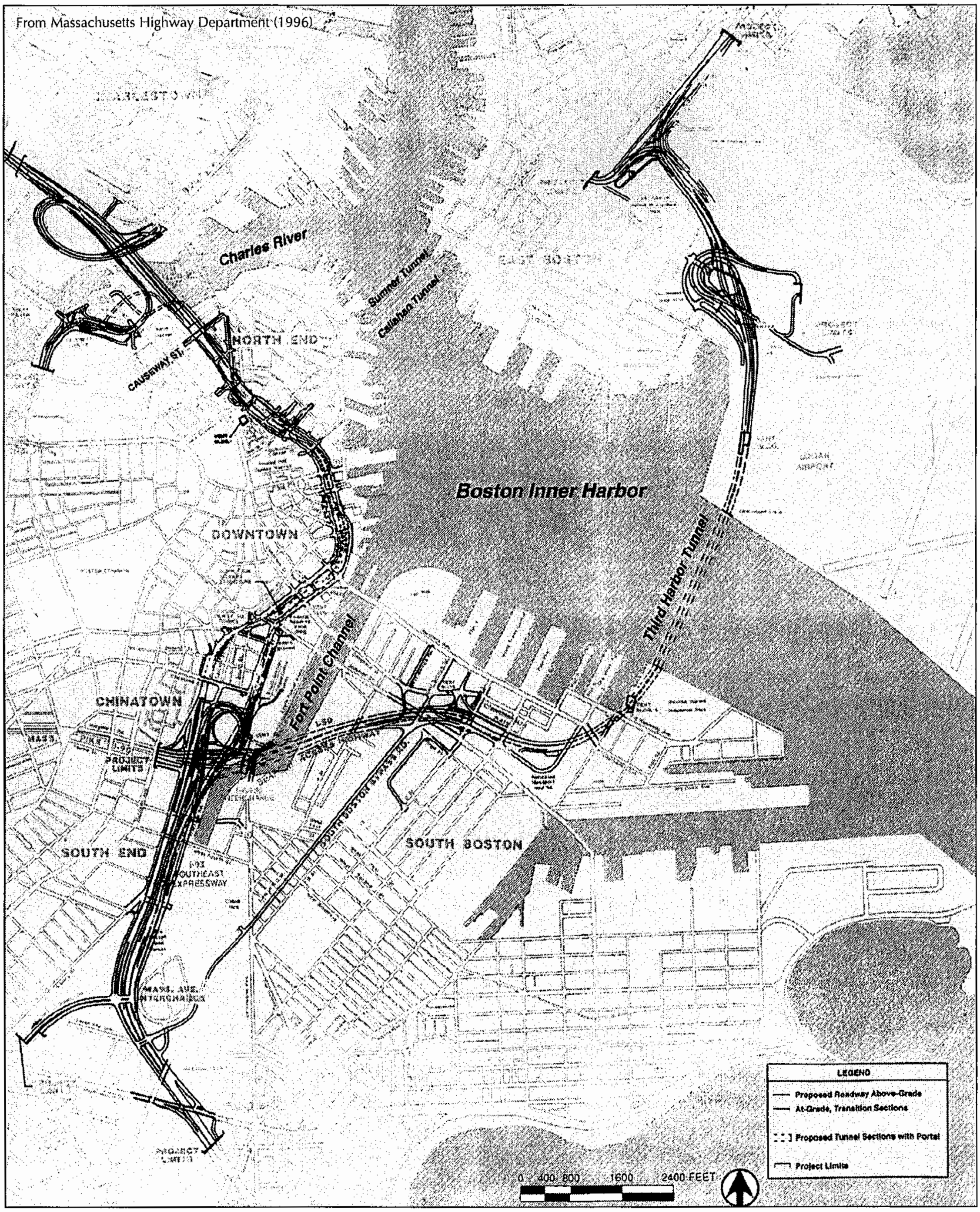


FIGURE 6-23. Plan of the Interstate 93 Central Artery/Tunnel routes.

Point Channel, which was isolated using cellular coffer dams in order to keep it dry during construction. Bridge construction used many types, including pre-cast bulb-tree girders, pre-cast and pre-stressed butted-box beams, cast-in-place box beams and steel box beams. The variable geology of the CA/T Project areas had substantial impact on the engineering design and construction of various project elements.

Sources of Information on Geology of the Project Area. Although the geology of the Boston area is extremely complex, subsurface conditions along the Central Artery/Tunnel route were generally known from several sources of available data that included:

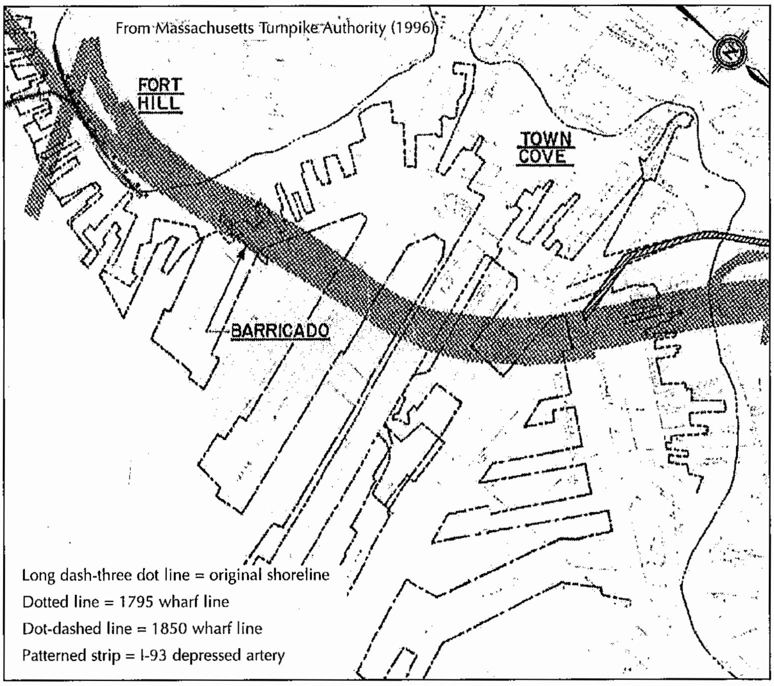


FIGURE 6-24. Map of the Town Cove area of Boston's inner harbor showing the original shoreline, historic wharves and depressed route of Interstate 93 (view southwest).

- Historical maps dating back to the seventeenth century that showed the original shoreline of the Shawmut Peninsula, and what was then the highlands associated with the Trimountain. These maps were important because the artery route followed the old shoreline along Atlantic Avenue and Commercial Street from South Station to the Charles River. The original Fort Point Channel ran through the South Station area and had been filled with a succession of wharfs from the late 1700s through 1900 (see Figure 6-24).
- Compilations of test boring records dating back to the early 1900s published in two collections by the Boston Society of Civil Engineers in the late 1960s.
- The record of previous subsurface investigations conducted over the previous thirty years by Boston's geotechnical engineering firms who were selected to work on the new Central Artery.
- The geological data on file with the United States Geological Survey (USGS) as part of its Urban Geology Program (which Clifford A. Kaye had directed).
- Various publications by several non-USGS sources.
- The publication of *The Geology of the City of Boston* by Woodhouse and Barosh (1991), which included a compilation of the existing structures and their foundation types along the artery route.

From an historical point of view, the route of the depressed CA/T from north (Zakim Bridge) to south crosses the former colonial Mill Cove and then enters the original higher Shawmut Peninsula and the adjacent North End. From there, it proceeds across the Town Cove, crosses the southeast portion of the Shawmut Peninsula and then into the South Boston Bay (see Figures 6-24 & 6-25). The Massachusetts Turnpike Connector passes through the east side of the Boston Neck, the South Cove, Fort Point Channel and through South Boston Bay before traversing Boston Harbor, the Bird Island Flats area and up to Noddle's Island. The types of geologic deposits underlying the artery route have been described in general; the description here looks at specific conditions along the exact alignment.

A section along the route of the Central Artery displays a sequence of typical deposits below the low-lying areas that surrounded the original Shawmut Peninsula. Surface fill materials overlie and compress an organic sediment layer that represents estuarine deposits.

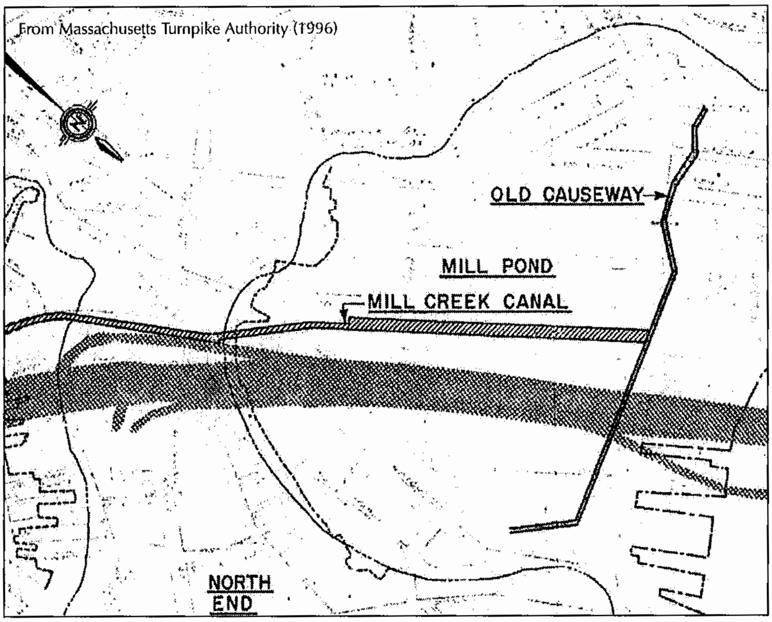


FIGURE 6-25. Map of the Mill Pond area near Boston's North End, showing the original shoreline and the depressed route of Interstate 93 leading to the Zakim Bridge at the right side of the old Causeway.

The till has been found to be locally absent or thin (such as under the Thomas P. O'Neill Building at North Station), or to reach considerable thickness in the Fort Hill-South Station area and near Charlestown (see Figures 3-86, & 3-110). In addition to these vertical changes in material, the pinching out of units and their surface relief results in great lateral variation over short distances (see Figures 3-82 & 3-94). This variation, in turn, results in widely different foundation conditions, amounts of water inflow and characteristics of material to be excavated.

A discontinuous outwash sand layer underlies the organic sediment and overlies marine clays known to reach considerable thickness. The clay layer is for the most part a competent bearing stratum but where it is eroded and redeposited, or reworked (such as in the Fort Point Channel and Charles River areas), the reworked clay is softer, less over-consolidated and has much lower strength. Some of the clay encountered in test borings contains coarser material such as sand, gravel and cobbles. Although this mixed clay has a till-like appearance, it is part of a glaciomarine deposit. Foundation engineers learned lessons about this material on earlier projects when piles driven into what was classified till or till-like often did not take up as planned and instead became friction piles. This problem also occurred where the actual till contains a high percentage of clay and behaves plastically. This behavior, for example, was experienced during the construction of the Little Mystic housing project in Charlestown, in the Fenway area of Boston and in Haymarket Square. A second discontinuous outwash deposit below the clay occurs on top of the till.

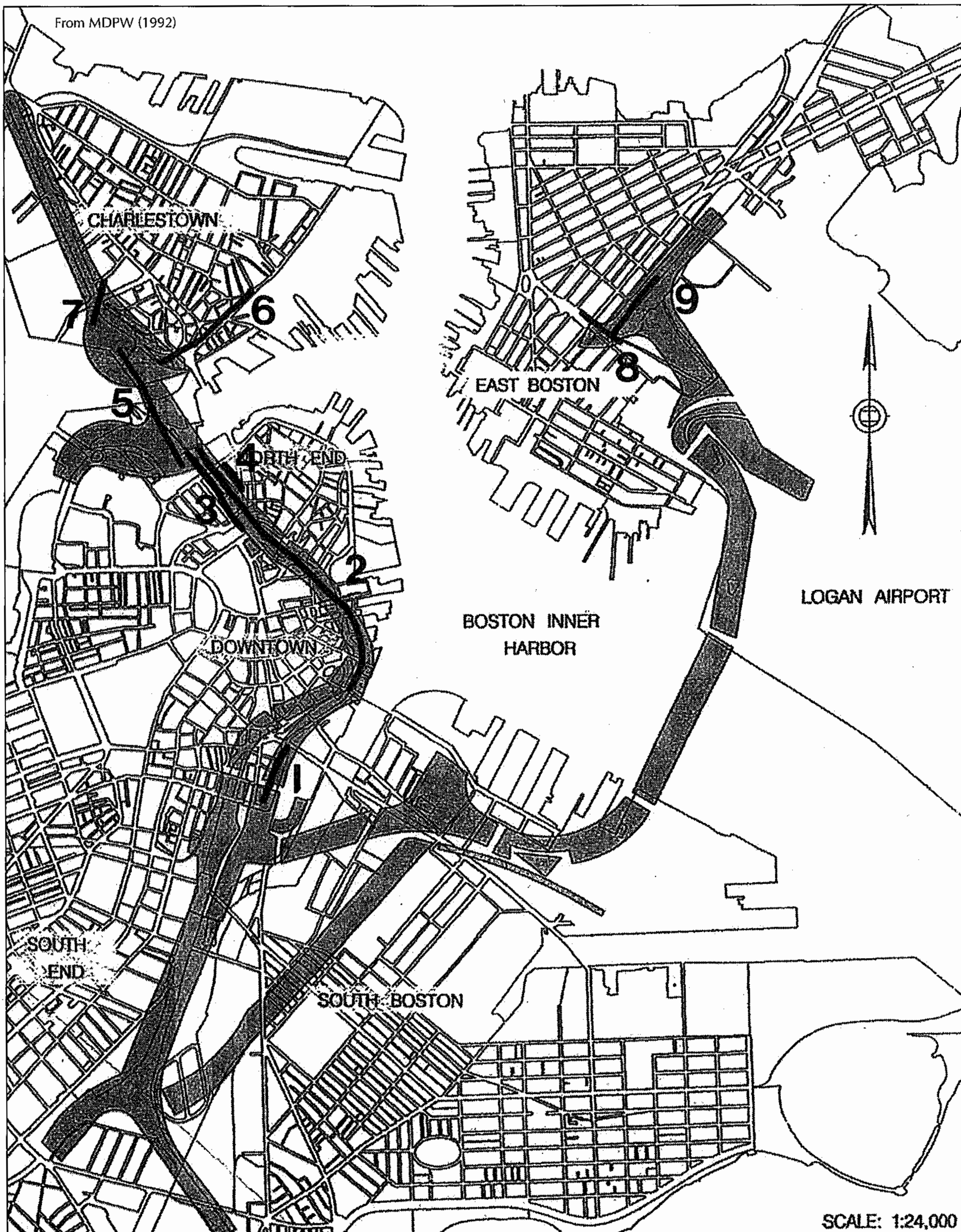
The lithology of the bedrock of Boston and the bedrock contours in the project area along Atlantic and Commercial avenues are shown on Kaye's maps of 1980 and 1982, respectively (see Figures 3-12, 3-51 & 3-54). The bedrock argillite surface is at an elevation of roughly –30 meters (–100 feet) MSL, in agreement with that found in explorations for the International Place (Fort Hill) office building near South Station. However, the top of bedrock varies considerably along the lengths of the entire CA/T Project. Many more details of this argillite surface are now known along the project area, along with the character and variations of the surficial geology.

Central Artery. The new tunnel section of the Central Artery wraps around the northeast side of Boston between South Station and North Station, which serve Amtrak and commuter rail lines. This section is officially the Thomas P. O'Neill, Jr. Tunnel, which extends 2.4 kilometers (1.5 miles) from Kneeland Street northward to Causeway Street. From there, it rises to cross the mouth of the Charles River and expands into a maze of viaducts and ramps over the western edge of Charlestown. Hundreds of test borings were drilled between 1989 and 1997 along this route to add to the data provided by previous explorations for the design of the new highway. Lines of boreholes were designated the West, Center and East Slurry Wall Test Borings and the West and East Tunnel Wall Test Borings. The test borings were spaced 30 to 46 meters (100 to 150 feet) apart. The findings allowed a series of well-controlled geologic profiles (see Figures 6-26 through 6-39) to be drawn both parallel and transverse to the roadway.

The surface of the argillite shows two low bedrock mounds in the south and only local irregularities to the north on the nearly continuous section from near South Station to the Charles River (see Figures 6-26 to 6-35). The irregularity of the bedrock surface is due to stream and some glacial erosion. The degree of erosion is influenced by kaolinized zones, fault zones and the degree of weathering. The surface climbs along a distance of 1 kilometer (0.6 mile) from about elevation –32 meters (–105 feet) MSL at the south side of Kneeland Street, opposite the southern end of the platforms of South Station, to over elevation –20 meters (–65 feet) MSL near the terminal building at Summer Street and then descends back down to –30.5 meters (–100 feet) MSL a short distance of 0.5 kilometers (0.3 miles) to the north at Congress Street. The surface rises again to –24.4 to –18.3 meters (–80 to –60 feet) MSL between Congress and Oliver streets, a distance of 0.6 kilometers (0.37 miles). The surface is at about elevation –36.6 meters (–120 feet) MSL on the north side of Oliver Street, from which it gradually rises to approximately –12 meters (–40 feet) MSL at North Station, with moderate local variable relief of 3 to 6 meters (10 to 20 feet) over a distance of 3.6 kilometers (2.25 miles).

The argillite was known to be locally kaolinized. For CA/T design and construction purposes, argillite samples that could be crumpled by hand and sampled with a split spoon sampler were classified as severely to completely weathered and given the designation B_1 on the soil profiles. Its geotechnical properties were generally equivalent to hard clay. The geotechnical engineers recommended that the end-bearing design contact pressures for the slurry walls be reduced in the areas where thick weathered rock was found. The B_1 rock was found in many of the borings. South of Essex Street, the B_1 rock was generally confined to the top 1.5 meters (5 feet) of the rock. The B_1 rock is mostly encountered north of Essex Street and is thickest near Congress and Summer streets, and one of the borings just south of Summer Street penetrated more than 30.2 meters (99 feet) of kaolinized argillite. This area coincides with a fault zone shown on Kaye's 1982 map (see Figure 3-51). The rock is so soft that split spoons for standard penetration tests could be readily driven to depths of 14.6 meters (48 feet) below the surface of the rock. From Congress Street to North Street, the B_1 rock is on the order of 6.1 meters (20 feet) thick, except near Congress Street, where it is up to 27.4 meters (90 feet) thick. It is generally less than 3 meters (10 feet) thick between North and Causeway streets. The kaolinized zone was usually confined to the top of the rock, but was also found deeper, where it is associated with major jointing and faulting.

The surfaces of the overlying Pleistocene units have much greater relief, which causes them to vary greatly in thickness and commonly pinch out laterally. The thickness of the till is less than 3 meters (10 feet) at Kneeland Street, over 10.7 meters (35 feet) at the edge of South Station and Summer Street, and reaches 35 meters (115 feet) a little north of Oliver Street (see Figure 6-27), where it constitutes the thick till of the Fort Hill drumlin. Farther north near Milk Street, the till thins to about 3 meters (10 feet). The south and north slopes of the till appear close to that of the original drumlin, which is not "cored" by bedrock. Along the rest of the section toward North Station, the till generally ranges between 1.5 to 7.5 meters (5 to 25 feet) in thickness and is absent locally. Two large clay lenses occur within the southern part of the Fort Hill till (see Figure 3-82) and a thicker 10.8 meter (35 foot) clay and sand lens lies within the till over a slight bedrock low at Valenti Way farther north in the North Station area (see Figure 6-32). These lenses apparently separate the two tills seen in the harbor and are related to the thrusted deposits in Beacon Hill to the west. Similar



1= Figure 6-27
2 = Figures 6-28 to 6-35
3 = Figure 3-110
4 = Figures 3-82 & 6-36
5 = Figure 6-37
6 = Figure 6-38
7 = Figure 6-39
8 = Figure 3-94
9 = Figures 3-92 & 3-93

FIGURE 6-26. Plan of the Central Artery/Tunnel Project showing sites of sections.

lenses on the other side of Boston at the Feldberg Building of the Beth Israel Hospital on Longwood Avenue were interpreted as local ponding. Of particular interest is a lens of sand and gravel found between the till and bedrock near Congress Street that could represent a glaciation older than that of the lower of the two tills. (Such an occurrence of sand was also found under Tech Square in Kendall Square, Cambridge.)

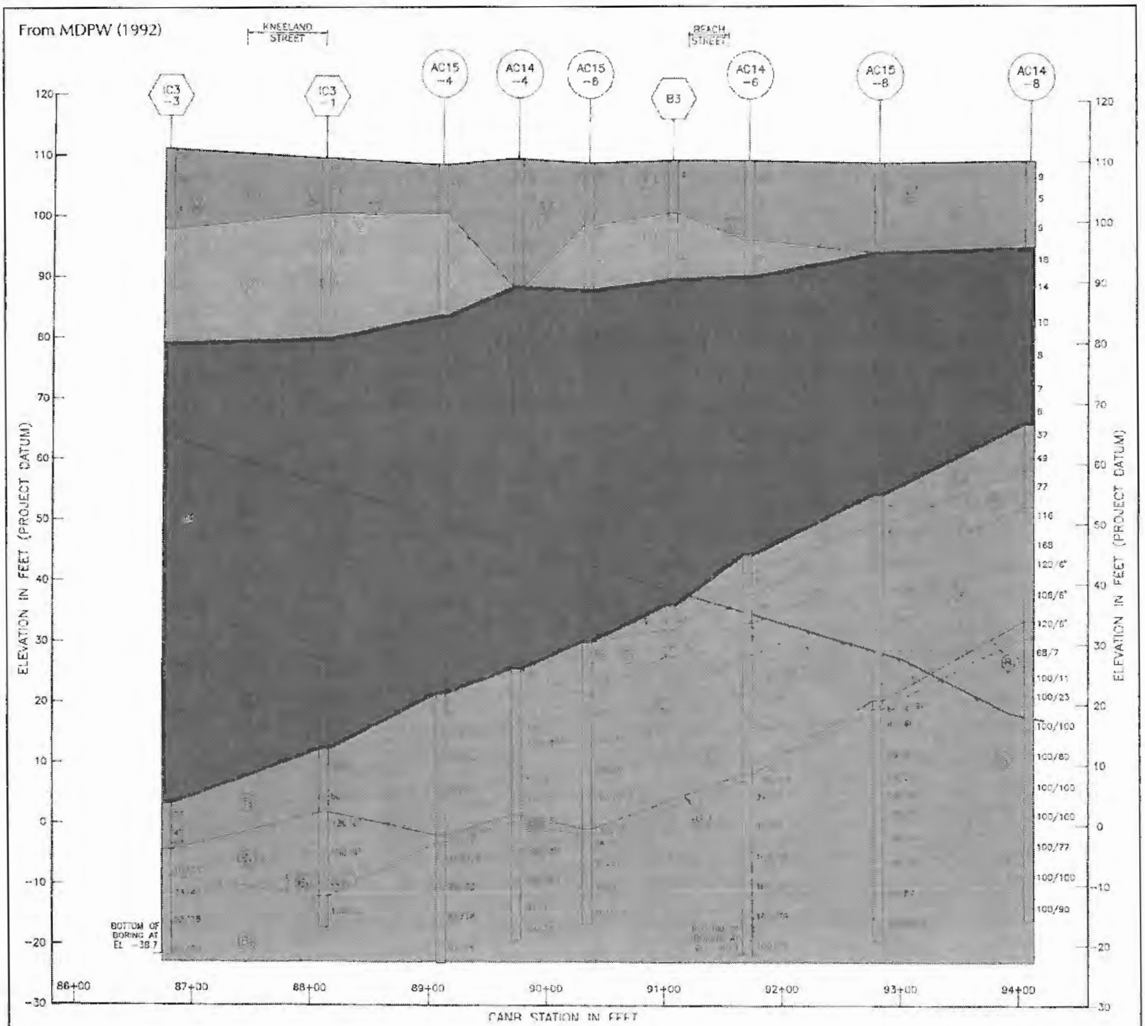
Marine clay flanks the sides of the Fort Hill drumlin and rests directly on the till. At Kneeland Street, the clay is 23 meters (75 feet) thick, and thins to about 4.6 meters (15 feet) at Beach Street or Essex Street, at the south edge of the South Station terminal building, before pinching out a short distance to the north at Summer Street (see Figure 6-27). The Blue Cross-Blue Shield Building at 100 Summer Street did not encounter any clay in the excavation. A shallow and very dense clayey till was encountered close to the surface. The clay wedge on the north flank of the drumlin begins near India Street and thickens northward to 16.8 meters (55 feet) where it underlies the old Town Cove area between North Street and Broad Street (see Figure 6-30). North of State Street, a mound of glaciomarine material rises beneath the clay and expands opposite Quincy Market to a thickness of about 13.7 meters (45 feet) and the clay is reduced to 3 to 4.6 meters (10 to 15 feet) locally (see Figure 6-31). The marine clay again thickens to about 24.4 meters (80 feet) as the glaciomarine material pinches out at the south edge of North Street for a short distance. The glaciomarine deposit again appears and thickens northward at the expense of the clay to about 22.8 meters (75 feet) near Hanover Street as the clay pinches out (see Figure 6-32). Just south of Hanover Street, a lens of sand and gravel nearly 7.6 meters (25 feet) thick occurs in a channel cut into the top of the glaciomarine deposit. The clay again appears at the projection of North Marginal Street and thickens northward to about 9.1 meters (30 feet) where the glaciomarine once more pinches out beneath it near the south edge of North Washington Street (see Figure 6-33).

Organic sediment with a thickness of 6.1 meters (20 feet) is present near Kneeland Street and thins to the north in the area of the South Station terminal building. Organic sediment also overlies the clay in the Town Cove area (see Figure 6-30) between India Street and the south edge of North Street, and reaches a thickness of about 6.1 meters (20 feet). Organic sediment comes in above the clay at Endicott Street in the North End and thickens northward to nearly 15.2 meters (50 feet) at Causeway Street as the clay wedges out between it and the thin till below (see Figures 3-82 & 3-110). The organic sediment thins northward in passing North Station, where the overlying fill increases to over 12.2 meters (40 feet) in thickness.

Fill is found over the entire Central Artery. It is generally in the range of 3 to 6.1 meters (10 to 20 feet) in thickness with 3 to 7.6 meters (10 to 25 feet) in the Town Cove section and 6.1 to 9.1 meters (20 to 30 feet) between Congress and Oliver streets (see Figures 6-26 through 6-36).

The surficial deposits were well expressed by the original colonial topography. The Fort Hill drumlin was formed by thick till, with the spine of the drumlin connected to the North End by a mound of glaciomarine deposit. The general lowlands north of Fort Hill, at the Town Cove and in the Mill Pond areas, were connected by marine clay, with specific low areas corresponding to the presence of organic sediment. The low areas were first used for the colonial town docks at the present-day Dock Square and Long Wharf, and Mill Pond at the Bullfinch Triangle. These areas were subsequently sites of thick filling, with urban expansion following shortly thereafter. The Town Dock area in particular received heterogeneous building material such as granite blocks, wood used for cribbage and debris that caused many construction problems over the centuries (see Figure 6-24).

The northbound depressed artery descends from the southern artery entry, which is about 380 meters (1,250 feet) south of Kneeland Street. Proceeding north and downward, the tunnel between Kneeland Street and South Station descends through clay, till, and 4.9 meters (16 feet) into the argillite, which is severely weathered. The roadway joins the



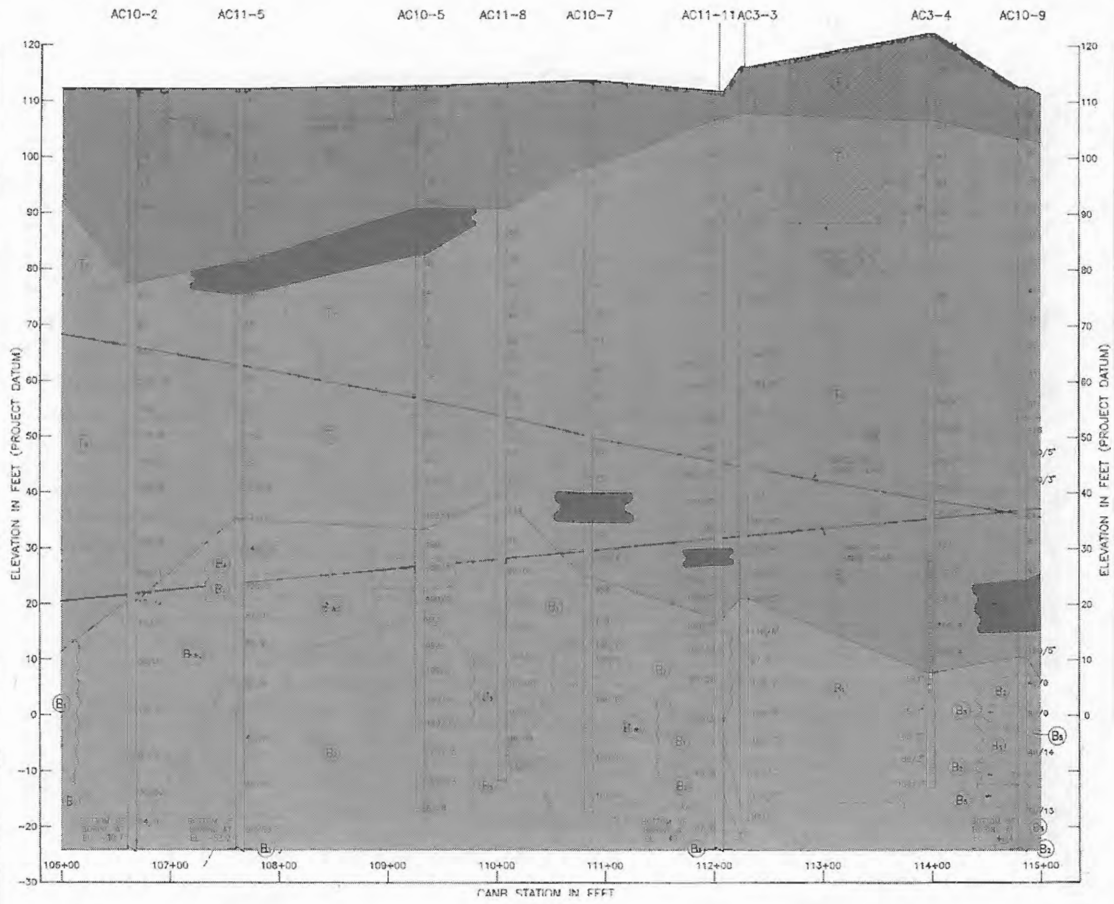
B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite
T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 471)

FIGURE 6-27. Section along the Central Artery west of South Station (middle slurry wall between stations 87+00 and 94+00) showing the marine clay overlapping the south side of the Fort Hill drumlin (view west).

southbound tunnel at about Northern Avenue where it re-enters the till south of Congress Street and continues through it past Oliver Street and International Place, following along Atlantic Avenue. Near the old Fort Hill and Northern Avenue, the highway continues through the thick layer of till, which is part of the excavated Fort Hill drumlin. Very hard clay lenses up to 9.1 meters (30 feet) thick are found in the till. A section in the area of Oliver Street, Rowe's Wharf and International Place to Harbor Towers near India Street shows the roadway ascending through the Fort Hill till into a marine clay layer in the area of India Street to State Street. From there, 'the artery tunnel passes over the Blue Line Tunnel and begins a descent through the clay northward to the Quincy Market area where it passes

From MDPW (1992)



B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

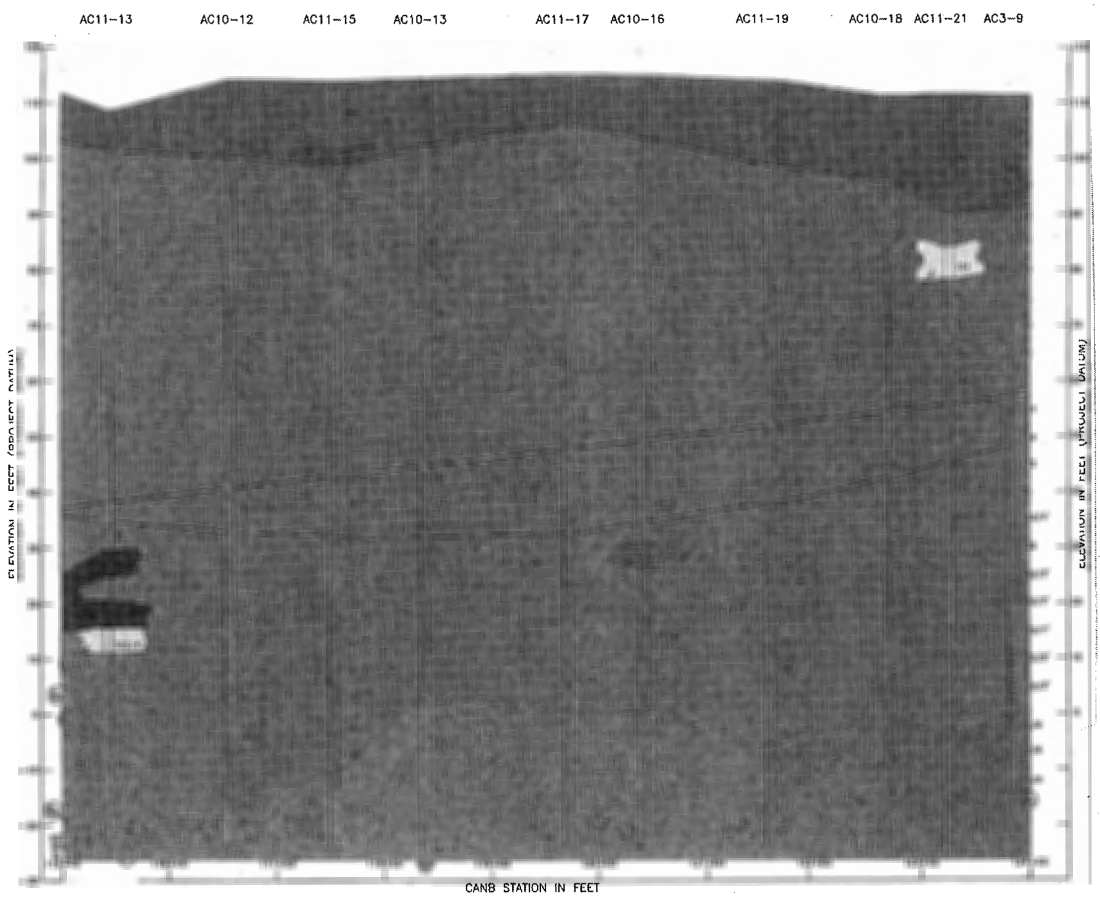
(see color version on page 472)

FIGURE 6-28. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 106+00 and 115+00 (view west to southwest).

through a mound of glaciomarine material and back into marine clay. It re-enters the glaciomarine deposit near North Street, levels out for a short distance and begins a long, gradual ascent toward the Charles River as it enters thin till and argillite in passing the entrance to the Callahan Tunnel.

The tunnel invert continues to skim the top of the weathered bedrock and basal till through the North End and much of the old Mill Dam area as it ascends toward the Charles River Crossing. It re-enters the clay near Valenti Way and rises into the organic sediment at Causeway Street. The till near the Charles River Crossing contains a 4.6 meter (15 foot) thick layer of outwash and a hard compacted clay layer about 12.2 meters (40 feet) thick between the till and the bedrock. Water carried by such sand lenses can cause serious problems during construction, but did not cause problems for CA/T Project construction.

From MDPW (1992)



B_1 = Completely to severely weathered Cambridge Argillite
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B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
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C_1 = Very stiff clay
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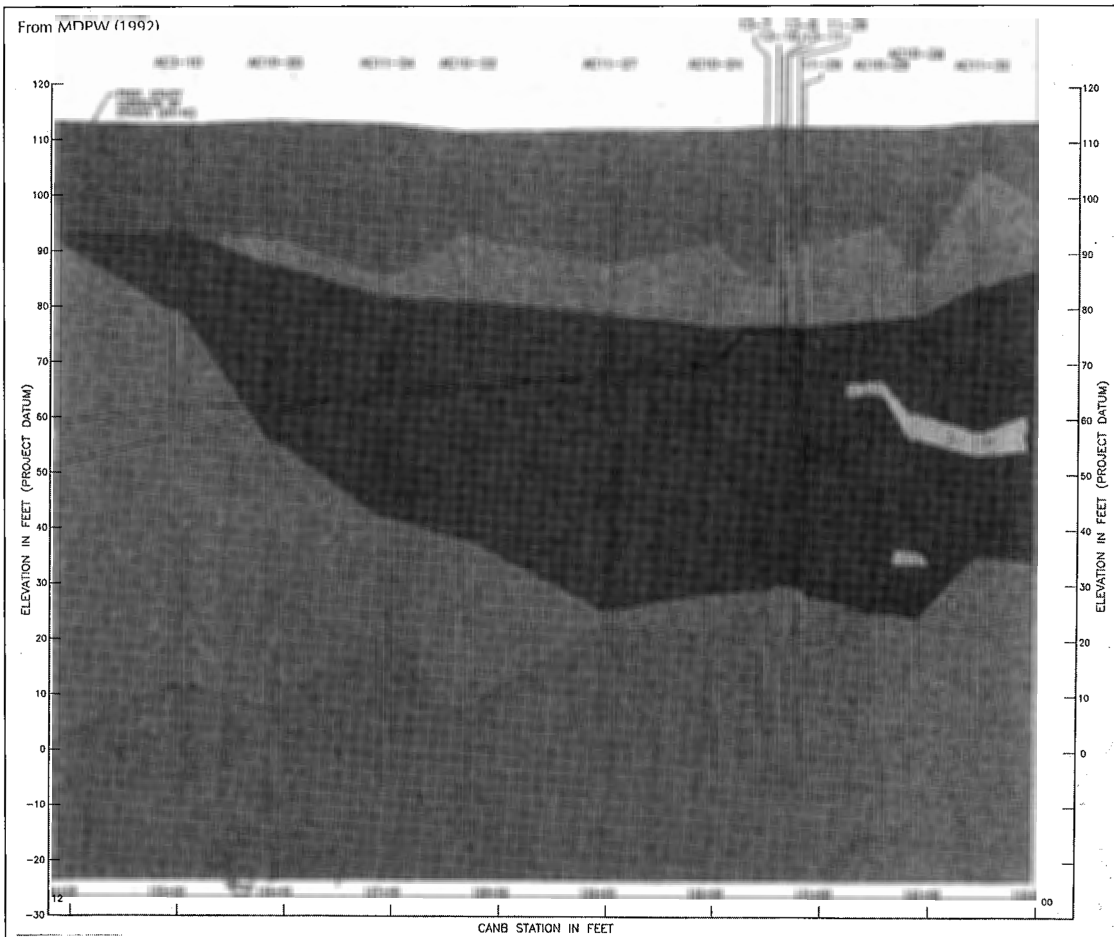
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 473)

FIGURE 6-29. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 115+00 and 124+00 (view west to southwest).

Leverett Circle-Charlestown. Very extensive drilling was carried out in stages around a broad area of the Charles River from Leverett Circle, North Station and southeastern Charlestown. An analysis of hundreds of these test borings was used to produce preliminary geologic profiles in 1980-1981 (see Figures 6-37, 6-38 & 6-39), and other more detailed profiles in the 1990s. The contours of the top of bedrock in this area were known prior to the final design of the new artery and shown in the early Central Artery working papers. The bedrock surface (see Figure 3-63) shows ridges and valleys that range from a high of elevation –3 meters (–10 feet) MSL near the former Massachusetts Registry of Motor Vehicle headquarters on Nashua Street to an elevation of –33 meters (–110 feet) MSL at the Museum of Science on the other side of the Charles River. The bedrock elevation –12 meters (–40 feet) MSL at the end of the Central Artery is on a narrow northwest-trending ridge that extends



B1 = Completely to severely weathered Cambridge Argillite
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B3 = Moderately to unweathered Cambridge Argillite
T1 = Dense cohesive till
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C1 = Very stiff clay
C2 = Stiff clay
C3 = Medium stiff clay
C4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

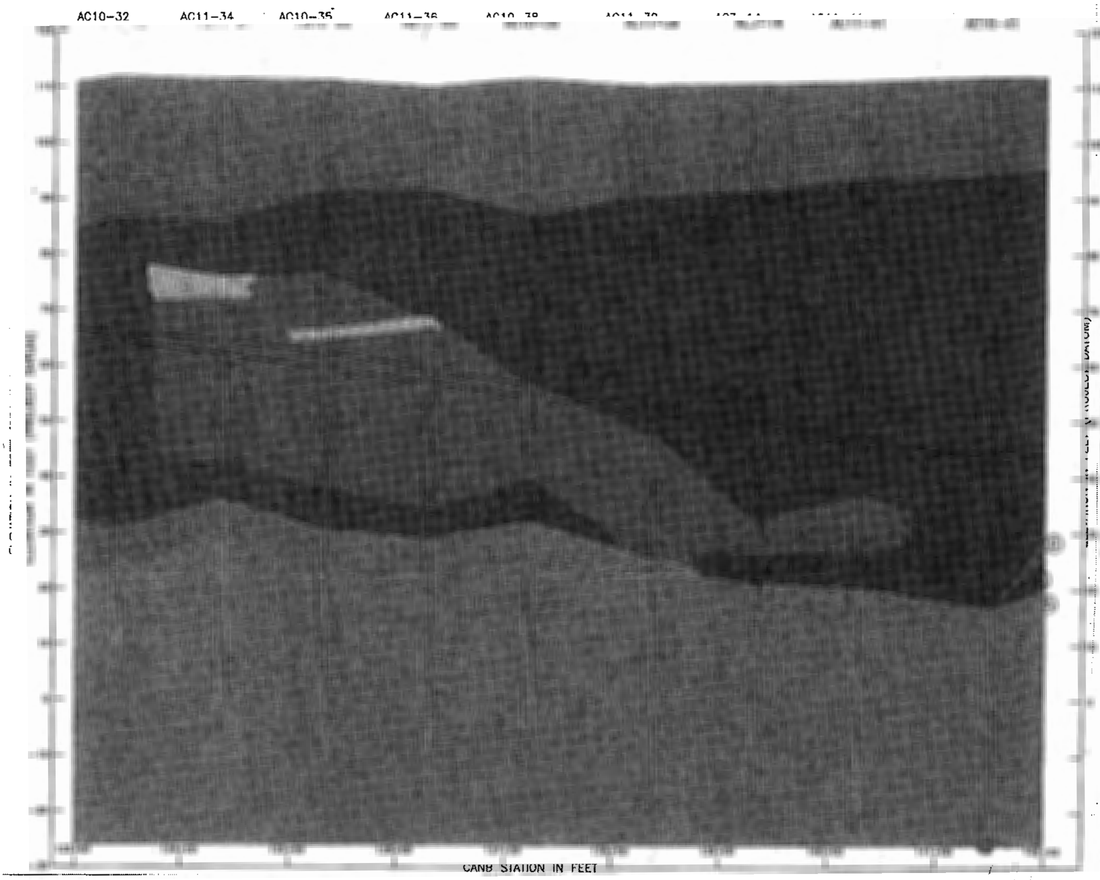
(see color version on page 474)

FIGURE 6-30. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 124+00 and 133+00 (view west to southwest).

into Charlestown from the east side of North Station. The ridge dips down slightly to the west and from there rises to elevation –3 meters (–10 feet) MSL into a broad north-trending arch northwest of the station. The south end of the arch is crossed by a northeast-trending swale under the Charles River. Farther to the northwest near Charlestown Neck, the bedrock rises to within 6.1 meters (20 feet) of the surface (Stone & Webster, 1996) and the drumlin at this location is apparently rock-cored. Bedrock consists of the argillite, which is kaolinized in places to a minimum depth of 15.8 meters (52 feet).

The overlying till is thin to absent from North Station northward into the southwest edge of Charlestown and generally ranges from 3 to 9.1 meters (10 to 30 feet) in thickness farther north, although it is absent locally. Within the till, pervious zones of sands up to 6.1 meters (20 feet) thick are found locally and possibly separate the two tills. The till increas-

From MDPW (1992)



B_1 = Completely to severely weathered Cambridge Argillite
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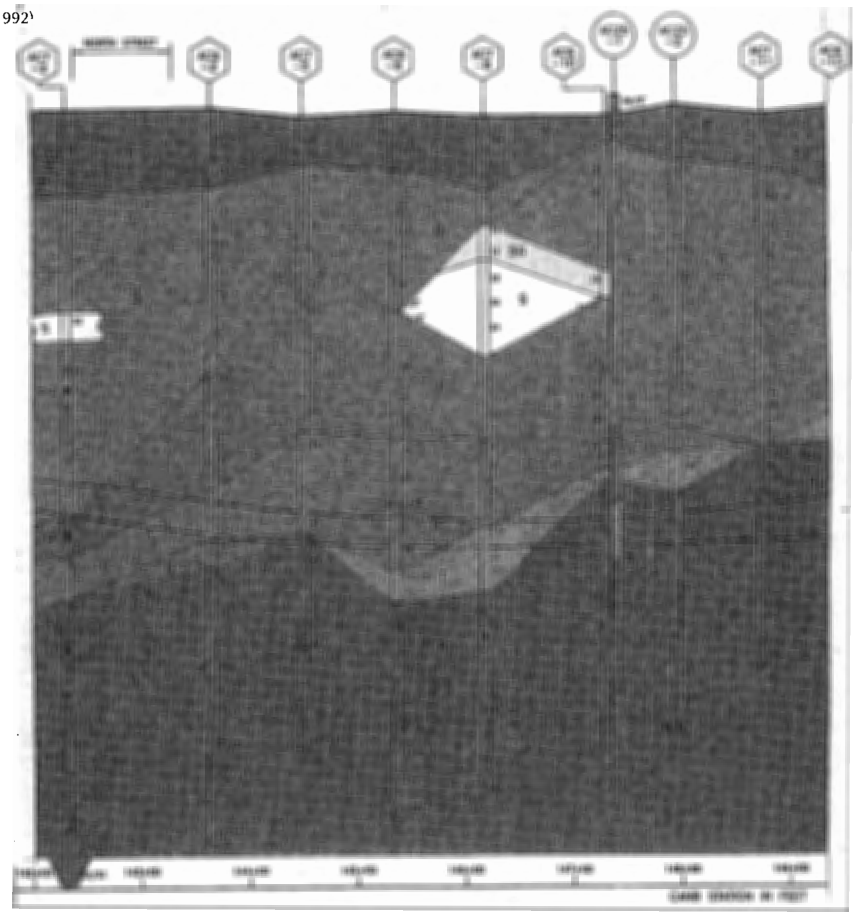
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 475)

FIGURE 6-31. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 133+00 and 142+00 (view west to southwest).

es northeastward of the highway alignment toward the drumlin complex, which forms most of Charlestown. The till is over 15.2 meters (50 feet) thick northeastward toward the Morton's Hill drumlin at the southern end of the Tobin Bridge. The glaciomarine material was not identified and separated from the till during the early work in this area, principally because the origin of this type of deposit was not known at the time of those earlier explorations. However, the till-like material that was recognized at places above the till is apparently the glaciomarine material. This material was found along the northeast side of the Millers River and in a zone extending northeastward from the Charles River near North Station to the old Charlestown Navy Yard. The additional drilling in the mid-1990s along the highway alignment indicates a considerable amount is present and that much of the earlier till had been eroded. A mound of glaciomarine material, about 5.2 meters (50

From MDPW (1992)



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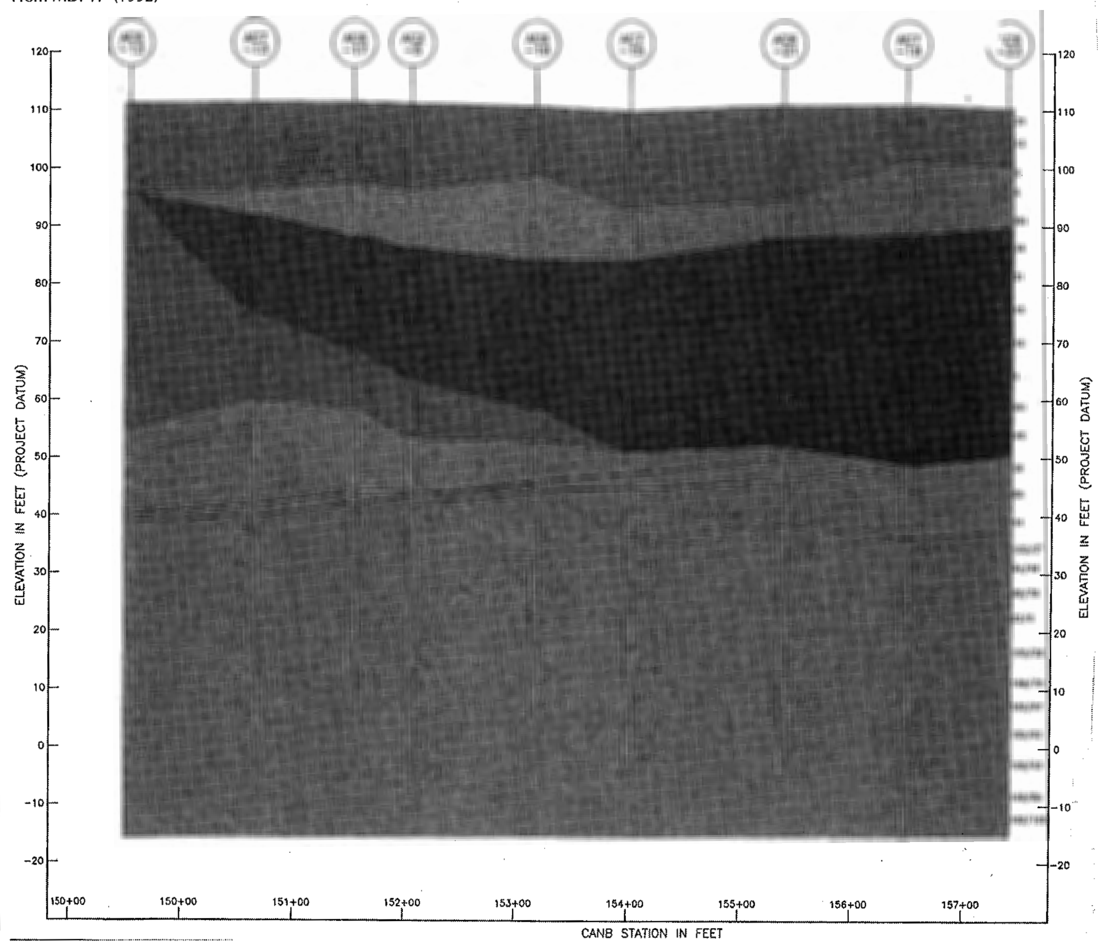
C_2 = Stiff clay
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 476)

FIGURE 6-32. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 142+00 and 150+00 (view west to southwest).

feet) thick (Stone & Webster, 1996), identified in the Gilmore Bridge-Bunker Hill Community College area, separates basins of marine clay to the north and south (see Figure 6-39). However, the material to the northeast in the drumlin complex is till.

The top of the till and glaciomarine deposit are eroded and cut by several channels. The deepest channel lies beneath the Charles River and close to the underlying swale in the top of the bedrock. Most of the channels are filled by marine clay, but the lower outwash sand and gravel occurs as fill below the clay in many places. This discontinuous layer of pervious sand and gravel is generally less than 3 meters (10 feet) thick, but ranges up to 6.1 meters (20 feet) in an east- to northeast-trending channel cut across the area. This channel likely traces the route of the former Millers River. The overlying marine clay stratum varies in consistency and thickness. The clay is generally found between elevations 1.2 to –15.2 meters (4 to –50 feet) MSL

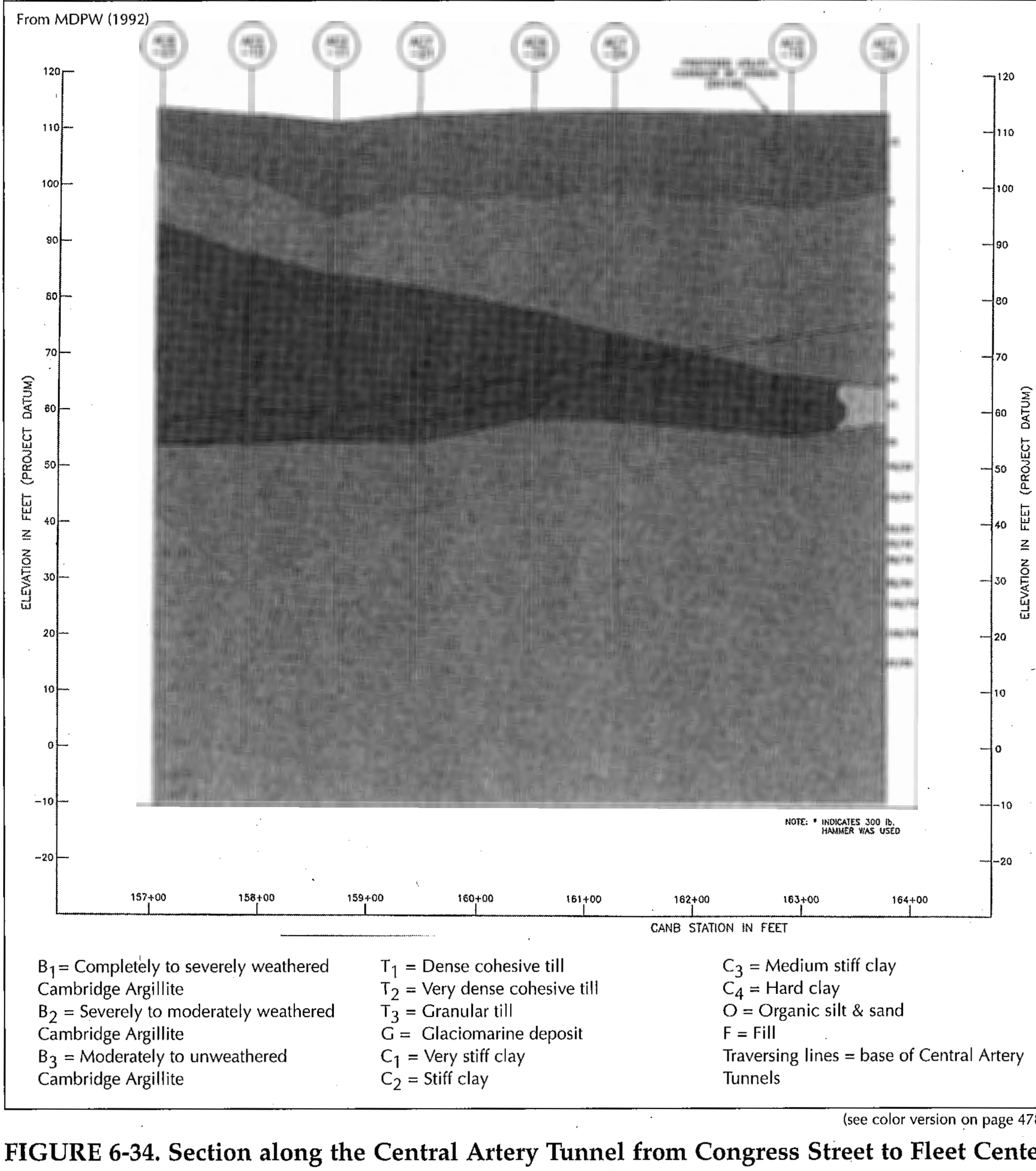


(see color version on page 477)

FIGURE 6-33. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 150+00 and 157+00 (view west to southwest).

and is up to 10.7 meters (35 feet) thick, but more commonly is between 2.7 and 7.6 meters (9 and 25 feet) thick. The clay pinches out due to deposition against the thick glaciomarine material or higher drumlin till and also locally due to later erosion (see Figure 6-37).

The undulating top of the clay, with a few channels, is due to erosion after a drop in sea-level or isostatic uplift. An upper discontinuous, generally 1.5 to 3 meter (5 to 10 foot) layer of sand and gravel outwash, representing the Lexington Outwash (and possibly some alluvium) overlies the clay. It is thickest in the shallow channels and missing over the areas of higher drumlin till. Organic silt deposits blanket the area and usually range from 0.6 to 6.1 meters (2 to 20 feet), being thinner where compressed by the overlying fill and pinching out against the drumlin to the northeast (see Figure 6-38). Some irregularities at the base of



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C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

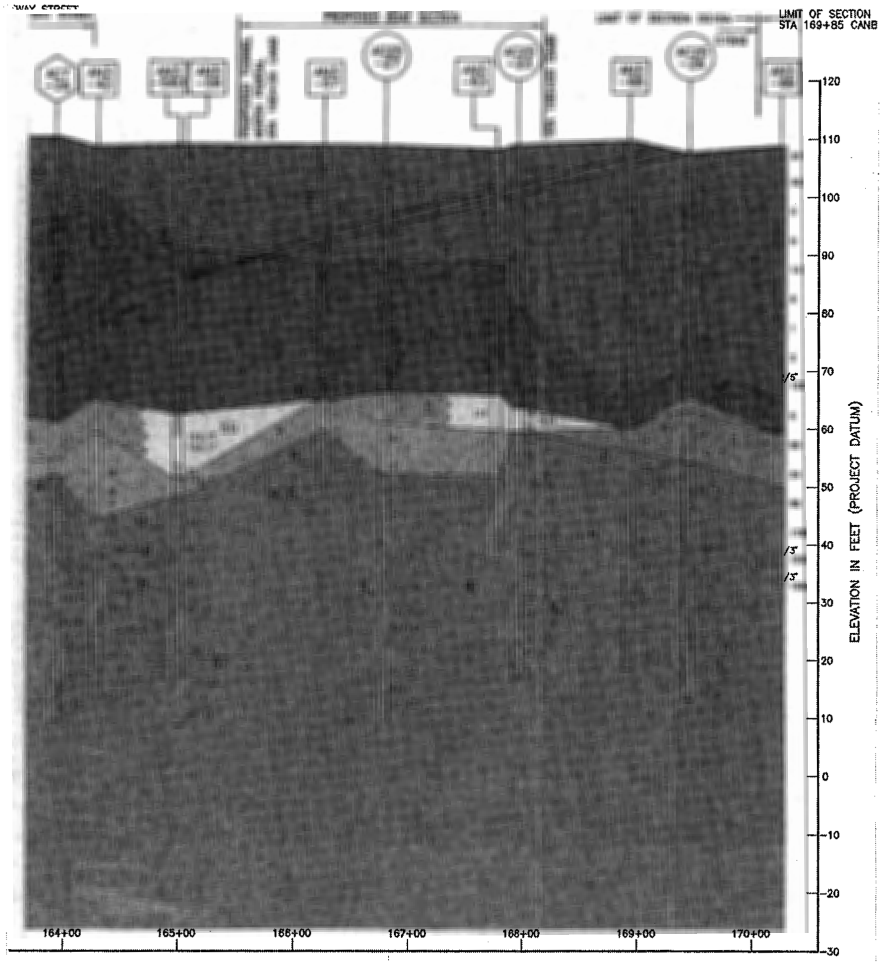
(see color version on page 478)

FIGURE 6-34. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 157+00 and 164+00 (view west to southwest).

the silt indicate at least slight erosion before its deposition. The upper limit of the organic silt at that location and elsewhere lies near the 1630 shoreline. Also, younger organic silt is found along the channels of the Charles and Millers rivers.

A channel in the till on the flank of the Morton's Hill drumlin displays the stratigraphic relations well and indicates a long geologic history (see Figure 6-38). It was probably first cut into a gently sloping southwest flank of the drumlin, filled by the Lower Outwash, and then apparently re-cut slightly before the deposition of the marine clay, creating a small surface depression that first received Lexington Outwash and then organic silt after additional erosion. Below the existing remnant of the Millers River are offset

From MDPW (1992)



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O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 479)

FIGURE 6-35. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 164+00 and 170+00 (view west to southwest).

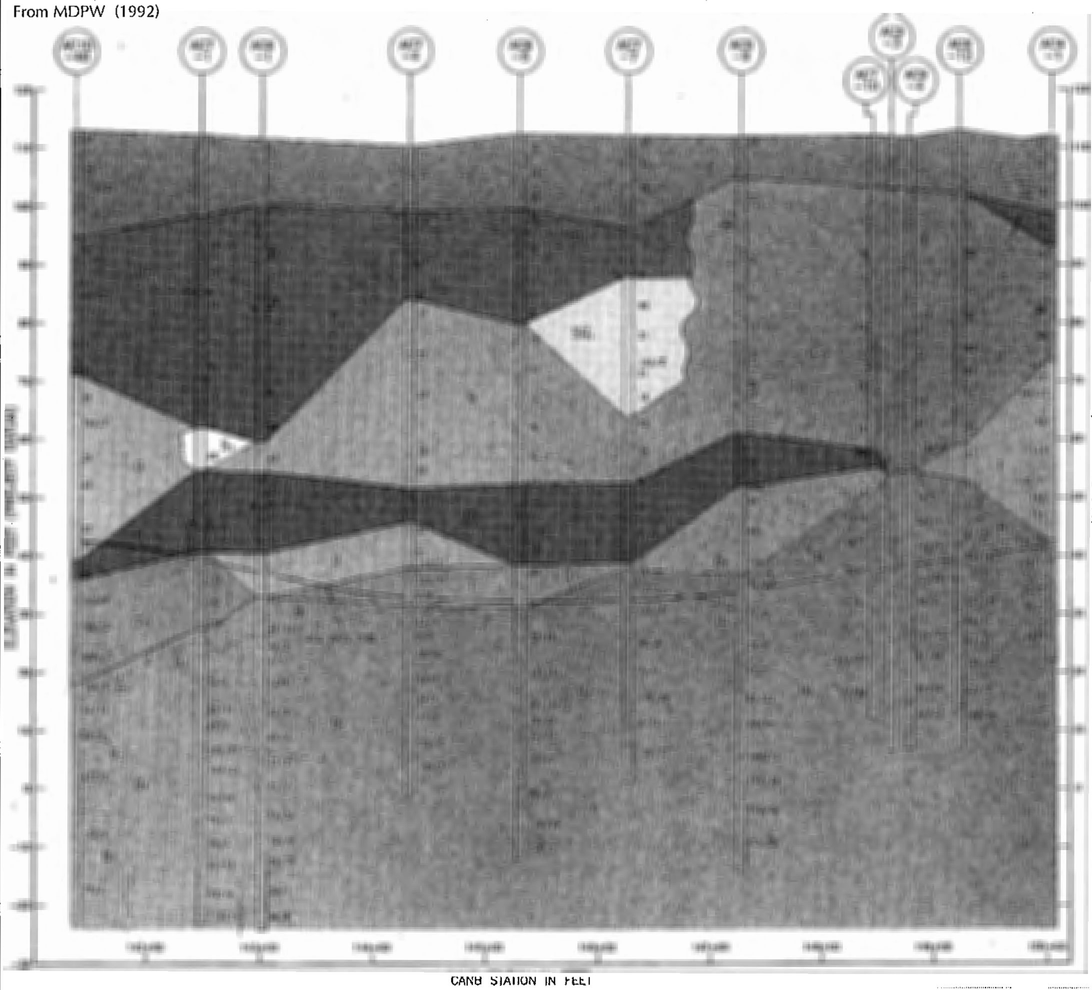
channels of the river's predecessors (see Figure 6-38).

Fill covers the entire area and varies in quality and quantity. It is thickest in the original lowlands bordering the lower Charles and Millers rivers, where it ranges from 9.1 to 12.2 meters (30 to 40 feet) in thickness, and thins across buried tops of small drumlins and the large ones of Charlestown to 1.5 to 4.6 meters (5 to 15 feet).

All the structures for the CA/T Project, with the exception of the Central Artery North Area tunnels through Charlestown, are founded on end-bearing piles or drilled shafts into the till or bedrock.

Interstate 90 (Massachusetts Turnpike) Extension. A major part of the CA/T Project was the Massachusetts Turnpike extension for 5.6 kilometers (3.5 miles) to Logan International Air-

From MDPW (1992)



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C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 480)

FIGURE 6-36. Section along the Central Artery Tunnel between North and Cross streets (east slurry wall Stations 142+00 to 150+00) showing the lower outwash sand and the gravel filling channel in the glaciomarine deposit and both covered by marine clay.

port via the South Boston Seaport Access Highway and the Ted Williams Tunnel (Third Harbor Tunnel) under Boston Harbor (see Figure 6-23). This construction accounted for approximately 45 percent of the nearly $15 billion cost of the CA/T Project. From an historical and geologic perspective, the extension passes through the now-filled South Bay, a portion of the filled Dorchester tidal flats, the filled South Boston tidal flats and what is now a part of the new Seaport in South Boston. It then passed under Boston Harbor, beneath/through Bird Island Flats and on to Noddle's Island in East Boston. The extension of Interstate 90 had to cross under railroad tracks at South Station and under the Fort Point Channel without interrupting the Red Line subway below, and traverse under Boston

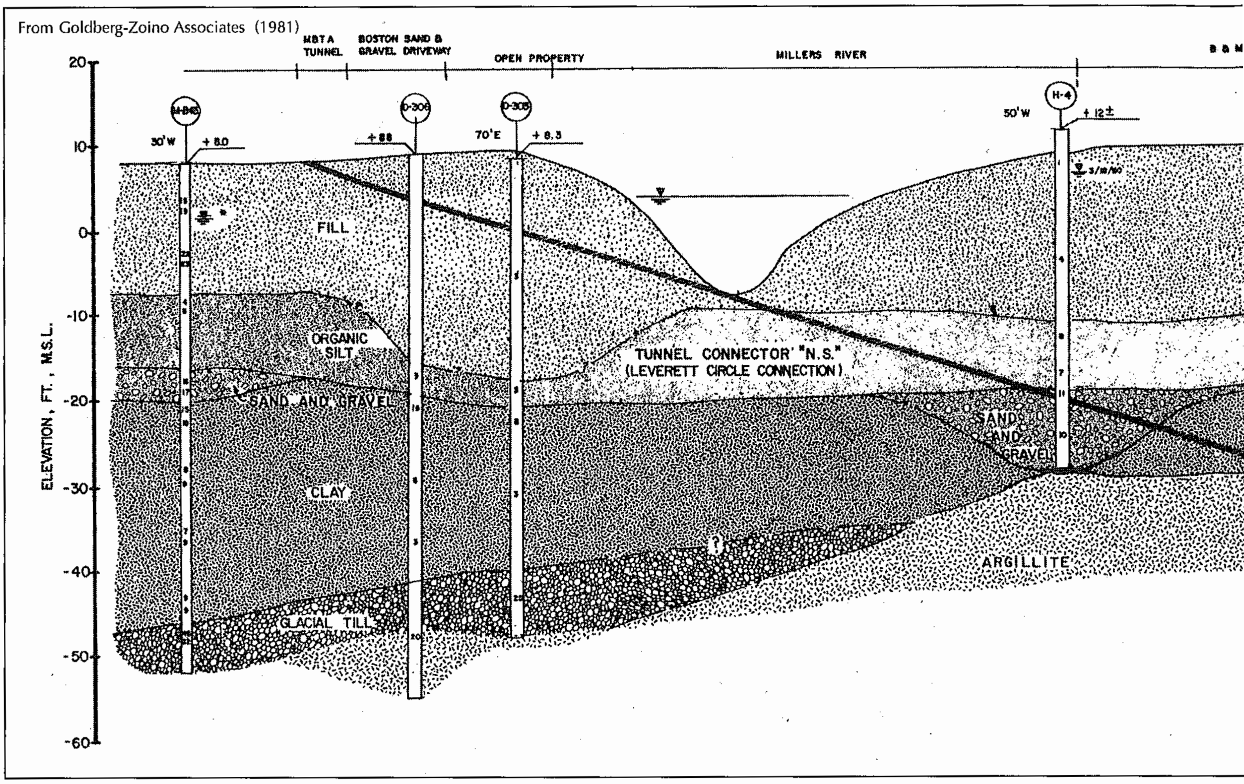
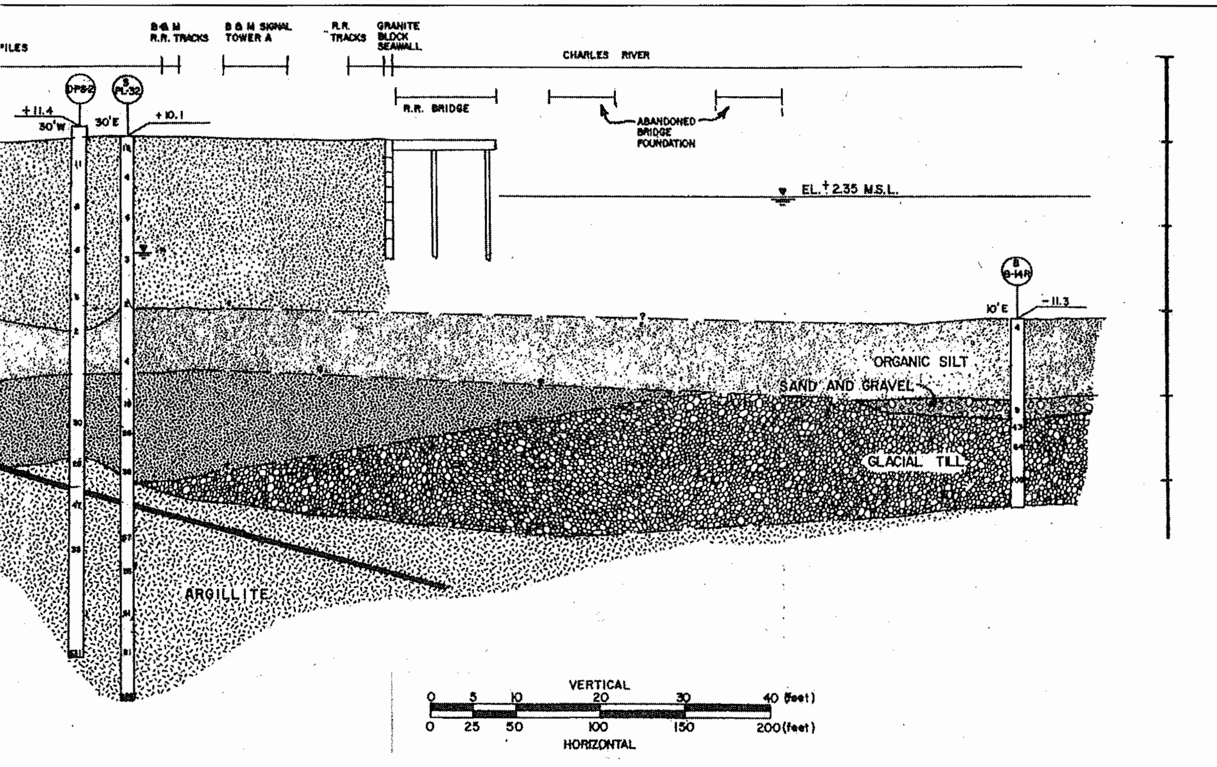


FIGURE 6-37. Section from south bank of the Charles River just west of the railroad bridge north into Charlestown and across the Millers River remnant to Interstate 93 midway between the Charles River and the Gilmore Bridge, showing marine clay with upper outwash channel fill capped by organic sediment and fill (view east).

Harbor, with 20 meter (65 foot) deep excavations on both sides for connections with the new 1,250 meter (4,100 foot) long four-lane immersed tube tunnel. Bottom stability issues and the typical in-situ reduction in shear strength of the clay with depth were particular problems for the excavations of unprecedented depths and size required just west of the Fort Point Channel (Lambrechts *et al.*, 1999).

In summary, except for a small area of the southern tip of the Boston Neck, which is clay, a thick layer of fill overlies the peat and organic silt in the former Roxbury tidal flats and South Boston Bay area. Until the 1970s, a grounded barge and pier could be seen west of the Central Artery Expressway at the Massachusetts Avenue exit. This area was filled in during the late 1960s and early 1970s for the construction of the Flower Exchange. Dredged clay and shells from Boston Harbor and Lynn underlie the South Boston Naval Reservation and areas to the south (according to Kaye). The remaining sequence of soil strata is typical of many areas outside the original Shawmut Peninsula. These strata include marine clay, outwash and till overlying deep argillite bedrock. Beneath the railroad yard behind South Station, subsurface conditions consisted of up to 8 meters (26 feet) of fill overlying about 5 meters (16 feet) of organic sediments. This layer in turn is underlain by thick clay on the order of 28 meters (92 feet) thick, but reaches more than 33 meters (110 feet) in some areas. The underlying till is up to 5 meters (16 feet) thick with the bedrock surface at elevation –33 meters (–100 feet) MSL at a depth of more than 43 meters (141 feet).

The extension presented a huge challenge behind South Station in having to advance tunnels through a 610 meter (2,000 foot) by 305 meter (1,000 foot) plot of harbor-side land composed of very soft ground that contains



over two hundred years of miscellaneous landfill, along with archeological artifacts needing to be preserved. In addition, the tunnels cross a waterway and eight highly active railway lines. Three tunnels were designed to cross under the railway using the tunnel jacking method (Lambrechts *et al.*, 1999). The tunnels were advanced through fill, organic silt, outwash sand and marine clay. The use of this technique was the largest and most complex set of tunnels ever installed using the tunnel jacking method. The size of the jacked tunnels was ten times that of any jacked tunnels ever attempted within the United States. Site constraints and available working space were also considerably less than ideal or even what is typically required for tunnel jacking operations.

The first step in the tunneling was to transform the entire tunneling zone from soft ground into solid ground, making it easier to excavate. The ground beneath the tracks was specified to be solidified by grouting, but the contractor selected to freeze the ground instead. The freezing was accomplished with the installation of as many as 2,000 vertical steel pipes drilled into the ground to depths of 21 meters (70 feet) through which a cold brine solution was injected that froze the soil. Three concrete jacking pits were dug out and inside each pit tunnel boxes measuring 24 meters (80 feet) wide and 12 meters (40 feet) high were constructed. Once the soil was hardened for excavation, crews then broke the head end of the concrete pit and began excavating soil in three-foot increments using a road header. The soil was removed from the back of the tunnel box using large buckets that were then lifted to the surface using a crane. Hydraulic jacks, as many as up to fifty at one point during the construction, were used to push the tunnel boxes forward from inside the concrete jacking pits into the frozen soil excavation zone. This process was repeated over and over again, and on average the jacking achieved advances of the tunnel sections through the ground about 0.9 to 1.8 meters (3 to 6 feet) per day with the trains rumbling just 6.1 meters (20 feet) above. Once the jacked sections were permanently placed, the jacking pits were incorporated as part of the highway paths. The application of this technique in construct-

From Goldberg-Zoino Associates (1981)

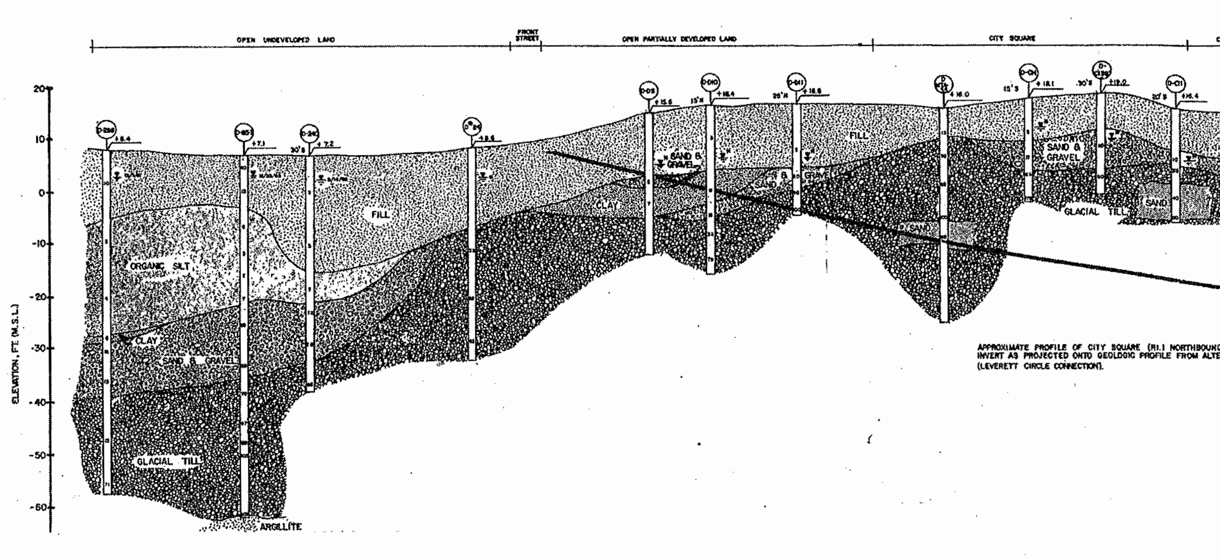
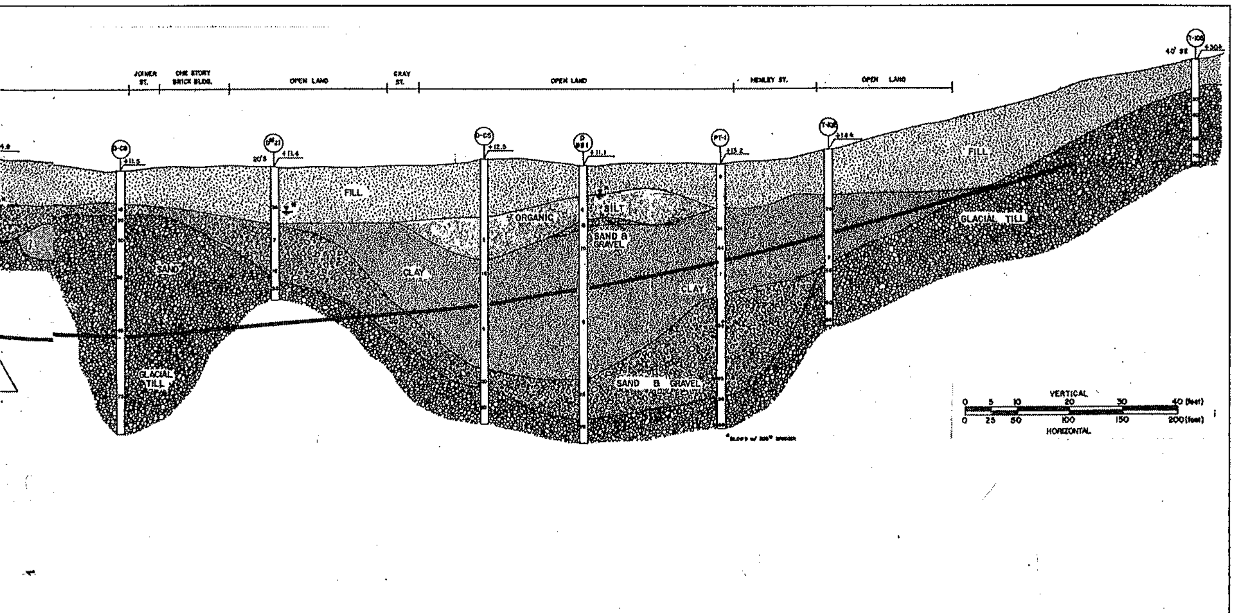


FIGURE 6-38. Section extending approximately along Route 1 northeastward from the Central Artery nearly to Mount Vernon Street in Charlestown, view northwest showing variety of units from lower outwash, very thin marine clay and organic silt in the south to a channel fill of lower outwash, marine clay, very thin upper outwash and organic silt on the flank of Morton's Hill drumlin.

ing the tunnels cost approximately $150 million, but saved considerable time. Deep soil mixing was used for tunnel foundations in the area between the Fort Point Channel immersed tube tunnels and the jacked tunnels and along the Fort Point Channel for a major ramp from Interstate 93 Northbound to Interstate 90 Eastbound. The new multi-level interchange between Interstate 90 and Interstate 93 was constructed adjacent to, over and beneath the eight railroad tracks on which there are over four hundred passenger train movements each day in and out of South Station. At Ramp D, 5 meters (16.5 feet) of fill overlies a 6 meter (20 foot) thick layer of organic soils. Clay up to 17 meters (56 feet) thick underlies the organics. About 2 meters (7 feet) of till overlies the bedrock at elevation 3 meters (10 feet) MSL.

The Casting Basin. Crossing Boston's Fort Point Channel with a highway tunnel proved problematic. Undertaking an operation similar to constructing the Ted Williams Tunnel (*i.e.,* the use of steel tube tunnel sections each longer than a football field and shipped in by barge) could not be carried out because there was not enough room to float the sections under the three bridges that cross the Fort Point Channel. Therefore, engineers decided to use concrete tunnel sections, which was a first in a U.S. construction project. Concrete tunnel sections were fabricated in such a way that they could be easily moved into place and assembled in the channel. This fabrication was performed within a casting basin — a huge dry dock 305 meters (1,000 feet) long, 91 meters (300 feet) wide and 18.3 meters (60 feet) deep. Over 344,050 cubic meters (450,000 cubic yards) of soil were excavated to form the basin on the South Boston side of the Fort Point Channel. A series of circular cellular cofferdams filled with crushed stone were used to seal off the channel end of the basin.

The cofferdams were founded on concrete drilled shafts that extended deep to the argillite. The tunnel sections, six in total, were built right in the bottom of basin and then completed sections were sealed watertight at either end. The basin was then flooded and all the crushed gravel removed from within the



cofferdams. Steel sheet piles were also removed so that sections could be floated out of the basin and positioned for lowering into a trench that was dredged on the bottom of the channel. The lowering of tunnel sections into position had to be done precisely since the sections had to be lined up and could not be moved once placed. Another problem was the support of such heavy concrete sections because an existing subway tunnel already ran directly under the channel and the extension of Interstate 90 would be just a few feet above it. The solution was achieved by the use of 110 concrete shafts 1.8 meters (6 feet) in diameter that were drilled into the bottom of the channel on either side of the subway tunnel as much as 44.2 meters (145 feet) into the bedrock.

Logan Airport. Excavations as deep as 20 meters (65 feet) using the deep soil mixing method for excavation support walls were required in soft marine clay for the construction of the deep cut-and-cover tunnels that lead Interstate 90 from the new Third Harbor Tunnel to Logan Airport. Total width excavated was from 60 to 87 meters (197 to 285 feet).

Considerable exploration was done around Logan Airport for the Ted Williams Tunnel and connections, and for the new approaches to the existing Sumner and Callahan Tunnels from the northwest side of the airport (see Figures 3-92 & 3-94). The work at the northwest side shows the types of variations found. One line of boreholes followed Route 1A from the tunnels past the MBTA Airport Subway Station and another perpendicular line extends from the subway station to the Airport Hilton Hotel adjacent to the airport's Central Parking garage.

The top of the argillite is deep along Route 1A. At the west side of the Airport Subway Station there is a slight mound in the till to just over elevation –38.1 meters (–125 feet) MSL. The mound slopes gently to the northeast before dropping off very abruptly to elevation –54 meters (–178 feet) MSL and the bedrock surface stays low farther to the northeast (see Figure 3-93). The till is stripped off the bedrock except for a few thin remnants. The overlying glaciomarine deposits have a highly variable thickness — 29 to 0 meters (95 to 0 feet) — due to the relief across its upper surface. The relief is apparently from the erosion of channels prior to the deposition of the marine clay. A north-trending channel, which passes east of the subway station and midway between the station and the Hilton Hotel, cuts through the glaciomarine and into the argillite locally. The channel is responsible for the drop off of the bedrock surface east of the subway station. The channel is asymmetric, with the west side having a steep slope that has a relief

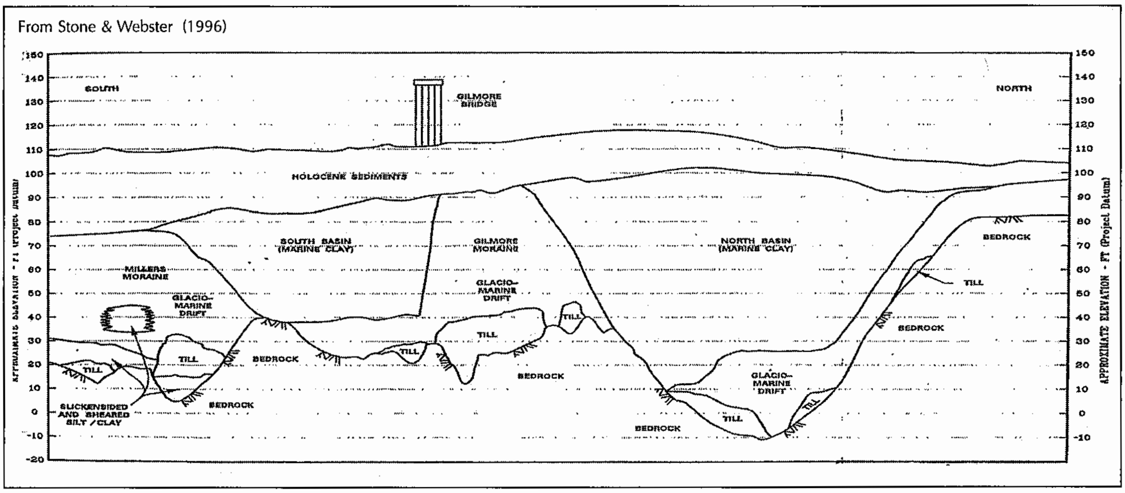


FIGURE 6-39. North-south section across the Gilmore Bridge and Interstate 93, Charlestown, showing marine clay filled channels cut into the glaciomarine deposit (view west).

of over 40 meters (130 feet) and with the east slope being gentle. The channel axis slopes to the north. Glaciofluvial sand and gravel up to 15.2 meters (50 feet) thick lie within it. The overlying marine clay ranges in thickness from 36.7 meters (120 feet) over the channel to about 7.6 meters (25 feet) over its western side. In all three surficial deposits are patches of apparently only partially reworked material of the underlying deposit above erosional unconformities. These unconformities are identified as lenses of till in the glaciomarine and sand and gravel deposits, and glaciomarine deposit in the clay. The top of the clay is relatively flat, with overlying marine silt 1.5 to 4.6 meters (5 to 15 feet) thick, capped by lenticular sand up to 3 meters (10 feet) thick that thins to the north. The sand and silt are apparently part of the Lexington Substage Outwash. The underlying silt may be the early, distal part of the outwash that was later overwhelmed by the coarser material as the glacial front moved closer — or, less likely, by the reworked top of the clay that concentrated a silt component. Peat and organic silt up to about 2.4 meters (8 feet) in thickness overlie most of the area under 2.1 to 6.1 meters (7 to 20 feet) of fill.

Boston Area Water Supply & Wastewater Tunnels

A summary of all of the major water supply and wastewater tunnels, with notes on how their construction added to understanding Boston's geology.

PATRICK J. BAROSH & DAVID WOODHOUSE

Massachusetts led in the development of methods of tunneling during construction in 1855 to 1876 of the nation's first great railroad tunnel — the 7,647 meter (25,081 foot) long Hoosac Tunnel in the western part of the state. Work on this tunnel led to the use of compressed-air rock drills, nitroglycerine for blasting, electric ignition in blasting, blasting caps, more efficient drilling patterns, modern accurate tunnel surveying and experiments with tunnel boring machines (Brierley, 1976) — all of which lent confidence to later tunnel projects around Boston and throughout the United States.

The city of Boston has made very extensive use of underground space since colonial days when wooden water pipes were laid underground for water supply and drainage. In the nineteenth century, pipes for illuminating gas were laid and at the close of the 1800s the first subway in the United States was constructed. Water supply and drainage tunnels have been constructed at various times across metropolitan Boston since the late 1800s (see Table 7-1). Major underground projects have included the construction of bedrock tunnels for the distribution of water from the Quabbin Reservoir, sewer interceptors to Deer Island, drainage tunnels and sewer outfalls. These tunnels are chiefly in granite, schist, gneiss and quartzite west of the Boston Basin and in conglomerate and argillite and lesser amounts of sandstone, arkose, shale, basaltic rock, diabase and altered rock within the basin. The geology was investigated as part of the careful planning of these tunnels from the first important Dorchester Bay Tunnel to the latest North Dorchester CSO Tunnel.

Tunneling under Boston has been extensive and a brief summary follows to show the scope of the work, type of construction and geologic materials encountered. More detailed information is provided in the references given and the many unpublished engineering-geological studies conducted by the major geotechnical firms in the area: Haley &

TABLE 7-1.
Major Bedrock Tunnels in the Boston Metropolitan Area

Name	Purpose*	Date Constructed	Length (km)	Lined Diameter (m)**	Approx. Depth (m)	Construction Method	Predominant Lithology	Geologic Face Mapping	Location	Reference
Dorchester Bay Tunnel	S	1879-1883	1.82	2.9	43	Cut & cover	Argillite conglomerate	None	Dorchester Bay	Clarke (1888); Dodge (1883)
Stony Brook Conduit	S	1880s	3.4	5.2x4.7	10-15	Open cut	Sand/gravel till		West Roxbury to Back Bay	Woodhouse & Barosh (1991)
Green Line Subway	T	1895-1912	5.7	H-B	6-10	Cut & cover, shield	Clay/till fill		North Station to Kenmore Square	Aldrich & Lambrechts (1986)
Wachusett Aqueduct Tunnel	W	1897-1899	3	3.4x3.6		Drill & blast	Granite, diorite, gneiss, schist	Yes	Wachusett Reservoir to Bolton	Crosby (1899a)
MWRA West Roxbury	S	1899-1902	8.3	3	4.5-15	Cut & cover, shield	Conglomerate, volcanic, sand & gravel, till, organic silt		West Roxbury	MWSB (1902)
Blue Line Harbor Crossing	T	1900-1903	2.6	6.2x7.0	19.2-25	Shield, compressed air	Clay		East Boston to Boston	Crosby (1903)
Weston Aqueduct Tunnels	W	1903	0.2-1.7	3.7		Drill & blast	Granite, quartzite, diabase	Yes	Framingham to Weston	Crosby (1904)
Orange Line Subway	T	1904-1906	4.5	H-B	3.9	Cut & cover	Clay, sand & gravel		North Station to Roxbury	Aldrich & Lambrechts (1986)
Red Line Subway	T	1912	4.0	5.8	7.2	Cut & cover	Clay, sand & gravel		Park Street to Harvard Square	Bechtel (1978); Woodhouse & Barosh (1991)
Red Line Fort Point Channel	T	1915-1916	4.1	6.1	18.3-23	Shield, compressed air	Clay, till, glaciomarine		Boston to South Boston	Cohill (1916)
Sumner Tunnel	V	1920s	2.3	9	10-40	Shield, compressed air	Clay		Boston to East Boston	Woodhouse & Barosh (1991)
Mystic River Cable Tunnel	O	1941	0.34	2.4	14-16	Shield, compressed air	Clay, till		Mystic River, Charlestown to Everett	Bray (1945)
City Tunnel	W	1947-1951	7.7	3.7	70-137	Drill & blast	Argillite, tillite, sandstone, conglomerates, andesite	1:240	Weston Reservoir to Chestnut Hill Reservoir	Tierney (1950b & 1951); MDC (1950); Tierney *et al.* (1968); Billings (1976a); Kaye (1979)
Boston Main Relief Drainage Sewer	S	1950	3.8	3.1	70-80	Shield	Clay		Boston to Deer Island	Woodhouse & Barosh (1991)
North Metropolitan Relief Tunnel	S	1950-1956	6.3	3.1	85.5	Drill & blast	Argillite	Partially mapped	Chelsea Creek to Deer Island	Kaye (1967a); Billings (1975)
City Tunnel Extension	W	1951-1956	11.4	3.1	70-122	Drill & blast	Conglomerate, sandstone, argillite	1:240	Chestnut Hill Reservoir to Malden	Billings & Tierney (1961 & 1964); MDC (1953)
Main Drainage Tunnel	S	1954-1959	11.5	3.1-3.5	89-92.5	Drill & blast, TBM	Conglomerate, sandstone, argillite, shale, till	1:240	Roxbury to Deer Island	Rahm (1959 & 1962); Ashenden (1982)
Malden Tunnel	W	1957-1958	1.6	3.8	85.5-100	Drill & blast	Felsite, argillite, diabase	1:240	Malden	MDC (1956a & 1956b); Billings & Rahm (1961 & 1966); Billings (1965)

Notes: *T = Transit Tunnel, V = Vehicular Tunnel, S = Sewer Tunnel, W = Water Tunnel, O = Other
**H = Horseshoe Tunnel, B = Box Tunnel, C = Circular

Name	Purpose*	Date Constructed	Length (km)	Lined Diameter (m)**	Approx. Depth (m)	Construction Method	Predominant Lithology	Geologic Face Mapping	Location	Reference
Callahan Tunnel	V	1960s	2.3	9	10-40	Shield, compressed air	Clay		Boston to East Boston	Woodhouse & Barosh (1991)
Cosgrove	W	1960-1967	12.8		60-90		Granite, gneiss, schist	1:12000 1:240	Wachusett Reservoir to Marlboro	Billings (1962); Skehan (1964 & 1967); Abu-moustafa (1969)
Dorchester Tunnel	W	1969-1974	10.2	3.1	30.5-61	TBM, drill & blast	Argillite, sandstone, conglomerate, basalts	1:240 1:120	Dorchester	Haley &Aldrich (1977); Richardson (1977); Woodhouse (1974); Aldrich & Dugan (1979); Dugan (1982); Ashenden (1982); Billings (1963, 1968 & 1982b)
MBTA Red Line Extension Northwest	T	1976-1985	5	5.8	15043	Shield (till), cut & cover	Till, argillite, sandstone, diabase		Cambridge to Somerville	Cullen *et al.* (1982); Woodhouse & Barosh (1991); Hatheway & Paris (1979)
South Cove	T	1979-1987	0.77	4.5	5	Cut & cover, shield	Fill, organic silt, clay, till		Boston Chinatown to Back Bay Station	Stacho (1968)
Southwest Corridor	T	1981-1985	0.9	6.7	11.6	Cut & cover	Fill, organic silt, clay, sand, till		Back Bay	Aldrich & Lambrechts (1986)
Wellesley Tunnel	S	1990	0.48	3.5	10	Drill & blast, TBM	Granite, diorite, dikes, sand & gravel		Dedham	Barosh & Woodhouse (1990 & 2001)
Deer Island Outfall	T=S	1990-2000	15.2	7.3	128	TBM	Argillite, dikes, tuff		Deer Island to outer harbor	Martin (2007)
Ted Williams Tunnel	V	1991-1995	2.6	12	16	Dredged channel, prefabricated setions	Argillite, organics, clay, till		South Boston to Logan Airport	Kwiatkoswki & Anderson (1997); Anderson (2007)
Inter-Island Tunnel	S	1991-1998	8	4.3	91	TBM	Argillite			Martin (2007)
Town Brook Tunnel	W	1993-1995	1.2	4.4	56	Drill & blast, TBM	Argillite & granite		Quincy	Martin (2007)
Metro West	W	1996-2003	2.8	4.9	60-137	Drill & blast, TBM	Clay, fill, till		Weston to Marlboro	Eskilsson et al. (1997); Carnevale (2007); Carnavale & Hagar (2001); Carnevale *et al.* (2000 & 2001)
Silver Line	T	2004	0.1	8.5	12	NATM, cut-&-cover, SEM			Boston to South Boston	Boscardin (2005)
Braintree-Weymouth Tunnel	S	2004-2008	4.6	3.7	16	TBM	Argillite, dikes, volcanic rock		Braintree to Weymouth	Martin (2007)
North Dorchester Bay	S	Not completed	3.4	5.2	—	Earth balance machine	Metavolcanics, organics, cklay, till		Dorchester	MWRA (2011)

Notes: *T = Transit Tunnel, V = Vehicular Tunnel, S = Sewer Tunnel, W = Water Tunnel, O = Other
**H = Horseshoe Tunnel, B = Box Tunnel, C = Circular

Aldrich, Inc.; Goldberg-Zoino & Associates (GZA); Geotechnical Engineers, Inc. (GEI); McPhail Associates; Metcalf & Eddy and others; and those held by the many state agencies and the U.S. Army Corps of Engineers. Much of the earlier data in Boston was summarized on the maps of Kaye (1980a, 1979 & 1967a), but considerably more exists today.

The water supply and wastewater tunneling in the Boston area falls into three periods:

- early work prior to World War II for the water supply mostly west of the city — such as the Sudbury River, Wachusett and Weston aqueducts, which were well mapped by Crosby (1899a, 1904) and the Quabbin Aqueduct, which was mapped by Callaghan (1931) and Winsor (1936), and also includes the Wachusett Dam that ties into two tunnels;
- the tunnels in metropolitan Boston in the 1960s, which were mapped by the Metropolitan District Commission and the students of M.P. Billings at that time; and,
- the extensive water and sewer tunnels of the 1990s and other projects that were mapped by geotechnical firms.

A Brief History of Boston's Water Supply

Boston faced a much more difficult problem than most cities in supplying its citizens with water after it outgrew the use of local shallow wells. The threat of salt water intrusion, the lack of a deep general aquifer and not being adjacent to a large river with suitable locations for reservoirs made urban water supply a very difficult task. The city met the challenge by progressively utilizing ponds and reservoir sites across the topography to the west and connecting them to the city via bedrock tunnels and aqueducts. Thus, one of the first extensive water supply systems in the country was built for the city of Boston (see Figures 7-1 & 7-2). This system is founded on excellent engineering geology.

The city of Boston owes its founding to its abundant fresh water springs that led John Winthrop and his Puritan followers to abandon their water-poor settlement across the Charles River in Charlestown and to accept William Blackstone's invitation to use the springs on the Shawmut Peninsula. The dense drumlin till that composes most of Charlestown did not provide a good source of fresh water, whereas on the Shawmut Peninsula water from shallow dug wells produced water of good quality under artesian pressure (Kaye, 1976a). The Town Well was located at what is now called Washington Mall and the Town Spring was in Spring Lane downhill from Washington Street. Wells in the lower part of Boston tended to be somewhat brackish since they were close to sea level and affected by salt-water intrusion.

The early colonial wells were first lined with slabs of local rock, then by cobbles retained by wooden sheathing and finally by loosely mortared brick. Pumps consisting of hollow log pipes with a moving wooden piston and flap-valve have been found in the deep wells unearthed during recent construction. Thin lift-rods were attached to the valve piston and activated by a pump handle at the surface. Log pipes were used for the distribution of water until the mid-nineteenth century. Woodhouse has excavated several of these old wells when encountered in various excavations in Boston and donated parts to the Bostonian Society, the Old South Meeting House, the United States Geological Survey (USGS) and the Boston Athenaeum.

Aqueduct Company (a privately owned water company that was organized in 1795) brought water downslope from Jamaica Pond at elevation 18.6 meters (61 feet) mean sea level (MSL) through a 64 kilometer (40 mile) long distribution system of hollowed-out log pipes (Kaye, 1976a). However, wells continued to be used on the higher elevations such as Beacon Hill because of a lack of sufficient pressure in the system to reach up the slopes of Beacon Hill. In 1848, the city initiated a new public supply system that carried water from Lake Cochituate, about 24 kilometers (15 miles) west of the city via the Cochituate Aqueduct. A connecting reservoir was built on top of Beacon Hill to receive water pumped up to it, from which it would flow by gravity to all parts of the hill. Water also was brought in from the Sudbury River, about 40 kilometers (25 miles) west of Boston via the Sudbury

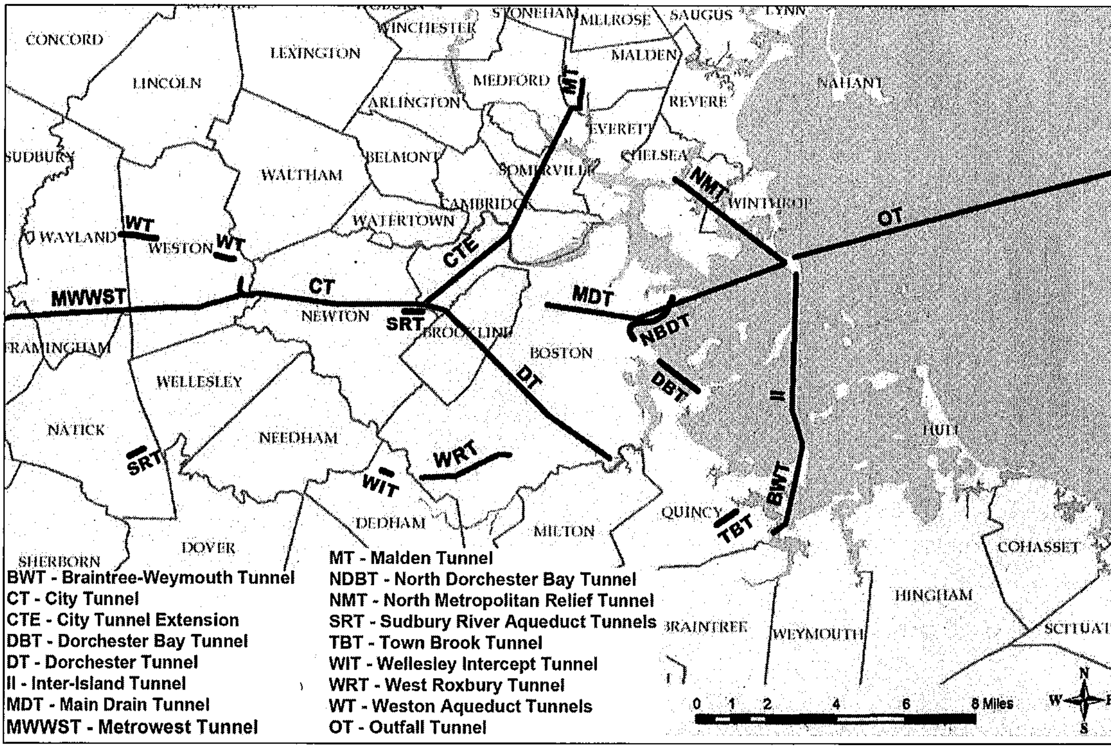


FIGURE 7-1. Map of metropolitan Boston showing locations of bedrock tunnels. (Modified map courtesy of the MWRA.)

Aqueduct (built from 1867 to 1876). Thus began a piecemeal westward expansion of the water supply. A scheme to expand the supply source northwestward in the 1850s by using the Middlesex Canal as an aqueduct was not carried out.

In the early 1890s, it was realized that the water supply problem could only be solved on a regional basis. Thus, the Metropolitan Water District was created in 1895 and work began on a major expansion. The Wachusett Reservoir was built 64 kilometers (40 miles) west of Boston, mainly in the town of Clinton. It was the largest public water supply reservoir in the world when completed. Excellent exploration studies were done for the dam and the tunnel aqueduct leading from it by Crosby (1899a). The water quality of the Wachusett Reservoir was at one time endangered because the Metropolitan District Commission (which manages the reservoir) owned only eight percent of the watershed and development within it was taking place at a rate unequaled in any other part of the state. A watershed protection program was enacted later under the Massachusetts Water Resources Authority (MWRA). Water was conducted from the Wachusett Dam along the Wachusett Aqueduct (see Figure 7-2) to the Sudbury Reservoir for transport to metropolitan Boston. The aqueduct (which was completed in 1903) consists of 3.2 kilometers (2 miles) of rock tunnel and 11.3 kilometers (7 miles) of unreinforced concrete sections. An additional connection was built from the Sudbury Reservoir (see Figure 7-2) to supply Boston. This connection was both tunneled and excavated by the cut-and-cover method to form the Weston Aqueduct, which ended at the Weston Reservoir (see Figure 7-2).

The demand for more water led in 1926 to a twenty-year program for the construction of the Quabbin Reservoir 104 kilometers (65 miles) west of Boston (in a valley then occupied by six towns) to impound the water of the Swift River, a tributary of the Connecticut River, by the construction of two earth dams referred to as the Winsor Dam and the Good-

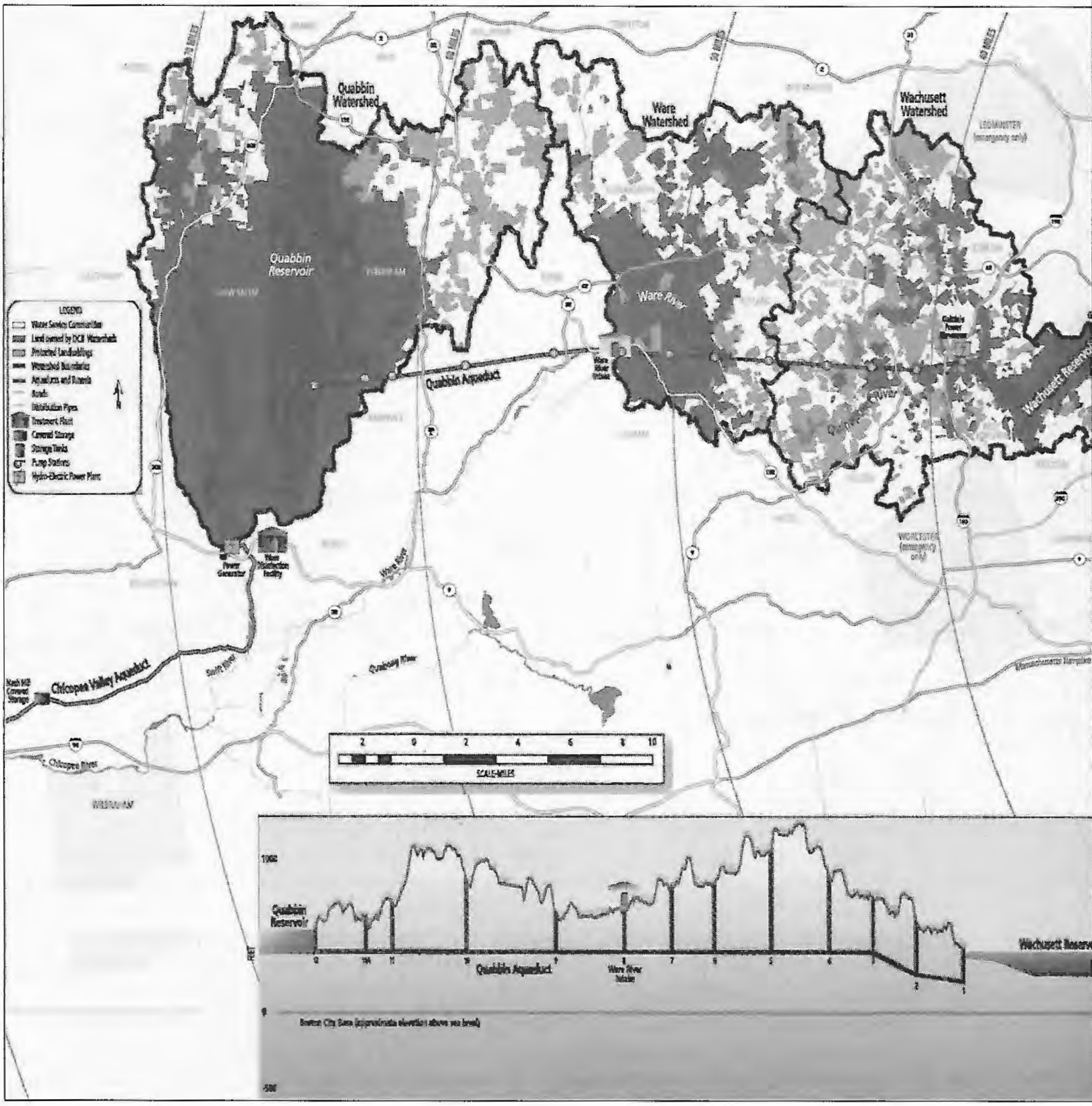
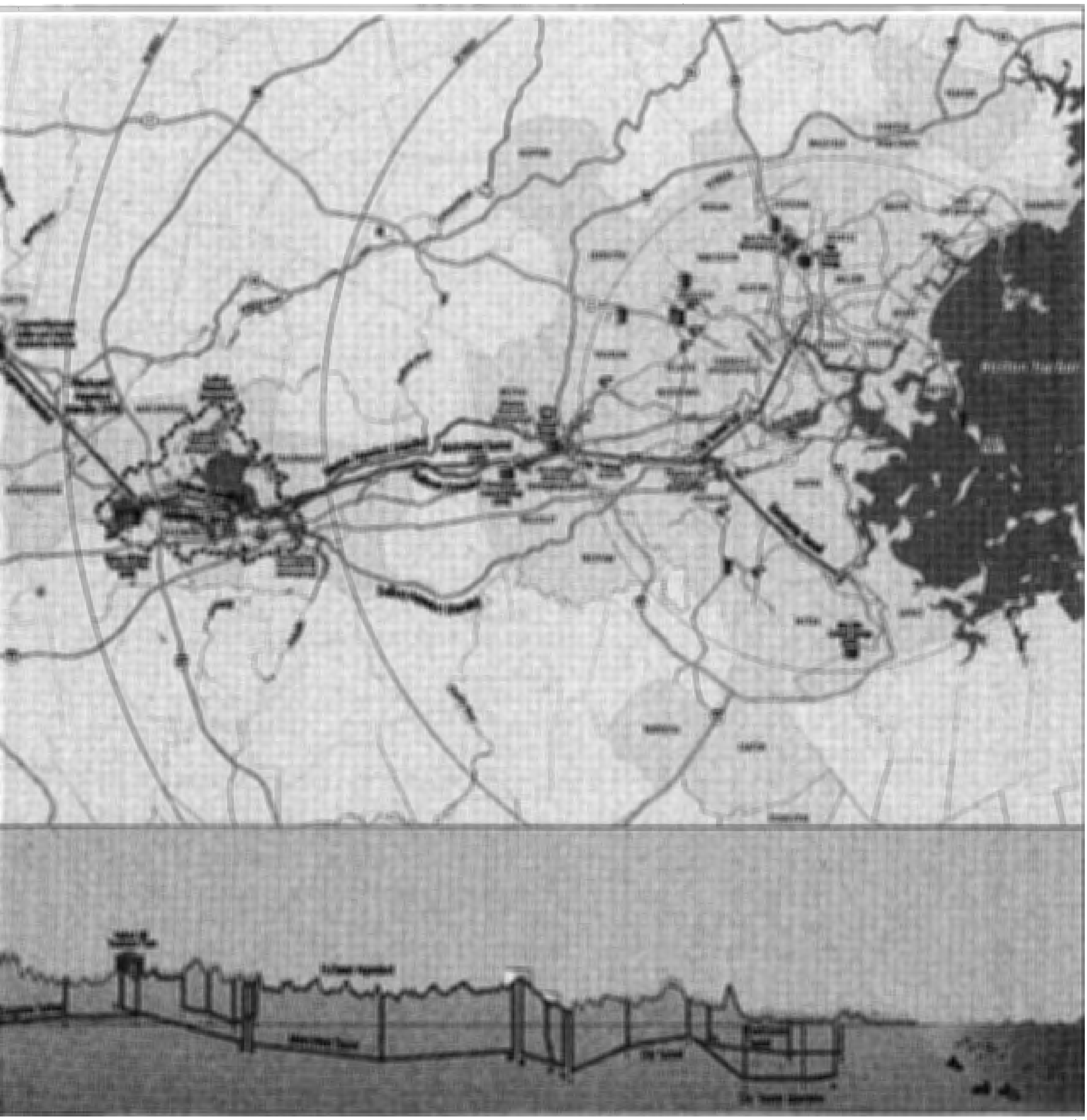


FIGURE 7-2. Map of central and eastern Massachusetts showing aqueduct tunnels and reservoirs of the MWRA. (Courtesy of the MWRA.)

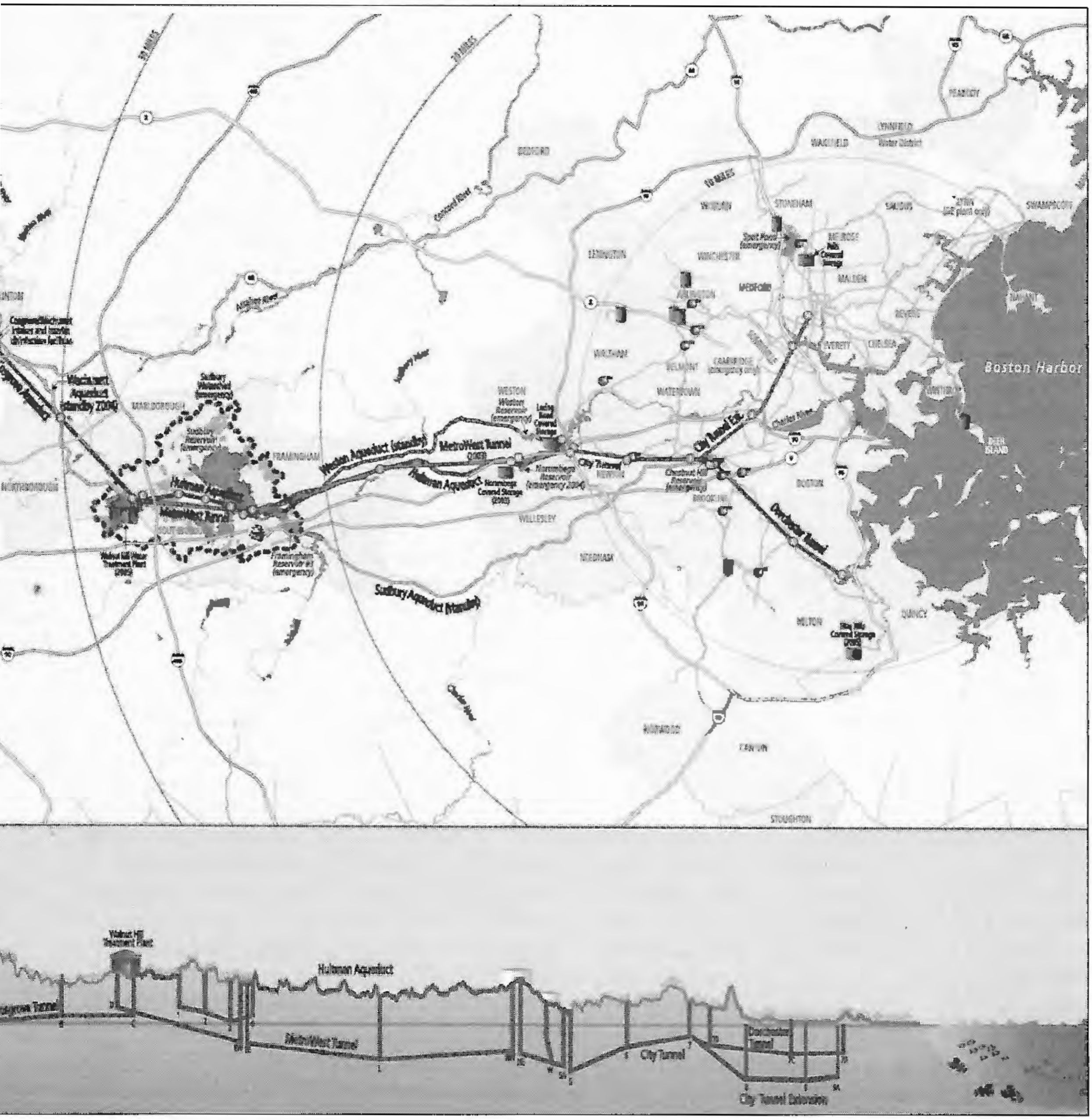
nough Dike. In 1946, when the reservoir was completed and filled, it had a capacity of 412 billion gallons, and covered a surface area of 10,000 hectares (39 square miles). Today, it provides all, or at least the majority, of the water for forty-four cities and towns, thirty-nine of which are located within the metropolitan area (and served by the MWRA).

A new high-service-pressure aqueduct system, with additional holding reservoirs, was planned in the late 1930s to expedite water delivery to Boston. The 27 kilometer (17 mile) long Hultman Aqueduct was built in 1940 between the Sudbury Reservoir and the Norumbega Reservoir west of Boston. It is a cut-and-cover and mound-covered surface



pipe that snakes across the countryside. World War II stopped further work on the system, but after the war a series of bedrock tunnels was built toward Boston. These tunnels include: the City Tunnel (built from the end of the Hultman Aqueduct in 1951), the City Tunnel Extension (built in 1961), the Cosgrove Tunnel (built in 1965) and the Dorchester Tunnel (built in 1978). The deep bedrock Cosgrove Tunnel (first called the Wachusett-Marlborough Tunnel) was bored below the Wachusett Aqueduct in the 1960s to provide increased capacity and redundancy. The Wachusett Aqueduct was then taken out of service in 1965.

The sixty-year-old Hultman Aqueduct then began to develop leaks in the 1980s as it aged, but it could not be repaired without shutting down Boston's water supply. By the 1990s, the aqueduct was losing 400,000 gallons a day. To remedy this problem, a new deep 28.4 kilometer (17.6 mile) MetroWest Water Supply Tun-



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The chief water sources for metropolitan Boston remain the Quabbin Reservoir, the Wachusett Reservoir and the Ware River. Water is transported to the metropolitan area by a series of aqueducts and bedrock tunnels that recently have been augmented or renovated to now provide redundancy for the entire system. The tunnels and aqueducts are 3.7 to 4.3 meters (12 to 14 feet) in diameter, and local distribution tunnels within Boston are generally 3 meters (10 feet) in diameter. A backup water supply system consists of the Norumbega, Weston, Chestnut Hill, Sudbury and Spot Pond reservoirs, along with the Fells Basin Numbers 1 and 2 and a new covered reservoir in the Blue Hills. Note that federal law dating back to circa 1980 required that concrete-enclosed open-air reservoirs containing untreated water be covered. The U.S. Environmental Protection Agency in 1986 passed regulations that require finished concrete-enclosed reservoirs to be covered. Because the water sources are located in less populated areas, the water quality is excellent and requires little treatment. However, the water is treated with state-of-practice ozone and ultraviolet light systems and then the water is finally fluorinated. As expected for an old system, elevated levels of lead sometimes occur in Boston and Cambridge where much of the old distribution system consists of lead pipes. However, these pipes are being replaced by these cities as part of on-going modernization programs.

Bedrock tunnels began to be increasingly more important as the water system grew. The need to expand Boston's water supply as the city grew was met by a network of small reservoirs connected by shallow surface pipes. These pipes lay within or adjacent to the Boston Basin where there are no insurmountable topographic barriers, but farther westward development of water sources crossed barriers that needed to be breached by tunnels. The tapping of the Sudbury River waters just west of the Boston Basin by the Sudbury River Aqueduct crossed no particular barrier. However, the building of the Wachusett Reservoir in the late nineteenth century in the Nashua River Valley (which lay beyond a rock ridge) and a portion of the Wachusett Aqueduct needed to convey the water eastward required a rock tunnel (see Figure 7-2). The Weston Aqueduct was built to facilitate moving this water closer toward metropolitan Boston. The Weston Aqueduct needed only short tunnel segments to keep its alignment fairly straight. When the Quabbin Reservoir was later constructed in the west-central part of the state in the 1930s, the 40 kilometer (25 mile) long bedrock tunnel of the Quabbin Aqueduct was the most practical way of moving its water across several ridges to the Wachusett Reservoir (Callaghan, 1931; Winsor, 1936).

The development of a high-pressure water system for Boston began with the 27 kilometer (17 mile) long surface pipe of the Hultman Aqueduct in 1939 to connect the end of the Wachusett Aqueduct to the west edge of metropolitan Boston. This system gradually spread eastward over the city through a series of deep rock tunnels: City Tunnel, City Tunnel Extension and Dorchester Tunnels (see Figures 7-1 & 7-2). In addition, the relatively shallow Wachusett Aqueduct was replaced by the deep rock Cosgrove Tunnel. The system is now entirely within deep rock tunnels.

Sudbury River Aqueduct Tunnels. The Sudbury River Aqueduct was built in the mid-1870s to transport water stored in a series of reservoirs on the Sudbury River to Boston's water distribution system. It extends nearly 26 kilometers (16 miles) from the gatehouse at Farm Pond in Framingham to the Chestnut Hill Reservoir at the west border of Boston. It is primarily a cut-and-cover aqueduct not far below the surface, but locally it is elevated on fill and bridges, and pierces rock hills with tunnels. The Echo Bridge over the Charles River — which is 152 meters (500 feet) long and one of the largest stone-arch bridges in the

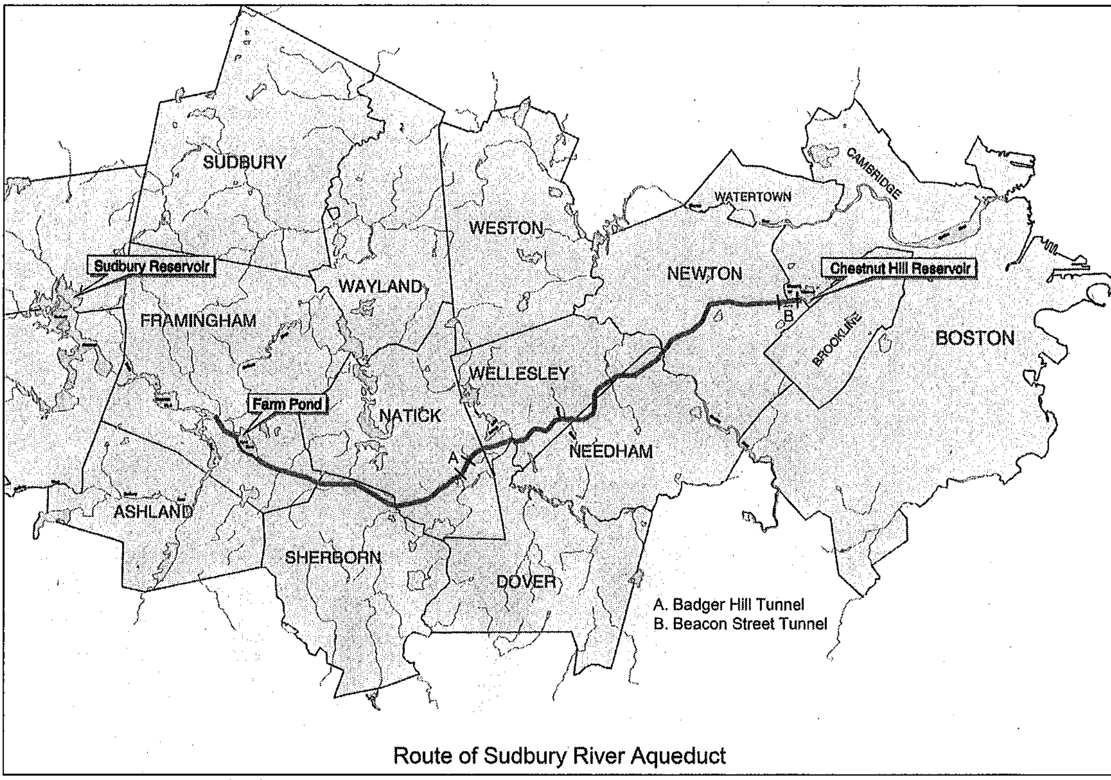


FIGURE 7-3. Map showing the Sudbury River Aqueduct and the location of Badger Hill (A) and Beacon Street (B) tunnels. (Modified map courtesy of the MWRA.)

world — and the Waban Arch Bridge are significant structures that carried the Sudbury River Aqueduct (see Figures 7-3 & 7-4). The aqueduct was built between 1876 and 1878 as a cement-lined brick pipeline of rectangular cross-section, with an arched roof equivalent to a round pipe 2.6 meters (8.5 feet) in diameter (Johnson, 2004). The Badger Hill Tunnel and the Beacon Street Tunnel — which have total length of about 1,524 meters (5,000 feet) and are in bedrock — would have been dug by drill and blast. The aqueduct was noted for important water flow studies that were conducted soon after it was put in service (Fteley & Stearns, 1883). The aqueduct was taken out of service in 1978 upon the completion of the Dorchester Tunnel and is now maintained for backup service, if needed.

The 610 meter (2,000 foot) long Badger Hill Tunnel in South Natick trends northeast beneath Badger Hill, now shown as Carver Hill, at a roughly 45 meters (150 feet) MSL elevation. The hill is composed of mainly Late Proterozoic quartzitic rock of the Westboro (Plainfield) Formation cut by some Dedham Granite (Nelson, 1975a). The bedding strikes northeast to north which is roughly parallel to the tunnel, and dips 50 to 65 degrees northwest. The southwest portal lies adjacent to the northeast-trending, northwest-dipping Western Border Fault of the Boston Basin and parallel breaks would be expected to cut the tunnel rock. A small drumlin caps the 90.5 meter (297 foot) MSL high hill.

At the Beacon Street Tunnel, the aqueduct disappears eastward into rock just north of Beacon Street at Grays Cliff Road east of Newton Center, and reappears from the rock 914 meters (3,000 feet) beyond at the southwest side of the Chestnut Hill Reservoir (see Figure 7-5). As Crosby wrote in 1880: "the aqueduct tunnel, which has a course almost exactly parallel with the strike of the beds. . . begins on the west in conglomerate, but soon passes [obliquely downward] into the slate [argillite]; which it follows for perhaps one hundred and

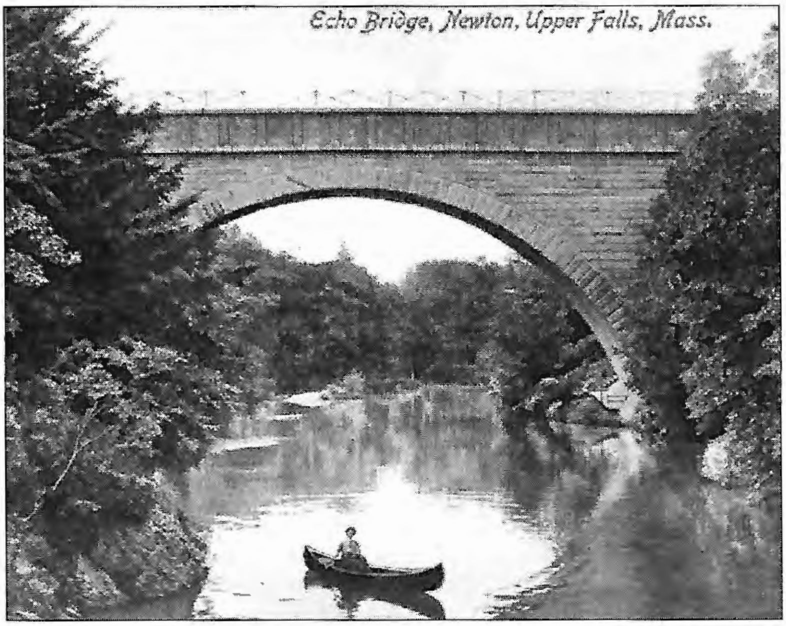


FIGURE 7-4. Echo Bridge, built from 1875 to 1877 by the Boston Water Works, carries the Sudbury River Aqueduct over the Charles River at Newton Upper Falls.

fifty feet, and then re-enters the conglomerate, both transits being entirely abrupt." Crosby (1880) called the discontinuities at the contacts unconformities, but recognized some strike faulting along them to the west. He recorded a north dip of 30 to 40 degrees for the strata, which strike east-west to east-northeast (Kaye, 1980a). The western conglomerate-argillite contact is at a significant strike fault, which has greatly thinned the argillite. The argillite, which is apparently the Cambridge Argillite and not an interbed, expands both to the west and to the east in the Chestnut Hill Reservoir. The reservoir was largely carved out of Cambridge Argillite and some Roxbury Conglomerate during 1866 to 1870 (Shaler, 1869; Crosby, 1880; Kaye, 1982a). Three miners died constructing each tunnel segment (Johnson, 2004), but it is not known if this was due to a support problems or blasting accidents.

Wachusett Dam. In 1897, the Metropolitan Water Board recognized the need for more water as Boston developed into a major city and therefore it directed the impounding of the Nashua River just above Clinton by constructing the Wachusett Dam between 1901 and 1905 (see Figure 7-2). The reservoir first filled in 1908 and at that time the pool that had been formed was the largest public water supply reservoir in the world. The dam was the largest gravity dam in the world as well as the largest hand-built and dug dam in the world constructed of granite blocks on a bedrock foundation. The dam is 294 meters (965 feet) long and 62.5 meters (205 feet) high. The capacity of the reservoir is 65 billion gallons and it has a flow of 118 million gallons per day. Water flows by gravity from the dam southeastward via the Wachusett and Weston aqueduct tunnels (Crosby, 1899a & 1904) to the Weston Reservoir and then by pipeline to the Chestnut Hill and the Spot Pond reservoirs. The Wachusett Reservoir was later connected to the large Quabbin Reservoir in the west-central part of the state by the 40 kilometer (25 mile) long bedrock Quabbin Aqueduct Tunnel as the water-supply system expanded (Callaghan, 1931; Winsor, 1936). Later, the Cosgrove Tunnel was constructed to replace the Wachusett Aqueduct Tunnel, which was put on standby.

The geologic data from the Wachusett Dam, along with the two tunnels, provide a section across the Clinton-Newbury Fault Zone and the Nashoba Thrust Belt, which form the most important structural zone in the eastern United States. The dam is constructed across a narrow valley formed by a fault block of Ordovician metasiltstone and metamudstone bounded by Proterozoic granite (Peck, 1975; Barosh, 1999b). The dam site was extensively and thoroughly explored by W.O. Crosby (1899a) using some 500 boreholes (see Figure 7-6). He correctly interpreted boreholes that went through bedrock into surficial material and back into bedrock as a buried overhanging cliff, which was revealed when the surficial material was stripped off. The "cliff" is controlled by a fault, which is a splay off the Clinton-Newbury Fault Zone that runs under the dam (Peck, 1975). In later testing, core from four borings across the base of the dam showed evidence of various kinds of past movement in the rock and a significant fault zone along the metasedimentary-granitic rock contact. This fault apparently moved during the Mesozoic, but there is no obvious indication that the Pleistocene outwash northeast of the dam is disturbed by the fault (Barosh, 1983b). Crosby (1899a) also mapped many steeply northwest-dipping faults in the Nashoba Thrust Belt just southeast of the dam in the 3.2 kilometer (2 mile) long bedrock Wachusett Aqueduct Tunnel. In 1907, during the first filling with water, a liquefaction flow fracture occurred in the upstream slope of the North Dike. Fine sand flowed 100 meters (328 feet) into the reservoir (Olson *et al.*, 2000). The potential for liquefaction was assessed by the U.S. Army Corps of Engineers in the early 1970s and the MWRA did not find that liquefaction potential exists for the local seismic design conditions.

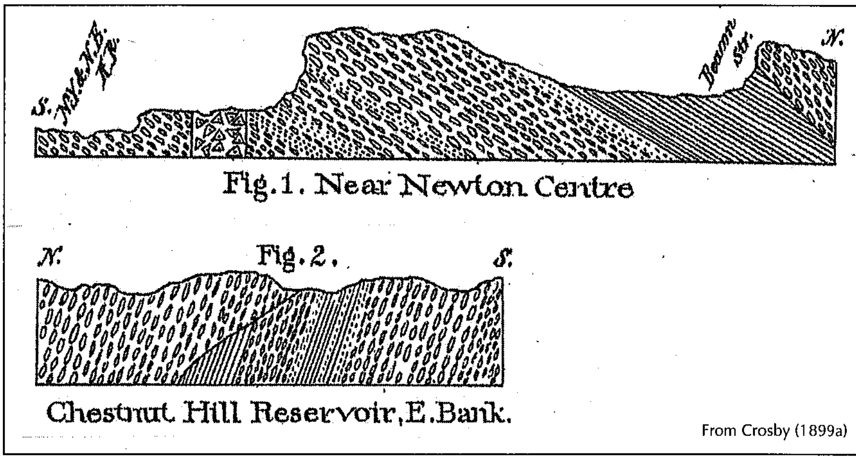


FIGURE 7-5. Sections through Beacon Street Tunnel of the Sudbury River Aqueduct (top) and east side of the Chestnut Reservoir (bottom) (view north).

Wachusett Aqueduct Tunnel. The 14.5 kilometer (9 mile) long Wachusett Aqueduct was built between 1897 and 1905 as the western part of a system to convey water from the Wachusett Reservoir to Boston. It lies near 91 meters (300 feet) elevation MSL and extends from the reservoir to a treatment plant at Walnut Hill in Marlborough (see Figure 7-7). The aqueduct consists of a rock tunnel, shallow cuts and even elevated portions crossing streams. The 3 kilometer (2 mile) bedrock portion carries water from the reservoir southeastward beneath the adjacent ridge that forms the border of the Nashua River Valley. The drill-and-blast tunnel has a minimum brick-lined height and width of 3.4 meters (11 feet) and 3.6 meters (12 feet), respectively, and included four shafts in its construction. The tunnel was dug between 1897 and 1899, and apparently was not greatly delayed by the faults and water inflows that were encountered.

The rock tunnel crosses a variety of faulted rock mapped by Crosby (1899a) from the edge of the Nashua Trough through the Clinton-Newbury Fault Zone and the northwestern part of the Nashoba Thrust Belt (see Figure 7-7). He mapped the faults, shear zones and dikes, as well as the lithology across this complex structural zone in some detail. His units can now be dated (Peck, 1976; Barosh 1977a & 2009). The northwestern end consists of slickensided phyllite and argillite of the Ordovician Worcester Group faulted against Proterozoic foliated porphyritic granite and minor Late Ordovician non-foliated granite, which in turn is faulted against an altered diorite stock. The eastern half of the tunnel passes through schist and gneiss of the Late Proterozoic Tadmuk Brook Schist and the Nashoba Formation with some Proterozoic muscovite granite, as well as pegmatite and dike rock. Most of the beds and the many faults strike northeast and dip moderately to steeply northwest, but a cen-

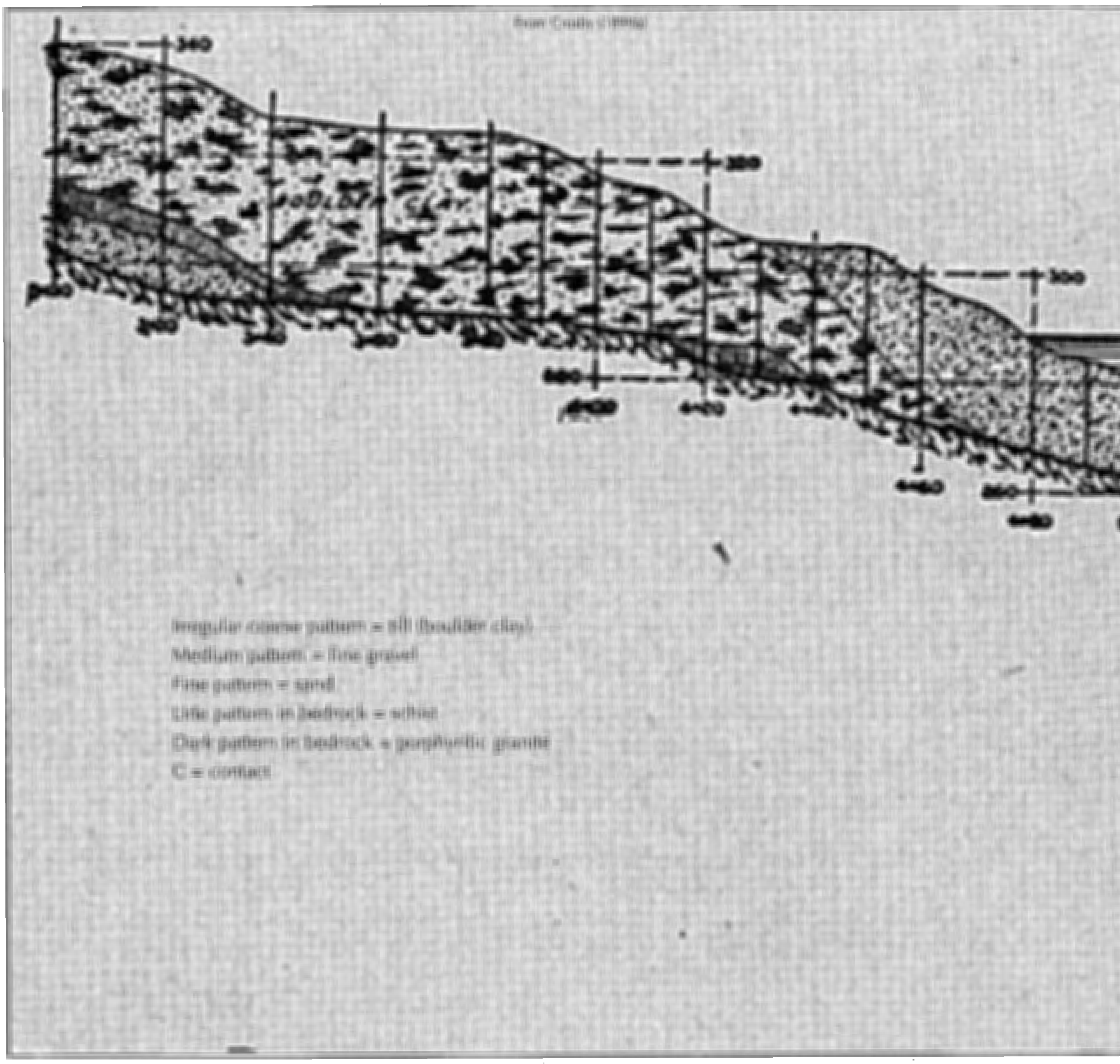


FIGURE 7-6. Surficial geologic section across the Nashua River Valley 24 meters (80 feet) south of the site of the Wachusett Dam, in Clinton, Massachusetts (view southwest). The overhanging buried bedrock cliff on the right side is due to erosion along the northwest-dipping Late Ordovician fault.

tral 1,220 meter (4,000 foot) long section is bent to a northwest strike with a steep northeast dip where it wraps around a faulted contact with the muscovite granite (Crosby, 1899a). Many of the faults encountered are water-bearing and the section beneath Clam Shell Pond is described as extremely wet. These sections, as well as other particularly faulted sections, of the tunnel were lined with brick masonry, including the entire section between Shafts 3 and 4. Crosby attributed the disintegration and kaolinization of the granite in these sections as due to the passage of water.

Weston Aqueduct Tunnels. Construction of the nearly 22.6 kilometer (14 mile) long Weston Aqueduct commenced in 1901 and it first carried water in December 1903. It

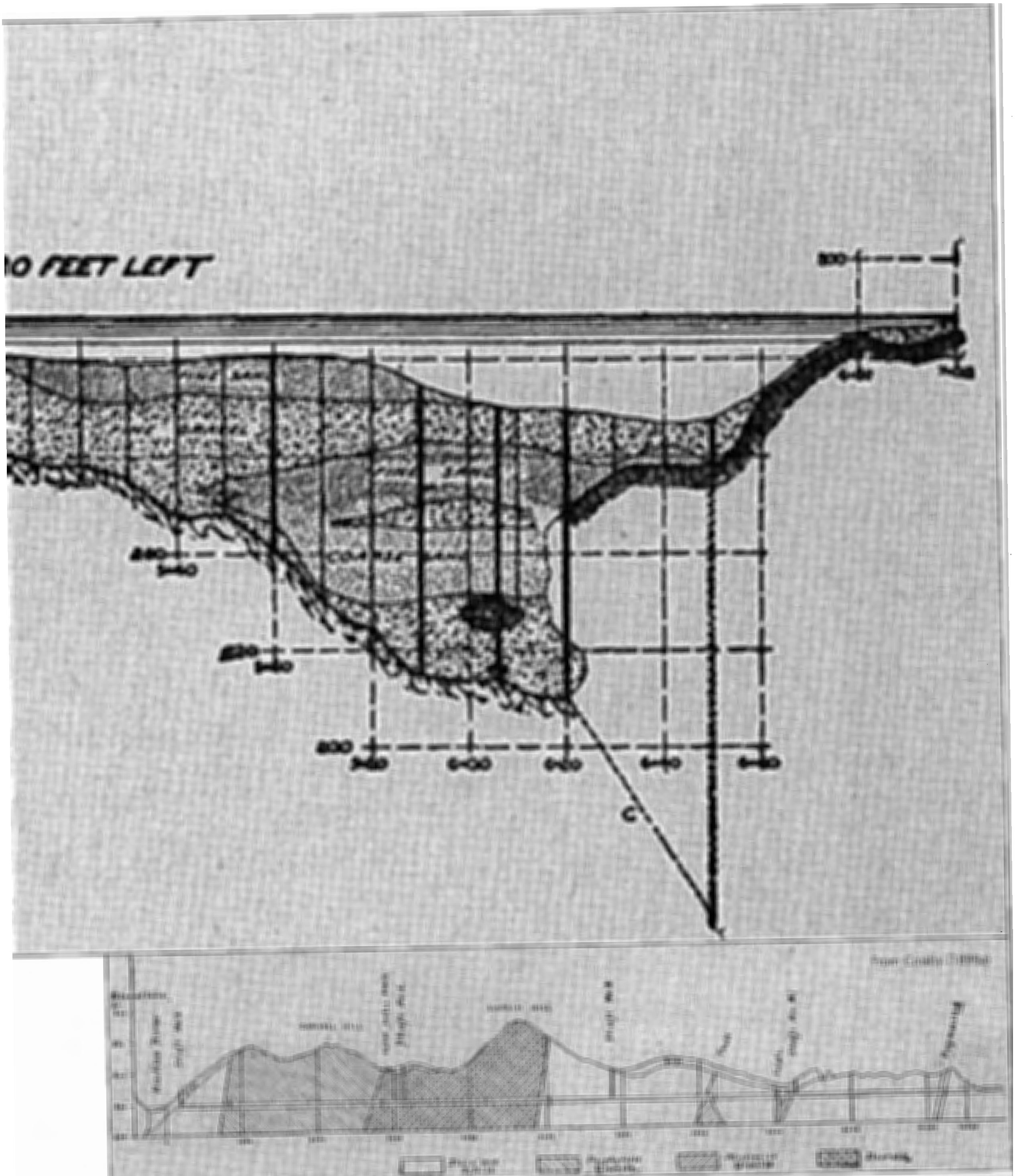


FIGURE 7-7. Simplified section of a portion of the Wachusett Aqueduct Tunnel showing general lithology (view northeast).

extends from the Sudbury Dam through the Weston Reservoir to the Terminal Chamber just west of the Charles River in Weston. Most of the aqueduct is in surficial material and it is

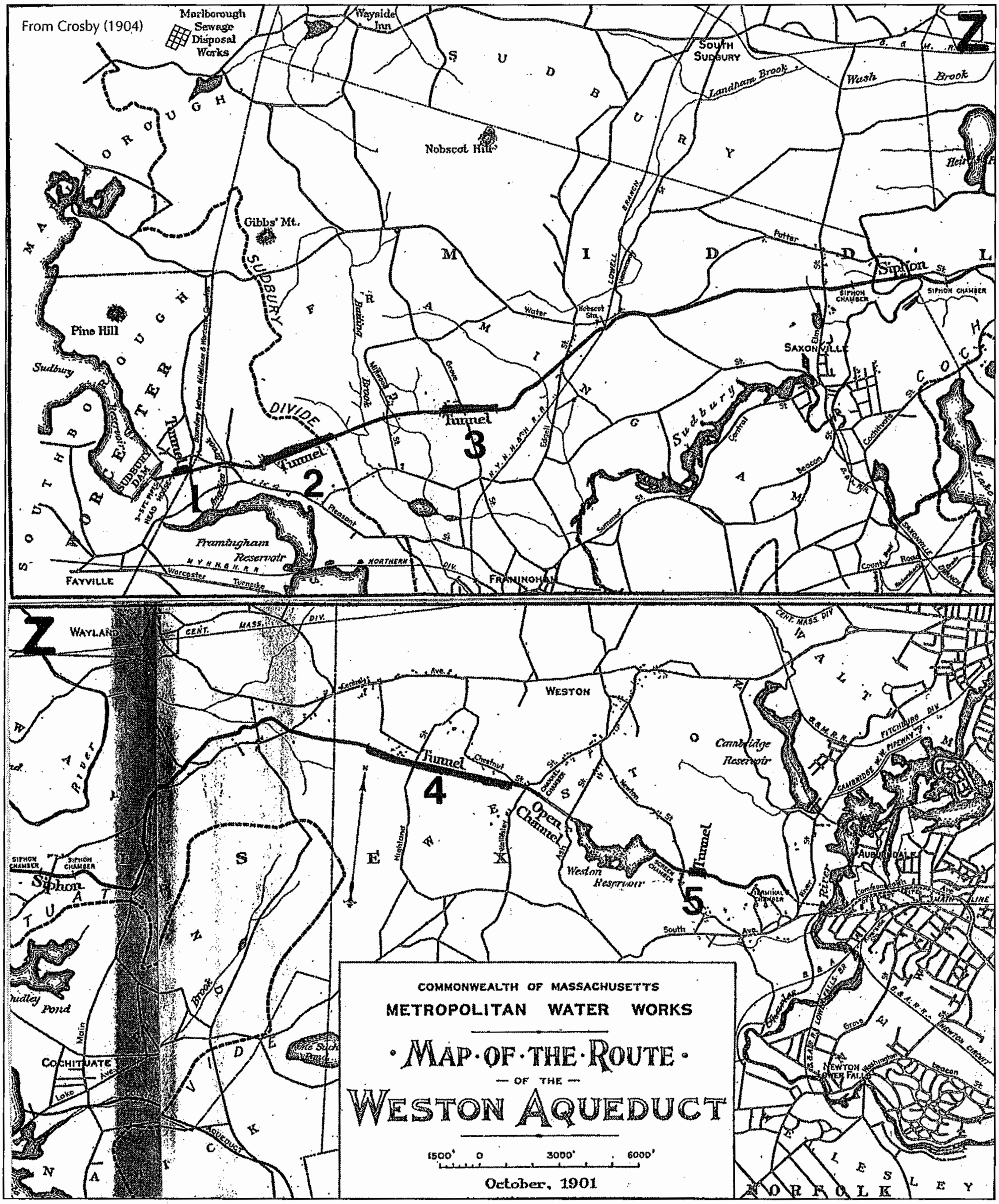


FIGURE 7-8. Map of the Weston Aqueduct Tunnel showing locations of the five tunnel segments.

partially a surface canal, but it includes five shallow tunnel sections where it pierces rock-cored drumlins (see Figure 7-8). These drumlins range from 183 to 1,734 meters (600 to 5,686 feet) in length and aggregate 3,709 meters (12,165 feet) and were drill-and-blast tunnels. They were mapped in some detail and described by W. O. Crosby (1904) and Warren (1904), who also described the mineralogy (MWSB, 1902). Three tunnels are near

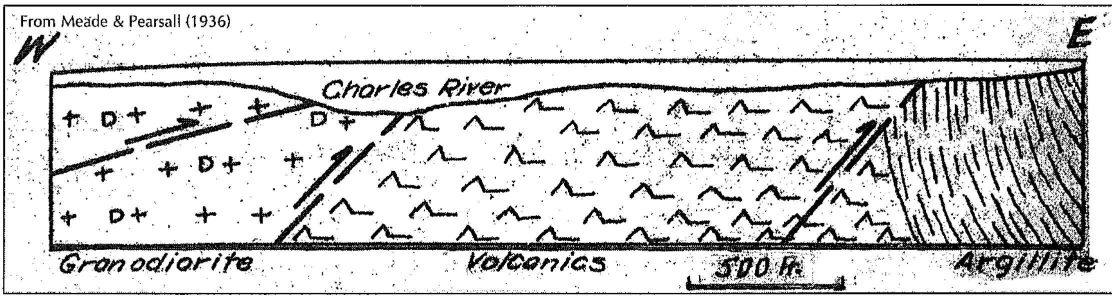


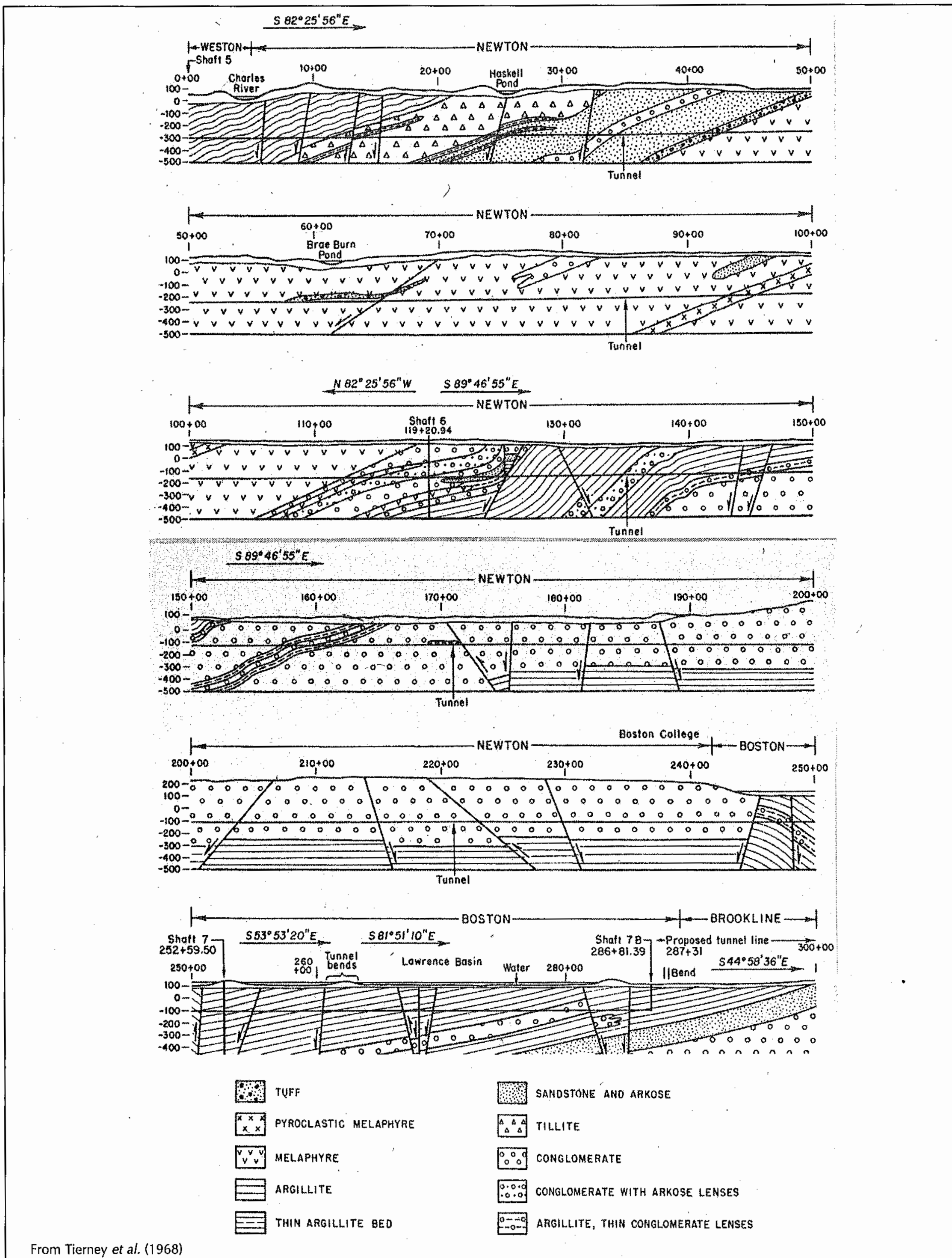
FIGURE 7-9. Section across the North Boundary Fault approximately 488 meters (1,600 feet) northwest of Shaft No. 5 at the west end of the City Tunnel.

the western end of the aqueduct and the other two on either side of the Weston Reservoir (see Figure 7-8). The 3 meter (10 foot) wide tunnels were lined with concrete masonry.

The first tunnel, a short distance east of the Sudbury Dam, passes through drumlin till that contains contorted stratified clay in its western end. This condition indicates a re-advance that thrust and contorted the clay (Crosby, 1904). The other tunnels skirt the northern, moderately north-dipping border zone of the Northbridge Granite and, at the east end, Dedham Granodiorite and intersect foliated granitic rock and related aplite along with pendants of quartzite and some mica schist of the Westboro (Plainfield) Formation. A younger diorite intrudes east of the Weston Reservoir (Crosby, 1904; Barosh, 2005). The tunnels also cross varying amounts of two sets of diabase dikes, which were up to 4.5 meters (15 feet) or more in thickness. An older dike set is east-west to northeast striking, north-dipping, about parallel to the foliation and consists of both hornblende and biotite varieties, which are sometimes altered to greenstone (Warren, 1904). A younger north-south, near-vertical dike set is much fresher and commonly displays columnar jointing. However, some dikes of the later set were kaolinized in the western tunnels. The main granite body is generally pink, but some deeper parts are gray, indicating that the color is due to later alteration, which apparently affected the east-west basic dikes as well.

The other two western tunnels farther east of the dam cross the Northbridge Granite and basic dikes. The tunnels to either side of the Weston Reservoir (along with the rock formerly exposed on the reservoir floor and adjacent to the eastern end of the aqueduct) display a long section of the granite border zone with scattered remnants of quartzite and intrusions of diorite and a few pegmatite dikes. Fewer basic dikes are present to the east where only rare north-south dikes occur. Some faults are noted near the east end, and slickensides are noted on the sides of various dike and quartz veins.

City Tunnel. The City Tunnel extends 7,701 meters (25,260 feet) from a connection with the Hultman Aqueduct on the west side of the Charles River in Weston eastward to the Chestnut Hill Reservoir in Boston (see Figures 7-1 & 7-2). A branch tunnel extends a further 1,043 meters (3,422 feet) southeasterly from the east end of the City Tunnel to the Chestnut Hill Pumping Station. The tunnel slopes upward from elevation –97 meters (–318 feet) MSL at the Charles River end to elevation –32 meters (–106 feet) MSL at Chestnut Hill. It was constructed by drill and blast, and completed in 1951 with an inside lined diameter of 3.7 meters (12 feet) for the main tunnel and 3 meters (10 feet) for the branch line. The tunnel extends eastward from the western border fault zone of the Boston Basin and traverses fault blocks of Cambridge Argillite and Roxbury Conglomerate (see Figures 7-9 & 7-10), which include a thick section of the Brighton Basalt (Melaphyre) (Tierney, 1950a & 1950b; Nelson, 1975a; Kaye, 1982a). These blocks are cut by numerous steep dikes of diabase, felsite and basalt to andesite that occur chiefly near fault zones and mostly strike to the northeast. The western half of the tunnel east of the Cambridge Argillite is in Late



From Tierney *et al.* (1968)

FIGURE 7-10. Simplified section (Stations 0+00 to 300+00, view north) of the west end of the City Tunnel that shows the general lithology and some of the faults, which have interpreted minimal offsets. The dikes are omitted.

Proterozoic rock composed of interbedded units of conglomerate, arkosic sandstone, sandstone, argillite and some tuff, along with a thick unit of basalt. The basalt appears to be mainly extrusive flows, encapsulating one flow of felsite, and is capped by tuff. However, some later bodies have intrusive characteristics. This section strikes northeast and has shallow to moderate northwest dips. The rest of the tunnel, except for the east end, was excavated through conglomerate that appears to strike east-west and dip moderately to the north. The east end and southeast extension to the pumping station are predominantly in moderately north-dipping Cambridge Argillite, which is apparently the west end of an overridden fault block that widens to the east (Kaye, 1980a).

Seventy-four large faults were mapped in the two tunnels (Tierney *et al.*, 1968). These faults fall into three strike trends. More than half strike to the northeast, but almost as many strike to the north, and several strike to the northwest. The majority have steep to very steep dips. Twenty-nine of the faults have gouge or breccia zones or both, which range in thickness from a smear to 3.4 meters (11 feet), and composite zones to 15 meters (50 feet) in width, but average 1 meter (3 feet) (Tierney, 1950a & 1950b; Billings, 1967). Along sixteen faults, the fault-trace separation ranges from several centimeters to 3 meters (few inches to 10 feet), averaging 1 meter (3 feet). Along six faults, it exceeded 3.7 meters (12 feet), the height of the tunnel. Along fifty-two faults, a precise determination was not possible, but in thirty-six cases the fault-trace separation was certainly only several centimeters to a meter or less (few inches or feet). Breccia and gouge along sixteen of the fifty-two faults suggest the possibility of greater movement. The majority of the faults show strike-slip offset with gouge zones; whereas many of the others are normal, cleanly sheared faults. The faults are expressed in the surface topography, despite the surficial cover, and evidence for several faults is found above the tunnel (Tierney, 1950a). A cluster of faults cut the east end of the tunnel near the Chestnut Hill Reservoir (Tierney, 1950a & 1950b). These faults consist of very steep north-trending faults and near-vertical northeast-trending faults. A group of large faults form the western border zone of the Boston Basin against the Dedham Granodiorite in Weston. These faults strike about N25° to 35°E and dip roughly 50°W, but one within the granodiorite dips only 10° to 15°W. Most reach the surface beneath the Charles River Valley (Meade & Pearsall, 1936; Tierney, 1950a). The adjacent argillite is broken into a series of fault blocks and the underlying conglomerate shows numerous horizontal faults (Tierney, 1950a). The border zone also was penetrated by the MetroWest Tunnel.

No ground support was needed in the approximately 2,134 meters (7,000 feet) of andesite found, nor in the approximately 457 meters (1,500 feet) of sandstone exposed in the western part of the City Tunnel (Tierney, 1950a & 1950b; Tierney *et al.*, 1968; Kaye, 1979). Only 4.8 meters (16 feet), or 0.05 percent of the entire tunnel, is supported by structural steel, which is placed at a fault zone in the argillite at the east end of the tunnel and no rock bolts were employed (Tierney, 1950a & 1950b; Billings, 1967).

City Tunnel Extension. The 11,436 meter (37,511 foot) long City Tunnel Extension extends from the City Tunnel at Chestnut Hill Reservoir northeastward to the town of Malden (see Figure 7-11). It slopes downhill from elevation –32 meters (–106 feet) MSL at Chestnut Hill to elevation –116 meters (–381 feet) MSL at Shaft 8 near the Charles River and thence to –121 meters (–396 feet) MSL at Shaft 9 at the Mystic River and from there upward to elevation –111 meters (–364 feet) MSL at its northeast end. The tunnel was dug by drill and blast to a 4 meter (13.5 foot) diameter and lined with concrete to a 3 meter (10 foot) diameter. It was constructed over six years from September 1951 to March 1956 and put into service in 1961.

The City Tunnel Extension passes through two different stratigraphic sequences (MDC, 1953; Billings & Tierney, 1961 & 1964). It crosses interbedded conglomerate, sandstone, argillite and tuff of the Roxbury Conglomerate, which is cut by dikes and bodies of the Brighton Basalt (Melaphyre) southwest of the Charles River

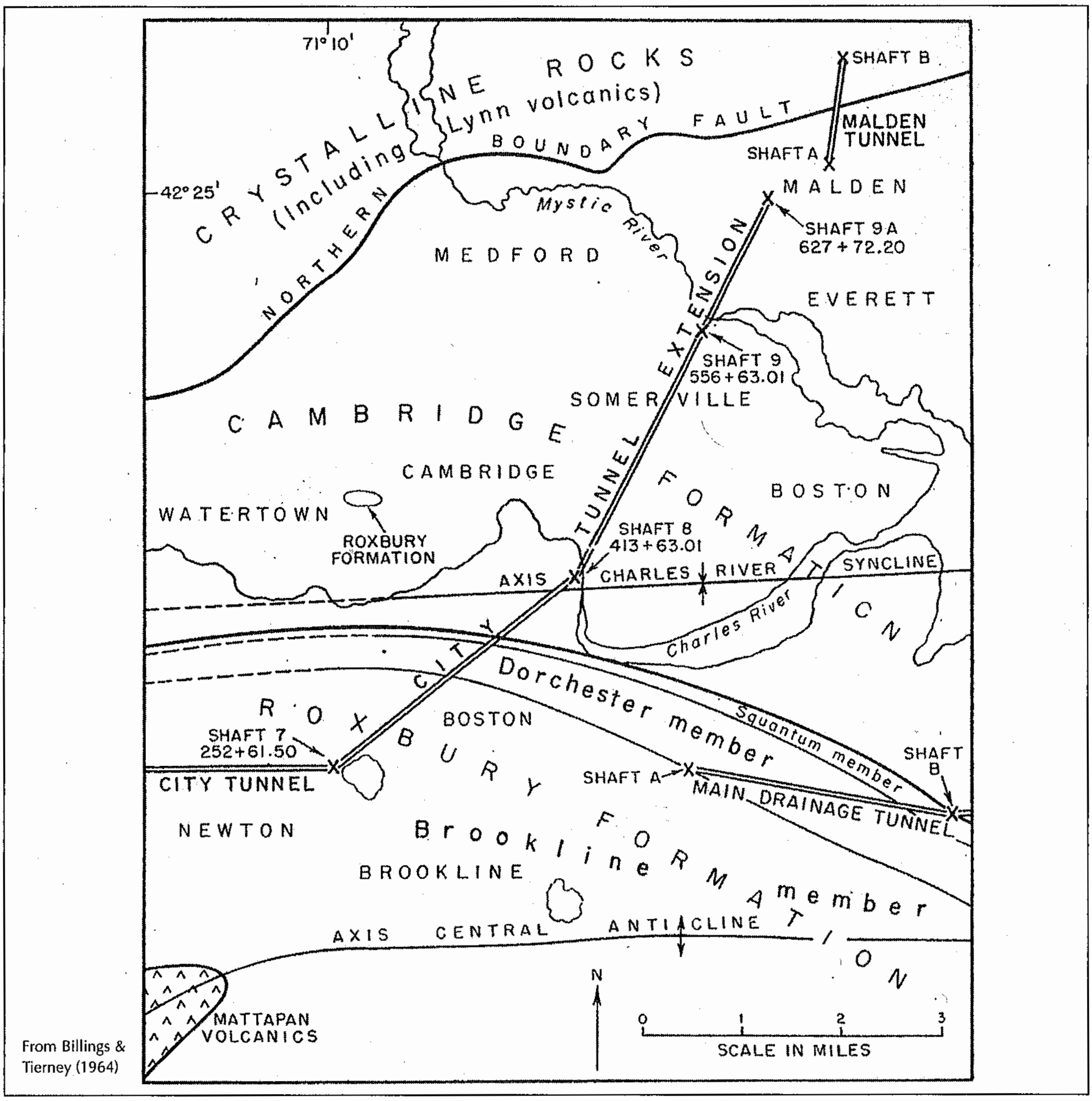
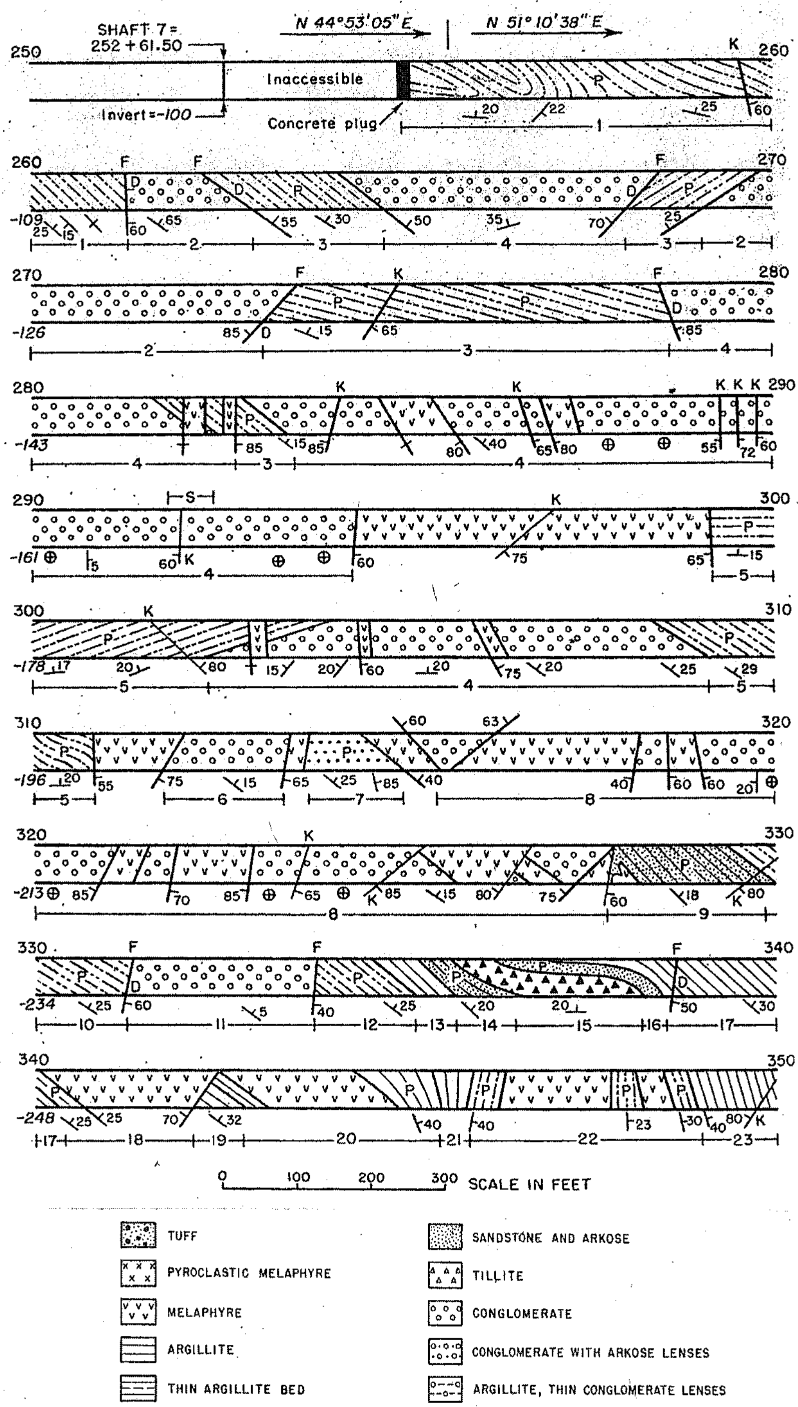


FIGURE 7-11. Map showing the location and shafts of City Tunnel Extension and hypothetical basin structure.

(see Figure 7-12). The beds strike east to northeast and dip gently to the northwest, mostly 5 to 20 degrees, but steepen to 40 degrees at the northwest end. Northeast of the river is a thick sequence of the Cambridge Argillite with some interbeds of sandstone and tuff, a sequence that is seen to continue northward to the Northern Border Fault in the Malden Tunnel. The southwestern portion generally has an east-west strike, but this strike varies from northwest to northeast. Both parts have variable moderate dips to the south, but with many contorted intervals. Both sequences are cut by numerous altered and unaltered diabase dikes. Billings and Tierney (1964) proposed that the two sequences were equivalent, having undergone abrupt facies changes, and that a synclinal axis along the Charles River separates them (see Figures 3-56 & 7-11). However, the abrupt differences in the diagram portraying this change (along with the difference in thicknesses) demonstrates that the sequences are entirely different and



From Billings & Tierney (1964)

FIGURE 7-12. Tunnel map of the faulted southern quarter of the City Tunnel Extension. Horizontal map projection with the bottom of each strip being the southeast wall of tunnel and the top edge being 15 meters (50 feet) northwest of the southeast wall. Section through the Roxbury Conglomerate and Brighton Basalt.

that they are separated by a large fault along the river, the Charles River Fault.

A total of 220 faults, including those called shears, were measured (Billings & Tierney (1961 & 1964), but this number did not include the faults followed by the 298 dikes and sills. Other faults probably lie within what is mapped as shale. South of the Charles River Fault, the most common orientations are N45°W, with an average dip of 60 degrees northeast, and N25°E, with steep dips to the southeast or northwest. North of the Charles River Fault, the faults are concentrated into four groups:

- N40°E strike and dipping 50 to 90 degrees northwest;
- N60°W strike and dipping moderately to steeply either northeast or southwest;
- N10°E strike and dipping steeply southeast; and,
- N60°E through east to N45°W strike and dipping steeply both north and south.

The last group is shown mainly by dikes, which generally follow faults. An attitude of N45°W with a 60 degree dip to the northeast also is a common dike trend. The faults range in observed length from 1 meter or so (approximately 3 feet) to a maximum of 82 meters (271 feet) and the actual lengths are always greater (Billings, 1967). Most of the faults are sharp, tight fractures several centimeters (few inches) or less in width; only a dozen exceed 30 centimeters (1 foot) in width and the maximum width of shearing is 1 meter (3 feet). In at least eight instances, several faults were close enough to form fault zones from 1.5 to 59 meters (5 to 194 feet) wide. Twenty-one of the faults contained gouge or breccia or both that ranged in thickness from a smear to 1 meter (3 feet). Of the 220 faults, 114 were characterized by finely sheared, foliated-looking (slaty) rock several centimeters to 30 centimeters (few inches to a foot) thick (Billings, 1967). The apparent fault offset measured on the tunnel walls along 84 percent of the fault traces showed separation of only a meter or so (few feet). The other 16 percent exceeded 3.7 meters (12 feet), the height of the tunnel. Slickensides, which were recorded along fifty faults, show oblique offset with an average dip on the fault face of about 45 degrees.

The Roxbury Conglomerate is shown to be offset primarily by normal faults, which strike both east-west and northwest and chiefly dip to the north. Where offset was measured by Billings and Tierney (1964), the great majority of all the faults were normal, and the east-west trending diabase dikes in both sequences appear to be following normal faults as well. These faults drop off in number to the north where the relatively few reverse faults become noticeable. A few of the faults in the northeastern part of the argillite are north-dipping thrusts, related to the Northern Boundary Fault, and have associated drag folds. Some other contortions in the argillite are probably related to this movement, with or without faults, and others are apparently drag folds against other types of faults, but a few would be large slumps as seen in other tunnels. The greatest concentration of axes of these small folds plunge 8°N87°E parallel to the basin faults. The major east-west trending fault along the Charles River would be a normal fault that dropped the Cambridge Argillite down to the north. This movement would have rotated the argillite to dip southward into the conglomerate.

Structural steel support with very few rock bolts was used along 634 linear meters (2,103 feet), which is 5.6 percent of the tunnel. Seventy-six percent of this support was necessitated by the presence of weak shale and argillite, or by badly fractured dike rock. Twenty-four percent — equal to 152 meters (498 feet) of this support — was related to faults and of this amount 29 meters (94 feet) of reinforcement was necessitated by faults striking across the tunnel and dipping 25 degrees north-northeast along with closely spaced joints. Support in 123 meters (404 feet) was necessitated mainly by steep shear planes striking nearly parallel to the tunnel, and by a few dikes. However, there are many faults, including some striking parallel to the tunnel alignment, that did not necessitate support. Only twelve of the recorded 220 faults were present in areas that needed support. The shale units required structural steel as did two short sections of sandstone where Billings and

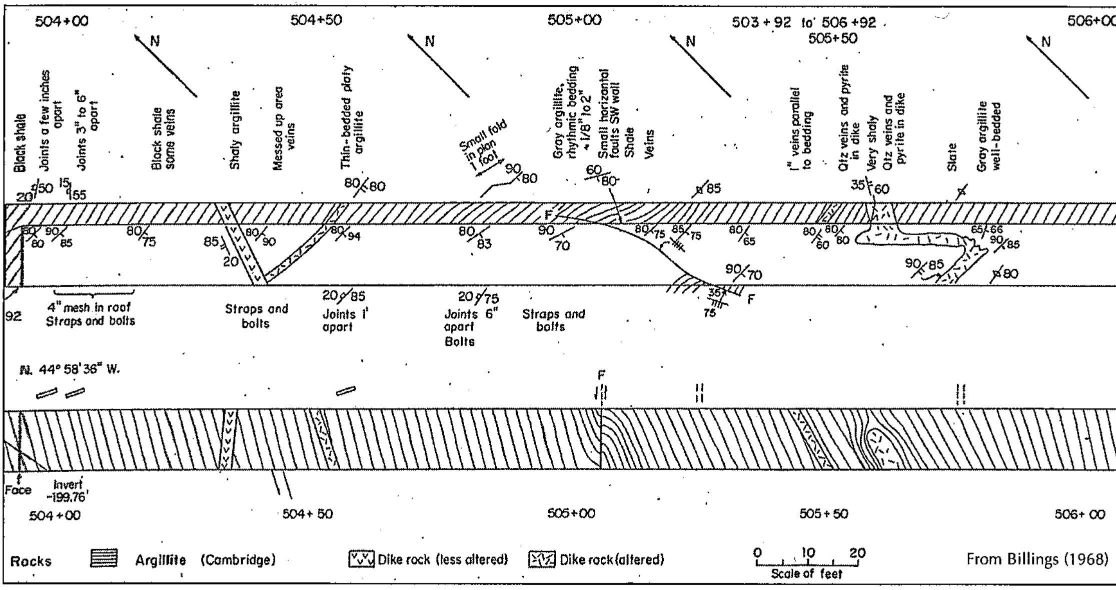


FIGURE 7-13. A portion of the Dorchester Tunnel in the Cambridge Argillite showing the northeast wall of the tunnel in section (lower part) and map (upper part) views (view northeast).

Tierney (1964) noted that "excessive splitting parallel to the bedding or to closely spaced joints" were present. A buff-colored sideritic tuff bed found interbedded with the shale is largely altered to kaolinite and also forms a weak unit. Only 17 meters (56 feet) in the Roxbury Conglomerate and its associated dikes needed support.

Dorchester Tunnel. The Dorchester Tunnel, which is part of the high-pressure 1,379 kilonewton per square meter (200 pounds per square inch) water supply to the southern greater Boston area, was constructed between 1968 and 1974. It extends southeastward about 10.5 kilometers (6.5 miles) from the Chestnut Hill Reservoir, where it connects with the City Tunnel supply, to Dorchester Lower Mills on the Neponset River estuary (see Figure 7-1). The tunnel slopes from approximately elevation –30 meters (–100 feet) MSL at Shaft 7B in Chestnut Hill to elevation –64 meters (–210 feet) MSL at Shaft 7D in Dorchester. The tunnel is circular in cross-section, and is lined with 0.3 meters (1 foot) or more of unreinforced concrete to provide a 3 meter (10 foot) finished internal diameter. The tunnel was excavated entirely in bedrock by traditional drill-and-blast methods except in the section extending about 2,110 meters (4,000 feet) from near Shaft 7C where an Alkirk tunnel boring machine (TBM) was used (Ashenden, 1982). The TBM was activated in argillite about 91 meters (300 feet) southeast of the shaft, but when the TBM crossed the Squantum Head Fault and passed into the Mattapan volcanic rock, it was unable to excavate the rock satisfactorily, and was removed from the tunnel. Traditional drill-and-blast excavation was then used to complete the tunnel to the shaft at Dorchester Lower Mills (Ashenden, 1982).

A short section of the tunnel was first mapped near Shaft 7A by Billings (1968), who showed lithology but little structure. Mapping was then completed by Richardson (1977). The tunnel is mostly in conglomerate, pebbly mudstone and argillite of the Boston Basin (see Figure 7-13). In addition, the tunnel passes through the Mattapan Volcanic Complex just southeast of the Squantum Head Fault of LaForge (1932), which Billings (1976a) called the Mount Hope Fault. The Dorchester Tunnel pierces the entire width of the original Roxbury Conglomerate outcrop line from Brookline, through Jamaica Plain, to Roxbury. About thirteen percent of the 6,310 meters (20,700 feet) of conglomerate traversed by the

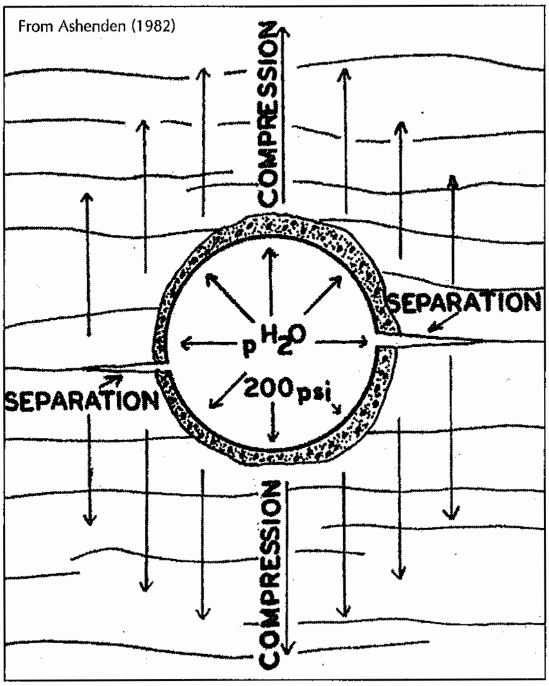


FIGURE 7-14. Section across the Dorchester Tunnel showing fractures along the spring line through which water escaped.

Dorchester Tunnel required steel support because of soft-rock alteration, which seems to be concentrated along a very wide fault zone (Ashenden, 1982; Richardson, 1977). About 884 meters (2,900 feet) of volcanic rock was pierced by the tunnel, of which 46 meters (150 feet) required steel supports necessitated by localized jointing. Closely-spaced joints, faults and the effects of a thick diabase dike and interbedded argillite are responsible for another two percent of supported rock.

Shortly after the tunnel was placed in service in November 1974, the basements of some homes in the overlying area became flooded. Tests performed by the Metropolitan District Commission (MDC) subsequently confirmed that the flooding was the result of hydraulic water pressure stemming from the Dorchester Tunnel. Inspection of the dewatered tunnel (Woodhouse, 1974) indicated that the lining was significantly cracked along the spring line, with major water flow occurring at two highly fractured locations between Stations 510 and 523 (see Figure 7-14). MDC engineers and the MDC's consultant, Haley & Aldrich, Inc., generally agreed that the internal water pressure in the tunnel was transmitted through the liner and caused compression of joints in the surrounding Cambridge Argillite (Dugan, 1982).

Following the investigations, plans and specifications were prepared for pressure grouting to repair the cracked lining from within the tunnel. Neat Type III Portland cement grout was used, with a maximum injection pressure of 2,758 kilonewtons per square meter (400 pounds per square inch). After grouting the primary stage holes, secondary stage grouting was undertaken at split spacing. Results of water pressure tests, grout take measured and subsequent core borings were used to evaluate the effectiveness of the grouting (Dugan, 1982). After the grouting was completed, a test section of the tunnel lining was instrumented in order to measure the behavior of the tunnel and adjacent argillite during repressurization. Instrumentation included diametric convergence meters, strain gauges, extensometers and piezometers. Over a period of six weeks, the tunnel was water tested under service pressures. In addition to the instrumentation readings, observation well measurements were made to observe the effect of water flow from the tunnel on groundwater levels in the area before the tunnel was drained, inspected and placed back into service. There have not been any subsequent reports of wet basements.

Cosgrove Tunnel. The Cosgrove Tunnel, also called the Cosgrove Aqueduct or Wachusett-Marlborough Tunnel, replaced the Wachusett Aqueduct when it came on line in 1965. It runs southeast 12,806 meters (42,004 feet) parallel to and deeper than the Wachusett Aqueduct to connect the Wachusett Reservoir to the Walnut Hill Water Treatment Plant in Marlboro, where it is now connected to the west end of the MetroWest Tunnel (see Figure 7-2). It descends and rises through shafts at either end and has one intermediate work shaft. The tunnel slopes upward from about elevation 9 meters (30 feet) MSL at the reservoir to elevation 18 meters (60 feet) MSL in Marlboro. It is the main conduit used to deliver water from the Wachusett Reservoir and has a capacity of 600 million gallons per day.

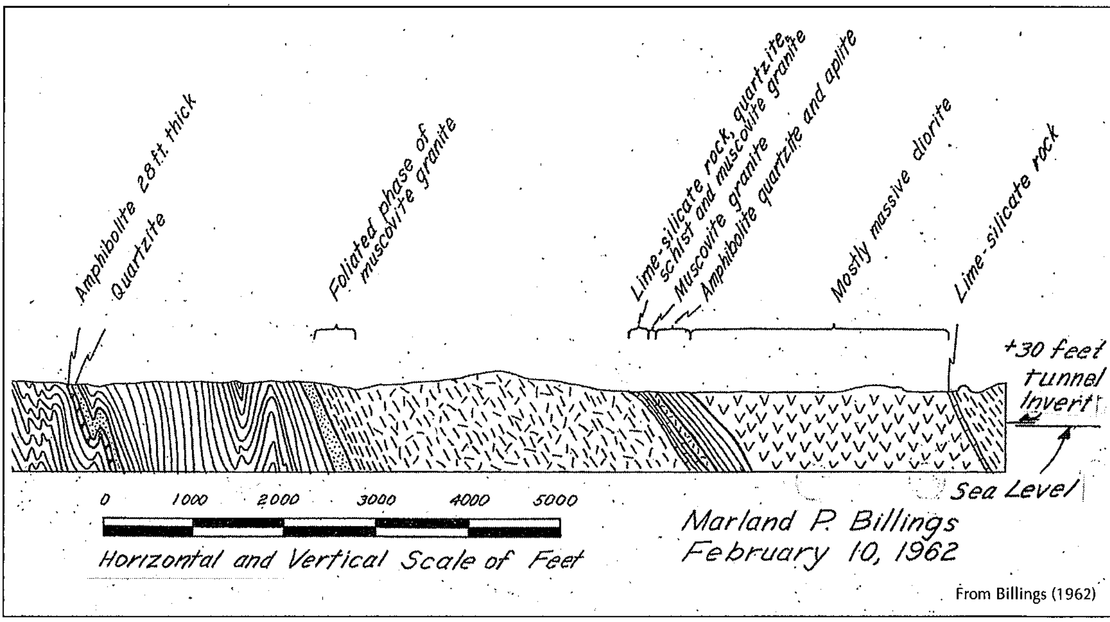


FIGURE 7-15. West end of the Cosgrove Tunnel adjacent to the Clinton-Newbury Fault Zone (view southwest).

The Cosgrove Tunnel crosses most of the Nashoba Thrust Belt. The northwestern portion of the tunnel crosses nearly the same lithologies and structure as the Wachusett Aqueduct Tunnel. These lithologies are the Late Proterozoic porphyritic Ayer Granite and muscovitic Chelmsford Granite, Late Ordovician medium-grained granite and coarse-grained Andover Granite, diorite, various other granite and dike rock, Tadmuk Brook Schist, gneiss and schist of the Nashoba Formation, and gneiss and amphibolite of the Marlboro Formation (Crosby, 1899a; Billings, 1962; Bell & Alvord, 1976; Abu-moustafa, 1969; Skehan, 1964 & 1967; Skehan & Abu-moustafa, 1976; Peck, 1976; Barosh, 1978a & 1978b).

Billings (1962) reviewed the results of exploratory borings along the proposed tunnel alignment and depicted northwest dipping rock units at 1:12,000 scale, but no faults. He only noted that numerous small faults and shears are present, despite Crosby's (1899a) mapping of large faults in the adjacent Wachusett Tunnel (see Figure 7-15). Skehan (1964 & 1967), Abu-moustafa (1969) and others added much more stratigraphic and structural detail with data gathered during the construction while under the general guidance of L.R. Page of the USGS. This mapping recorded great numbers of generally small steeply northwest-dipping faults striking northeast about parallel to that of the strata.

In addition, there are many large faults that are summarized below from Skehan and Abu-moustafa (1976). Several intensely deformed and fractured thrust and reverse fault zones are present. The Clinton-Newbury Fault Zone, which strikes N40°E and dips 35°NW, is the largest and several other major, more steeply dipping zones stand out. Many have associated drag folds. Many later normal faults also are present. These faults trend chiefly to the northeast and dip steeply in either direction, but several dip moderately to the northwest. A set of northwest-trending steeply dipping faults spaced a few hundred meters (several hundred feet) apart form the youngest faults, perhaps late Mesozoic in age (Barosh, 1990a). Several are known to have left-lateral offset. These extensional faults typically contain quartz, calcite, some barite and sulfide minerals as veins.

MetroWest Tunnel. The 28.2 kilometer (17.6 mile) MetroWest Water Supply Tunnel was constructed from Marlborough to Weston through mostly Late Proterozoic crystalline

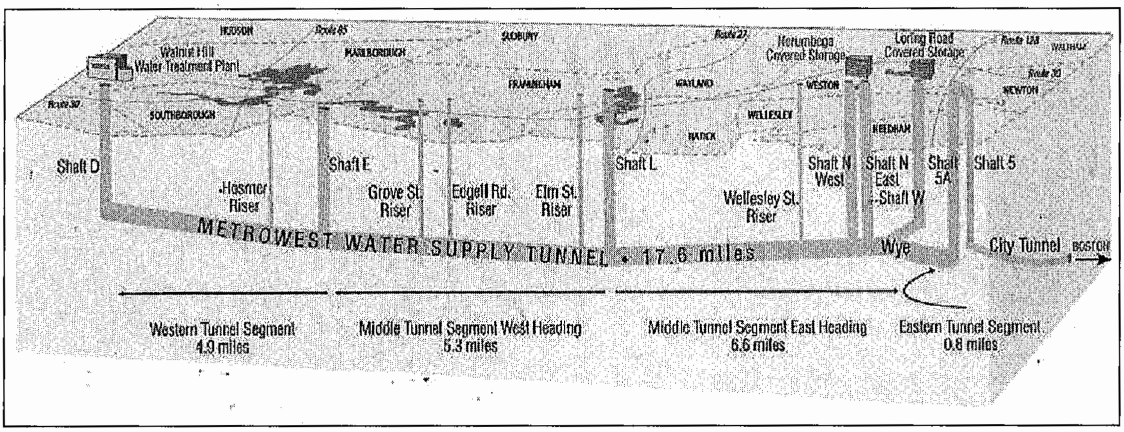


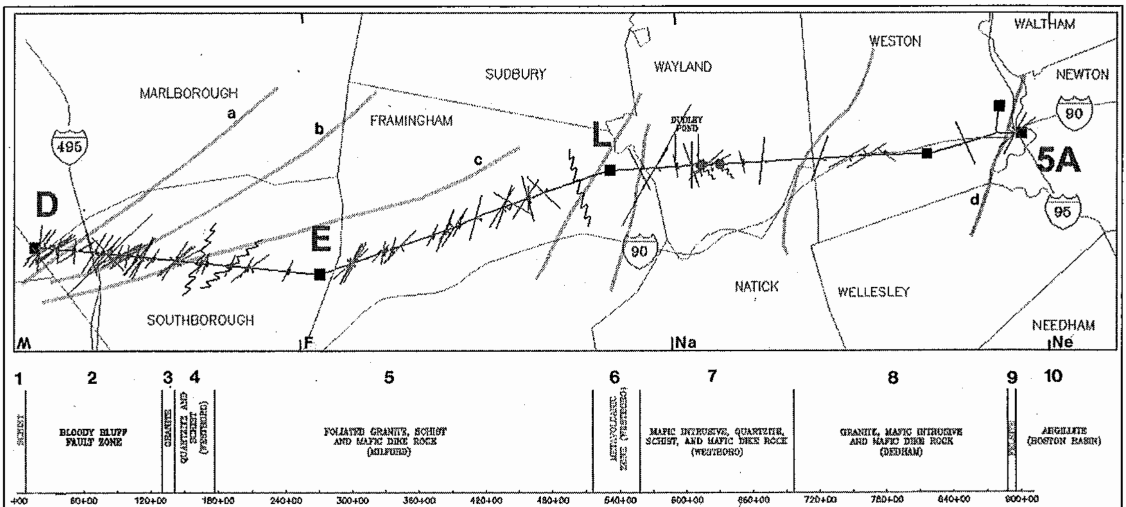
FIGURE 7-16. MetroWest water system. (Courtesy of the MWRA.)

rock to replace the aging and leaking Weston and Hultman aqueducts (see Figures 7-2, 7-16 & 7-17). This tunnel was the principal part of an estimated $665 million project that also included a renovation of the Fayville Dam, which holds the Sudbury Reservoir. Exploration for the tunnel included seismic refraction, very low frequency (VLF), down-hole geophysics, surface mapping and forty-three borings 213 meters (700 feet) or more deep (Carnevale & Hager, 2001). Conventional drill-and-blast methods were used for the six shafts, and three TBMs bored the 4.9 meter (16 foot) diameter tunnel, which was then lined with concrete before being put into service. The tunnel depths reached are on the order of 61 to 137 meters (200 to 450 feet). Ground was broken in 1996, tunnel excavation was completed in October 2000 and water was turned on in November 2004.

The tunnel extends westward from the western edge of the Boston Basin fill across the batholithic granite and xenoliths and into metasedimentary rock and granite of the Nashoba Terrane. The easternmost section includes five major rock types in fault contact consisting of laminated sandstone, siltstone and shale of the Cambridge Argillite (see Figure 3-61). The beds have a northeast strike and dip northwest and locally show gentle open folds plunging northwest. To the west, across the Boston Basin Fault, is the foliated Dedham Granodiorite (see Figure 7-17) with gently dipping shears, foliation and large tabular bodies of mafic intrusive rock apparently associated with the Salem Gabbro-diorite. Farther west are xenoliths and large blocks of the Westboro (Plainfield) Formation characterized by intensely sheared laminated quartzite and quartz schist and still farther west are some remnants of the overlying Middlesex Fells Volcanic Complex (Bell & Alvord, 1976) that had been called the Cherry Brook by Nelson (1974).

From Framingham to Marlborough, the predominant batholithic rock is the Northbridge Granite (mistakenly called Milford Granite by Nelson [1975a & 1975b; Barosh, 2005]), a slightly porphyritic foliated quartz monzonite with assimilated quartzite and chlorite schist of the Westboro, as well as patches of probable Middlesex Fells. The granite varies from coarse- to fine-grained and has an aplitic border preserved in places. Its composition changes locally depending on the degree of assimilation of the intruded strata. At the western edge is an intrusive complex of granite and granodiorite, with chlorite schist inclusions and altered mafic rock.

The tunnel crosses a broad complex contact zone of the batholithic granite with the country rock to the northwest that has been repeatedly faulted from the Late Proterozoic to the late Mesozoic. The foliation of the granite and lamination and bedding of the strata have a northwest to north dip and have been followed by intense shearing and local mylonitization along paralleling faults, which locally have reactivated later to produce minor amounts of gouge and breccia (Barosh, 2005). Branches of the northeast-trending, steeply



M = Marlboro quadrangle (Barosh, 1978)
F = Framingham quadrangle (Nelson, 1975b)
Na = Natick quadrangle (Nelson, 1975a)
Ne = Newton quadrangle (Kaye, 1980)
1 = gneiss of the Marlboro Formation
2 = mixture of Ordovician (?) granodiorite & Ordovician Salem Gabbro-diorite west of East Branch of the Bloody Bluff Fault & quartzite & quartz schist of Plainfield (Westboro) Formation & Northbridge Granite & aplite, east of the East Branch
3 = Northbridge Granite & aplite
4 = quartzite & quartz schist of the Plainfield (Westboro) Formation & minor Northbridge Granite & aplite & diabase dikes
5 = Northbridge Granite & aplite, quartzite & quartz schist of the Plainfield (Westboro) Formation, Salem Gabbro-diorite & diabase dikes
6 = amygdaloidal lava, volcaniclastic sandstone, crystal tuff & hornblende schist of the Middlesex Fells Volcanic Complex
7 = quartzite & schist of the Plainfield (Westboro) Formation, gneiss & quartzite of the Rice Gneiss below, Salem Gabbro-diorite & diabase dikes
8 = Dedham Granodiorite, & diabase dikes
9 = felsite of Mattapan Volcanic Complex (?)
10 = Cambridge Argillite;
a = West Branch of the Bloody Bluff Fault
b = East Branch of the Bloody Bluff Fault
c = Weston Fault
d = North Boundary Fault of the Boston Basin

Symbols
Plain line = fault
Line with box = prominent joint set
Wavy line = shear zone
Long faint line = major fault

Modified from Carnevale *et al.* (2001)

FIGURE 7-17. Generalized geology along the MetroWest Tunnel.

northwest-dipping Bloody Bluff Fault Zone (as well as other faults and shears) are high angle and dip to the southeast and cut the rock along with many relatively small north and northwest-trending faults. A set of significant east-west trending faults extend from the Boston Basin across the area (Barosh, 1977a).

West of the main Bloody Bluff Fault Zone (Barosh, 1984b) are granites with northwest-trending regional foliation and nonfoliated ones. These rocks are most likely the Assabet Quartz Diorite and Andover Granite, respectively, but other granite bodies might be represented as well as remnants of the Nashoba Formation. The rock has little evidence of folding and is highly fractured with relatively narrow fault-defined zones of several sets having been mapped both in the tunnel and on the surface (Carnevale & Barosh, 2001). Zones of water inflow and weak rock that is several feet to a few hundred feet wide are associated with faults and shear zones, especially at their intersections, and with adjacent hydrothermally altered rock. These zones also may cause local unstable areas. Relatively few exploration borings were made for the tunnel, and the tunnel alignment fortunately missed one of the major east-west trending faults in the area that run nearly parallel to the tunnel alignment and could have caused serious problems. A special system was set up to manage the data recorded in detailed mapping of the complex geology encountered (Carnevale *et al.*, 2001).

Sewage Removal, Disposal & Treatment

The environmental problems created from

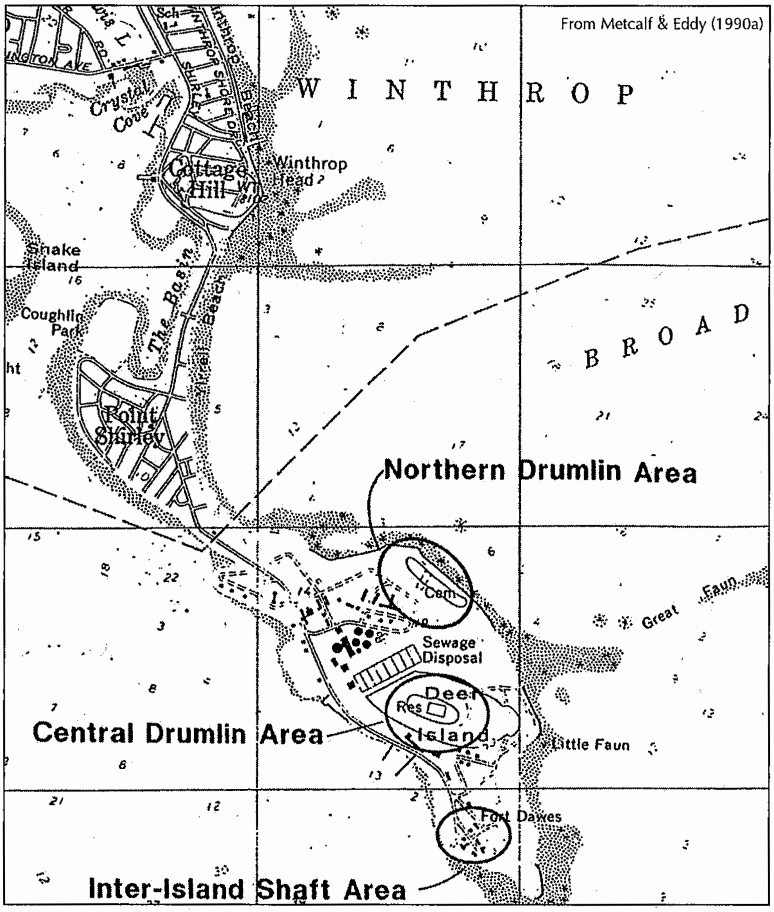
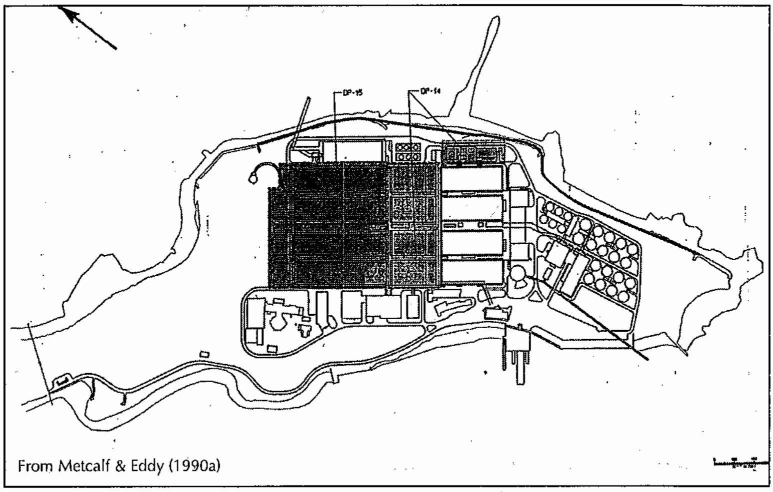


FIGURE 7-18. Deer Island showing location of drumlins and shaft for the Inter-Island Tunnel.

wastewater resulted in Boston becoming the leader in city-wide water and sewer drainage systems in the nineteenth century. Boston also led the nation in developing a structured solid waste program in conjunction with these systems. However, those once-innovative systems became outmoded and deficient as decades passed. In recent years, both new and future laws regulating the operation of these systems have resulted in an ever-changing need for enlarging these drainage systems. In addition, new state and federal regulatory statutes have had a significant impact on the treatment of the environmental problems in the metropolitan Boston area. The multi-billion dollar Deer Island Treatment Plant and Outfall Tunnel were constructed under the direction of the MWRA (see Figures 7-18 & 7-19) in responding to the 1985 court-ordered mandate to clean up Boston Harbor.

The wastewater management in the greater Boston area is not unlike that of other communities of similar age. A sanitary sewer system evolved in concert with the development of the city and its environs, and like many coastal cities, Boston first dumped its sewage farther and farther off shore. At first, sewers flowed into mudflats and other tidal areas. The tidal flats of the Charles River in the Back Bay became so polluted and offensive to the city fathers that the area was filled in during the latter half of the nineteenth century. The need for a sewer system to serve the entire city was emphasized in a mid-nineteenth century report from the Consulting Physicians of the City of Boston, who recommended a plan that would "carry the sewerage out so far at sea that point of discharge will be remote from dwellings, and beyond the possibility of doing harm to the citizenry" (Whitehill, 1968).

The 1875 plan called for two main drainage systems: one to serve the area north of the Charles River and one to serve the area south of it. Both systems were to collect and then discharge untreated sewage into the ocean on the outgoing tide. The southerly system, termed the Boston Main Drainage System, was constructed first and was placed into operation in 1885. It discharged into Boston Harbor at Moon Island. Key components in the city were the East and West Side Interceptor sewers. The North Metropolitan Sewer District was created to serve the northern area and was placed into operation in 1895, with its discharge into Broad Sound



From Metcalf & Eddy (1990a)

FIGURE 7-19. Layout of the Deer Island Sewage Treatment Plant as proposed.

from Deer Island, near the Town of Winthrop. In the same year, both districts were united into one administration, called the Metropolitan Sewer District (MSD) which served eighteen cities and towns. This tidal disposal process, while being state-of-the-art at the time, was only about half effective in that the subsequent incoming tide would return a good portion of the discharge back into the harbor. A scum developed on the outer harbor water that made Boston a very undesirable port.

By 1904 the MSD had expanded and constructed another flow release point at Nut Island. The Nut Island Plant was to serve additional southern and western towns, which were accepted into the system. In 1907, new regulations were formulated that prohibited the construction of combined sewer systems. Subsequent systems were to be separated so they could be discharged separately into the bay. In 1910, a new treatment plant was constructed at Deer Island for better waste dispersion. The MDC was established in 1919, to be later replaced by the above-mentioned MWRA in 1986. Under the 1994 Combined Sewer Overflow Plan, the MWRA has closed twenty-one of the eighty-four combined sewer discharge systems, a reduction of more than 70 percent of the prior sewage discharge.

Over the years, the MDC upgraded the disposal plants: Nut Island in 1949, Deer Island in 1952, and remote headworks for Deer Island in 1968. The Moon Island Plant was phased out with the operation of the new remote headworks. In conjunction with the upgrading of the various treatment plants, new collection, routing and outfalls were constructed. The MWRA has implemented various systems for the upgrading of the treatment and disposal system for compliance with new environmental requirements. To this end, the Deer Island Sewage Treatment Plant was constructed over a period of eleven years at a cost of $3.8 billion and includes the Inter-Island Tunnel and the Effluent Outfall Tunnel. The outfall is about 15 kilometers (9.5 miles) long, the longest of its kind in the world, and cost $380 million. It discharges about 500 million gallons of treated effluent daily since opening in September 2000.

The Deer Island Sewage Treatment Plant came on-line in 1995 and receives wastewater from four underground tunnels. The wastewater is raised about 46 meters (150 feet) to the surface using two pumping stations and where grit is first removed, and subsequently processed for an off-island landfill. The wastewater then passes through the primary treatment, which removes about half the pollutants and separates the sludge and scum. A secondary treatment removes the non-settleable solids using a micro-organism system aided by pure oxygen produced at the plant to reach over 85 percent reduction of pollutants. The wastewater is then disinfected so it will not harm marine life and then it is discharged through the effluent outfall tunnel far outside the harbor. The resulting sludge and scum is processed in a digestive system using the micro-organisms that are naturally present to reduce the quantity and separate it into methane, carbon dioxide, water and solid organic material. The methane is used in the on-site power plant. The processed sludge is then sent south via the Inter-Island Tunnel to a

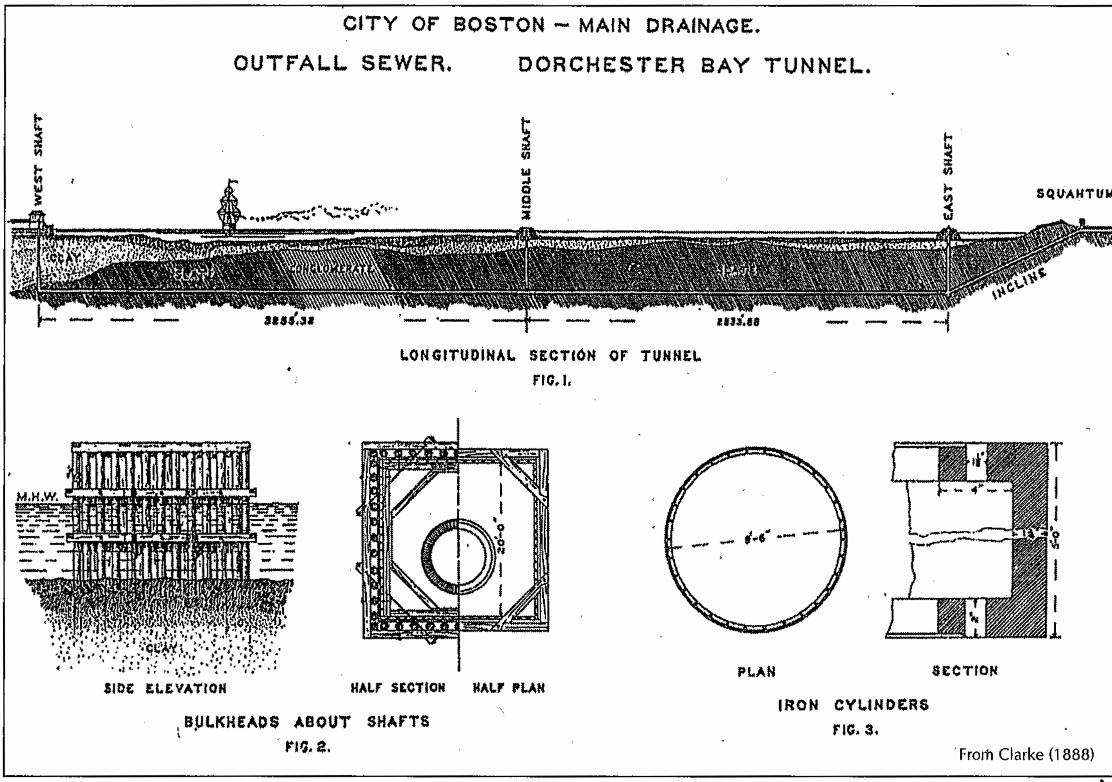


FIGURE 7-20. Section showing the Dorchester Bay Tunnel.

pelletizing facility at Fore River in Quincy and subsequently sold to others who turn it into fertilizer.

Conveyance pipelines and tunnels have been the backbone of sewage collection and treatment in Boston since its initial conception in the late 1840s. Early in its history, Boston managed its sewage by using small pipes to discharge sewage at the nearest shore. The collection system evolved with the waste being carried in brick conduits at shallow depths followed by deeper bedrock tunnels. The southern system carried waste via the Dorchester Bay Tunnel to a plant on Moon Island (see Figures 3-3 & 7-1). The unsewered parts of the south metropolitan area were then tied into a collection system, which included the West Roxbury Tunnel, to convey waste to Nut Island at the south side of the harbor. The need to increase the capacity of the sewage system after World War II led to constructing the Main Drainage Tunnel through the center of the district and across the harbor to Deer Island, and the North Metropolitan Drainage Tunnel in the north that also connected to Deer Island.

Dorchester Bay Tunnel. The Dorchester Bay Tunnel was a significant component of what was considered to be the best sewage disposal system in the world when built in the early 1850s. Metropolitan Boston's sewage lines were connected into a main drainage tunnel leading southward to Old Harbor Point (now Columbia Point). At that location the waste was pumped to a surface reservoir (see Figure 7-20), carried 366 meters (1,200 feet) into the harbor as some sludge was separated, taken to Squantum Head via the Dorchester Bay Tunnel that formed an inverted siphon, and thence piped under a causeway to holding tanks on Moon Island (Clarke, 1888). The tanks were emptied twice a day into the harbor on the outgoing tide. This huge project (for its day) opened in January 1884 and cost the city of Boston $6 million (Kales & Kales, 1983). The system eventually caused serious pollution of the harbor. It was augmented over the years, but was fully replaced by a facility on Deer Island in 1968.

The total length through which sewage flows in the tunnel is 2,183 meters (7,160 feet). The vertical drop in the West Shaft is 45 meters (149 ft) and it is 1,856 meters (6,088 feet) nearly horizontal from its base to the East Shaft, and 282 meters (923 feet) in the incline leading up to Squantum Head. The average elevation is –43 meters (–142 feet) MSL. The tunnel excavation was completed in June 1882 and the solid brick lining, 30 centimeters (12 inches) thick, of the tunnel had begun in March of the same year. All voids between the lining and the rock were solidly filled and the tunnel was practically finished July 1883. The tunnel was excavated to an average diameter of about 3.1 meters (10.2 feet) and the finished lining has an inside diameter of 2.9 meters (9.5 feet). The contract price for the shafts, exclusive of iron, was $86 per linear foot and for the tunnel it was $48 per linear foot. The contractor lost money after two years and to prevent abandonment, the remainder of the tunnel was done at about $92 per linear foot.

The tunnel was first planned to be cut shallower and lie partially in the marine clay, but the potential problem of tunneling through the loose water-bearing layer led to it being designed to lie wholly within the bedrock. Experience bore out this choice as sound. The fractures in the rock aided in the mining. The tunnel was excavated using both pneumatic drills and hand drills, with some use of nitroglycerine. An advance of 1.2 meters (4 feet) was considered a fair day's work. Dolen (in Clarke, 1888) reported that "[t]he chief merit of the air-drills seemed to be that they were not demoralized by pay-days, and never struck for higher wages."

The tunnel is dug through Cambridge Argillite from Squantum Head with an interval of Roxbury Conglomerate (then all known as the Roxbury "pudding-stone" beds) between the middle shaft and Old Harbor Point (see Figure 7-20). The exploratory boreholes showed the rock surface to be just below the harbor bottom from Squantum to midway into the bay and then plunges to 65 meters (214 feet) below ground surface at Old Harbor Point. The rock is cut by many faults, fissures and joints, but few of these cuts conducted water from above. The rock surface is somewhat broken and covered by a water-bearing unit of sand, gravel and boulders of apparently the lower outwash. This layer is overlain by the marine clay, which contains occasional layers of sand, and a cap of mud of varying thickness forms the harbor bottom.

The three working shafts, which extended from bulkheads, were built of stacked iron rings 2.9 meters (9.5 feet) in diameter, forced as deep as possible toward the rock and excavated farther by timbered works to the tunnel depth. The construction and ensuing problems were described by Clarke (1888). Special care was to be taken to avoid water inflow and compressed air was to be used if necessary. Two ringed shafts reached the rock easily, but the west shaft could only penetrate 18 meters (60 feet) below the harbor bottom. Despite warnings by the engineer in charge about the quality of the timbering work on this shaft, the method was not changed and water broke through the bottom of the shaft at a rate of about 10,000 gallons an hour. No pumps were in readiness and the shaft filled with water and was damaged before being pumped out. The repairs were difficult and additional inflows occurred, along with settling of the clay. By the time the shaft reached rock, the piled bulkhead above had settled nearly 1.5 meters (5 feet).

The maximum amount of water inflow into the tunnel at any one time was 64,000 gallons an hour. The sewage within the tunnel when in use was at a slightly higher pressure than the outside so that any leakage was outward. The excavated material was deposited around the shafts forming small islands. The west shaft is now on the shore of Columbia Point.

West Roxbury Tunnel. Around the turn of the twentieth century, the Massachusetts Water and Sewerage Board (MWSB) voted to construct a wastewater collection system in the unsewered parts of the South Metropolitan District. At that time, the population of the Boston suburbs (which included Quincy, Milton, Roxbury, West Roxbury and Hyde Park) was sparse. Wastewater was to be conveyed through 2 to 3 meter (7 to 10 foot) diameter reinforced concrete pipes from these areas to Nut Island and Deer Island. Construction for the sewers consisted of both open trench (cut-and-cover tunnel) in the glacial deposits and tunnels driven through the bedrock using tunnel shields with compressed air, the most common and current technology of that day. The method of construction was at the discretion of the contractor and depended on the depth of the sewer; an open trench was the obvious choice for shallow conditions. The sewers were constructed during the period 1899 to 1902.

The original West Roxbury Tunnel system was approximately 8.3 kilometers (5.2 miles) long with a nominal diameter of 3 meters (10 feet) and was constructed mainly by the cut-and-cover method, with a bedrock portion of approximately 3 kilometers (1.8 miles) driven through Mattapan Volcanic Complex and the Roxbury Conglomerate (MWSB, 1902). The tunnel was constructed in sections, each with its own contractor and designer, and is described as such. Westerly from the Hyde Park high-level sewer, the nominal 3 meter (10 foot) diameter tunnel is about 4.5 meters (15 feet) deep and runs for a distance of 1,615 meters (5,300 feet) through the Mattapan volcanic and dike rock. About 89 meters (288 feet) of this section were constructed as a cut-and-cover tunnel where sand and gravel was encountered. The next 100 meter (327 foot) section of the tunnel, at a depth of about 5 meters (17 feet), in the Stony Brook section of West Roxbury is a cut-and-cover tunnel in till. From that point, a cut-and-cover section of the tunnel in till runs down Hyde Park Avenue for a distance of 835 meters (2,738 feet). The next 791 meter (2,596 foot) section continues along Hyde Park Avenue area in a 9 meter (30 foot) deep cut-and-cover tunnel in the till. The cut-and-cover tunnel, which is 1,140 meters (3,740 feet) long, continues to South and Bussey streets. At that point, with the exception of a 57 meter (188 foot) long tunnel driven through sand and gravel at a depth of 2.5 to 5.5 meters (8 to 18 feet), an open trench was constructed for a distance of 669 meters (2,193 feet) through till and peat in the South Street area. At the Arborway, the tunnel is 918 meters (3,010 feet) long with all but an 11.6 meter (38 foot) deep, 348 meter (1,140 foot) long section constructed as open cut-and-cover trench. The tunneled section was through soft ground made up of sand and gravel and fine sand. Along Centre and South streets, the 1,456 meter (4,775 foot) long tunnel is 15 meters (50 feet) deep, which necessitated the use of compressed air and tunnel shields. This tunnel was constructed within soft ground in sand, except for 427 meters (1,400 feet) driven through Roxbury Conglomerate.

With the formation of the MWRA in 1984, the water and sewer infrastructure was modernized and the old pipelines were inspected and most abandoned. The sewer section, now designated as the West Roxbury Tunnel, from the New Haven Street drop chamber at the Dedham line to the Hyde Park high-level sewer was inspected in this effort (see Figure 7-1). The New Haven Street drop chamber picks up the Wellesley Extension Relief Sewer and conveys the wastewater from Boston's western suburbs to the Hyde Park high-relief sewer through the tunnel. The concrete liners of the West Roxbury sewer, along with the Wellesley sewer, were found to be badly corroded in 1999 and had to be repaired using a structural pipe liner called slip lining. Because of the age of the original West Roxbury Tunnel, it is now being replaced by the Upper Neponset Valley Relief Sewer Project.

Main Drainage Tunnel. The 11.5 kilometer (7.12 mile) long Main Drainage Tunnel slopes from elevation –91 meters (–299 feet) MSL at Shaft A at the west edge of the campus of Wentworth Institute of Technology in Boston easterly to Shaft B at Dorchester Bay and from there northeast to elevation –94 meters (–309 feet) MSL below Deer Island in Boston Harbor (see Figure 7-1). The western leg of the tunnel between Shafts A and B is 4,196 meters (13,763 feet) long and the eastern leg to Shaft C at Deer Island is 7,263 meters (23,823 feet) in length. The 3.7 to 4.3 meter (12 to 14 foot) diameter tunnel was lined to a 3 meter (10 foot) diameter in the western leg and 3.5 meters (11.5 feet) in the eastern leg. It was constructed between 1951 and 1959 by drill and blast.

The western 1,311 meters (4,300 feet) of the tunnel passes through interbedded shale, arkosic sandstone, sandstone and conglomerate, and the rest of the tunnel lies in argillite, except for a 122 meter (399 foot) thick conglomerate unit on the west side of Shaft B (see Figure 7-21). The strata in the western leg strike west-northwest to northwest and generally dip 20 to 40 degrees northeast, whereas the strike in the eastern leg swings to the northeast and the similar dip is to the northwest. The conglomeratic unit at Shaft B was called the Squantum Tillite by Rahm (1959 & 1962) and separated a Dorchester Member of the Roxbury Conglomerate to the west from the Cambridge Argillite to the northeast. However, the 63 meter (206 foot) thick conglomeratic unit, which has clasts similar to those of the Roxbury in a fine-grained matrix and interbedded with thin argillite and sandstone with isolated pebbles, is apparently a slide within the Cambridge Argillite and the contact with the Roxbury can be placed at the east side of the conglomerate 708 meters (2,323 feet) from the west end of the tunnel. These western conglomerate units contain abundant melaphyre (dark basaltic rock) clasts, but no melaphyre dikes were found in the tunnel. The entire tunnel is cut by both altered and unaltered diabase dikes and sills. The dike-like bodies range up to 37 meters (120 feet) and the sills to 23 meters (74 feet) in thickness.

The Main Drainage Tunnel skirts the northern side of the mass of Roxbury Conglomerate in the basin that is commonly referred to as the Central Anticline. The northeast dips in the western leg of the tunnel are consistent with a north slope of such a fold, but those dips in the eastern leg are not. Instead of maintaining this dip or one even more to the east, they swing to a northwest dip and indicate that a simple anticlinal concept has problems. Small-scale folds are of a different nature. The Cambridge Argillite in the center of the tunnel contains thirty groups of small- to large-scale slump folds, some of which are broken by faults (see Figure 7-22). Most of these folds are overturned to the east and apparently slid down an east-facing slope, but they present a complex overall pattern that might be expected in slumps. These slump folds are different from the drag folds associated with faults.

Rahm (1959 & 1962) mapped 158 faults in the tunnel. Of these, sixty-eight were determined to be normal, seventeen reverse and twenty-seven vertical. The remainder could not be identified. The great majority strike northeast and dip moderately to steeply northwest; the others strike north-northeast and dip steeply southeast or strike northwest and dip steeply southwest. Soft gouge is present along forty-five of the faults and has a thickness ranging from a smear to as much as 0.3 meters (1 foot). Fault breccia is recorded along five faults, where it ranges from a couple of centimeters to 0.3 meters (inch to a foot) in thickness. Eight of the faults have associated veins of quartz or calcite or both that are generally 2 to 9 centimeters (1 to 3.5 inches) thick, but may reach 60 centimeters (24 inches) in thickness. The stratigraphic throw for sixty-three faults is between 2 centimeters to 8.5 meters (1 inch to 28 feet), with a mean of 0.8 meters (2.5 feet) and a median of 1 meter (3 feet). The numerous steep dikes (which probably follow faults) fall into three sets. Most strike north-south with lesser numbers striking either northwest or east-west. The intensely sheared northwest-trending, northeast-dipping border of the conglomerate near Shaft B apparently represents a large fault below Dorchester Bay. The northeast-trending Stony Brook Fault apparently passes about 333 meters (1,200 feet) west of the west end of the tunnel.

Steel supports were used over 4,032 meters (13,226 feet) or 35 percent of the tunnel for several reasons (Rahm, 1959 & 1962). The argillite and clay in the western third of the tunnel that underlay a valley in the bedrock needed most of the support. Kaye (1979) felt that altered tuffaceous argillite was present in this area and controlled the valley. Ninety-five percent, 3,117 meters (10,225 feet), of these strata required support because of soft-rock alteration, which seems to be concentrated along a very wide faulted zone. In addition, roof bolts were used to stabilize flaggy argillite striking parallel to the tunnel and dipping gently northward. Only eleven percent, 825 meters (2,705 feet) of the much thicker argillite to the east required roof bolts and a mere nine percent, 54 meters (176 feet), of the intervening conglomerate did. All of the 293 meters (961 feet) of diabase forming the roof in the west-

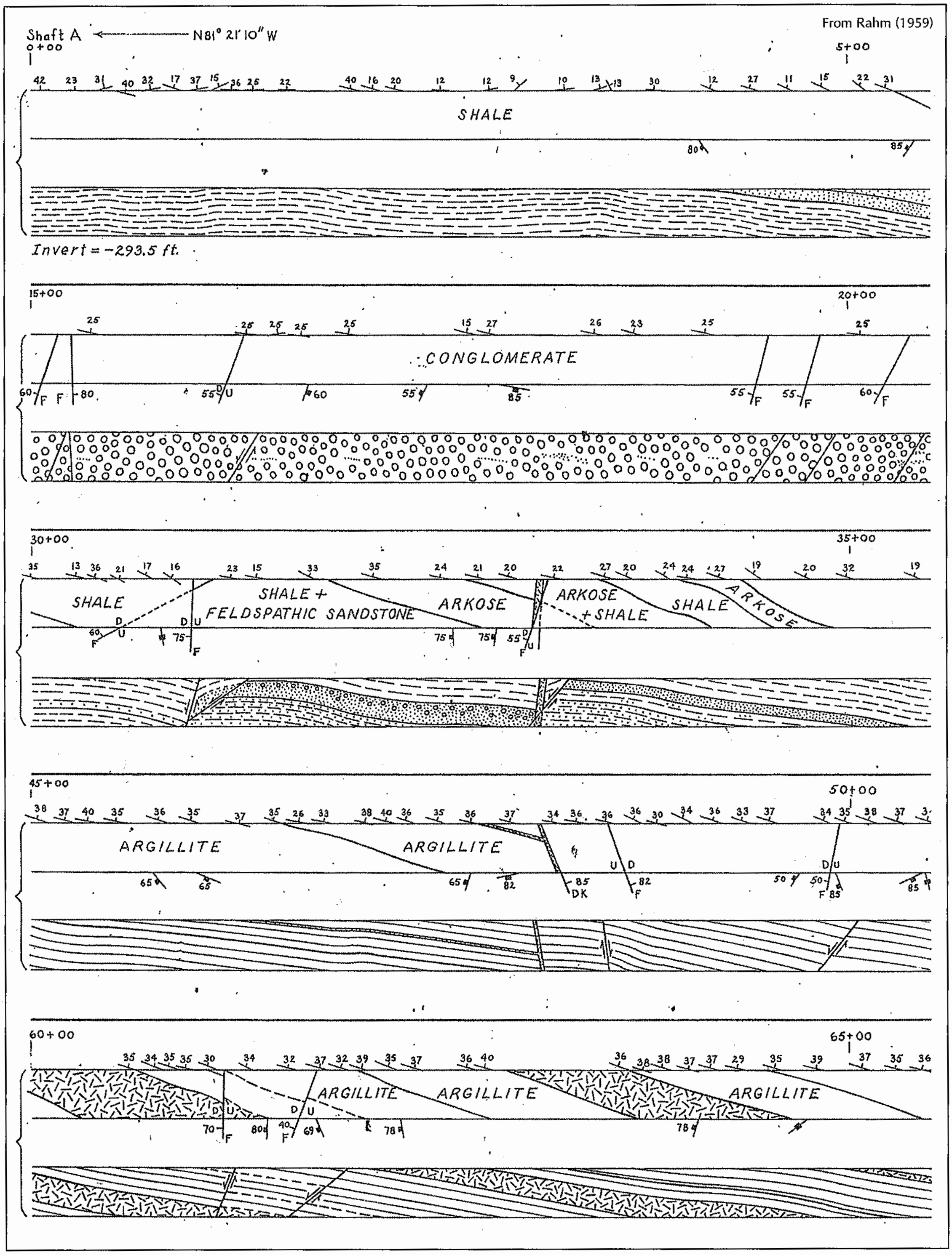


FIGURE 7-21. Typical western portions of the map of the Main Drainage Tunnel. In each couplet, the lower part shows the north wall of the tunnel and the upper part a map projection of these data.

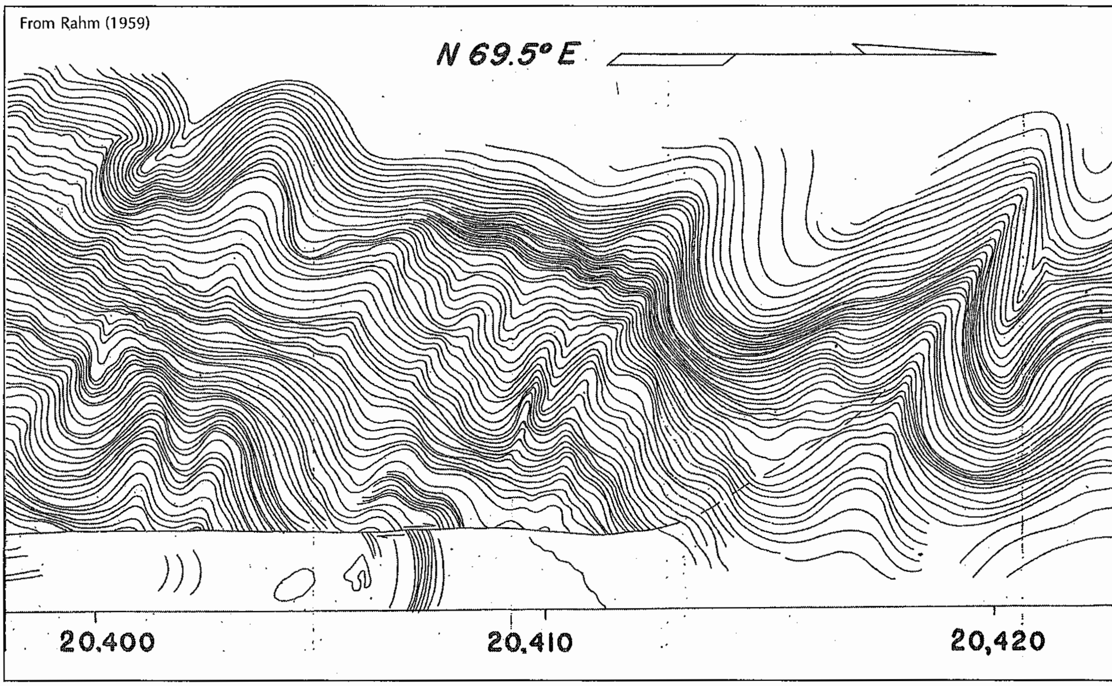


FIGURE 7-22. Slump folds in the north wall of the Main Drainage Tunnel showing apparent movement to the east-northeast.

ern leg required steel support, whereas support was needed on only twenty-six percent, 135 meters (444 feet), in the eastern leg. The need for support for these diabase intrusions in the eastern leg rarely extended into the adjacent argillite. Rahm did not feel that joints and faults were a major factor necessitating support, but the shaly and slabby nature of the argillite in the problem areas may have been due to fault movement.

The bedrock surface is lowest off Deer Island, where it reaches a depth in excess of 64.6 meters (212 feet) in a borehole that entered a fault zone (see Figure 3-69). This depth still provided 27 meters (87 feet) of rock above the tunnel. Overlying the bedrock is principally marine clay with some upper outwash and organic sediment (see Figure 3-68).

North Metropolitan Relief Tunnel. The North Metropolitan Relief Tunnel was also built in the early 1950s to carry sewage from the northern part of metropolitan Boston to the treatment plant at Deer Island (see Figure 7-1). It extends 6,333 meters (20,772 feet) southeastward from Chelsea to Deer Island sloping from about elevation –87 to –89 meters (–285 to –291 feet) MSL between 4.3 meter (14 foot) diameter shafts at either end (Billings, 1975). It was constructed by drill and blast and was lined with concrete to an inside diameter of 3 meters (10 feet) at completion in 1956.

The North Metropolitan Relief Tunnel was not mapped and the lithology of this tunnel is based on a study of the cores of exploratory borings (see Figure 7-23) and on a very rapid survey by Billings (1975) of the northwestern two-thirds (see Figure 7-24). The tunnel lies entirely within the Cambridge Argillite, which is nowhere exposed at ground surface above it. The strata consist of medium- to dark-gray argillite with scattered interbeds of feldspathic sandstone and some siltstone that is cut by both altered and unaltered diabase dikes. The argillite is very thin-bedded and laminated and displays small slump folds locally. The sandstone beds range up to 5.5 meters (18 feet) in thickness and contain orthoclase feldspar that is generally altered to kaolin. Light-gray kaolinized shale-like argillite was encountered in eight boreholes, but altered rock was not noticed in the exposed unsupported parts of the tunnel. The shaly strata constitute 24 per-

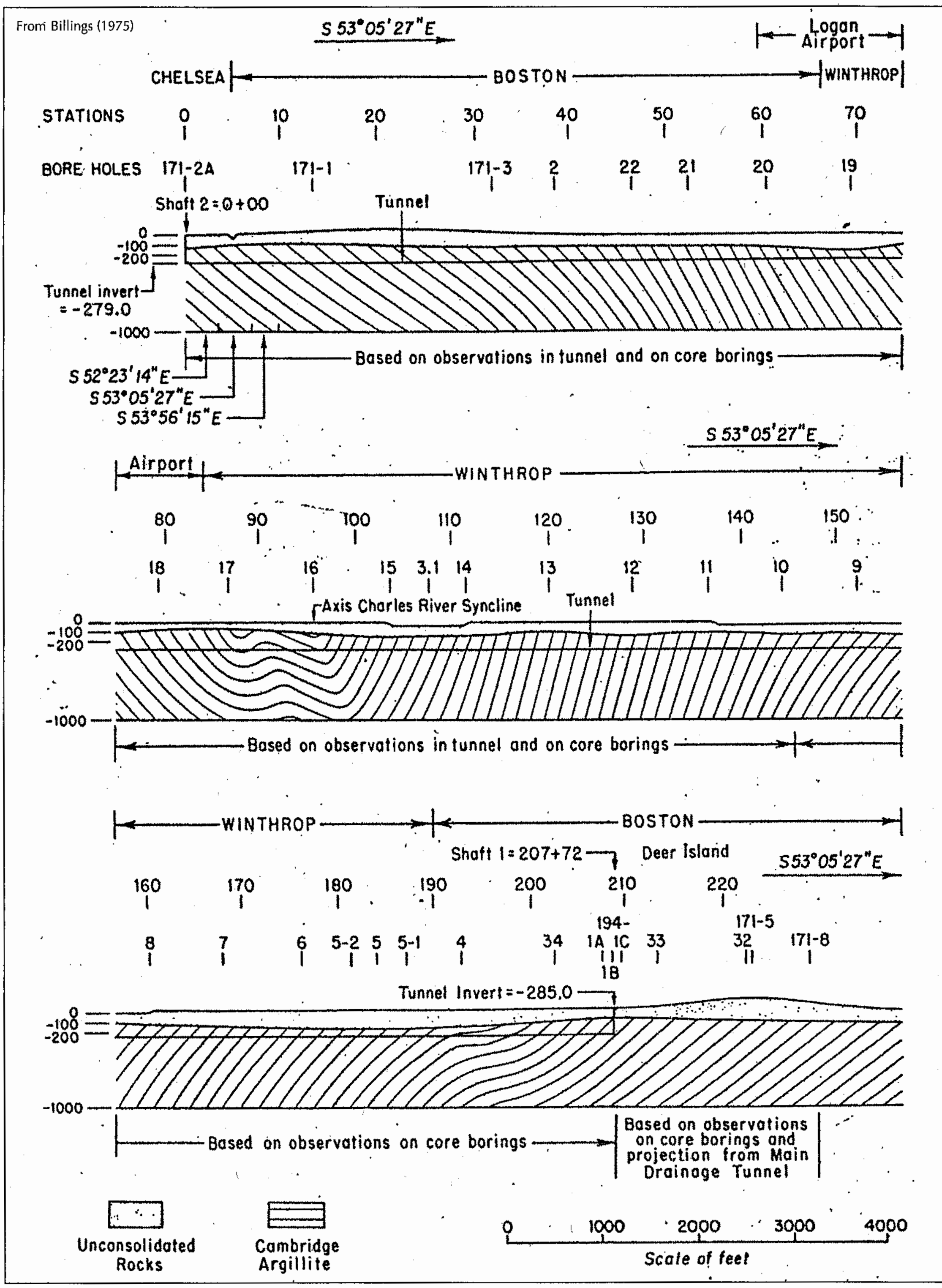


FIGURE 7-23. A section along the North Metropolitan Relief Tunnel showing the dip of the Cambridge Argillite. Plotted is the measured dip, and not the apparent dip as would be seen in this section.

From Billings (1975)

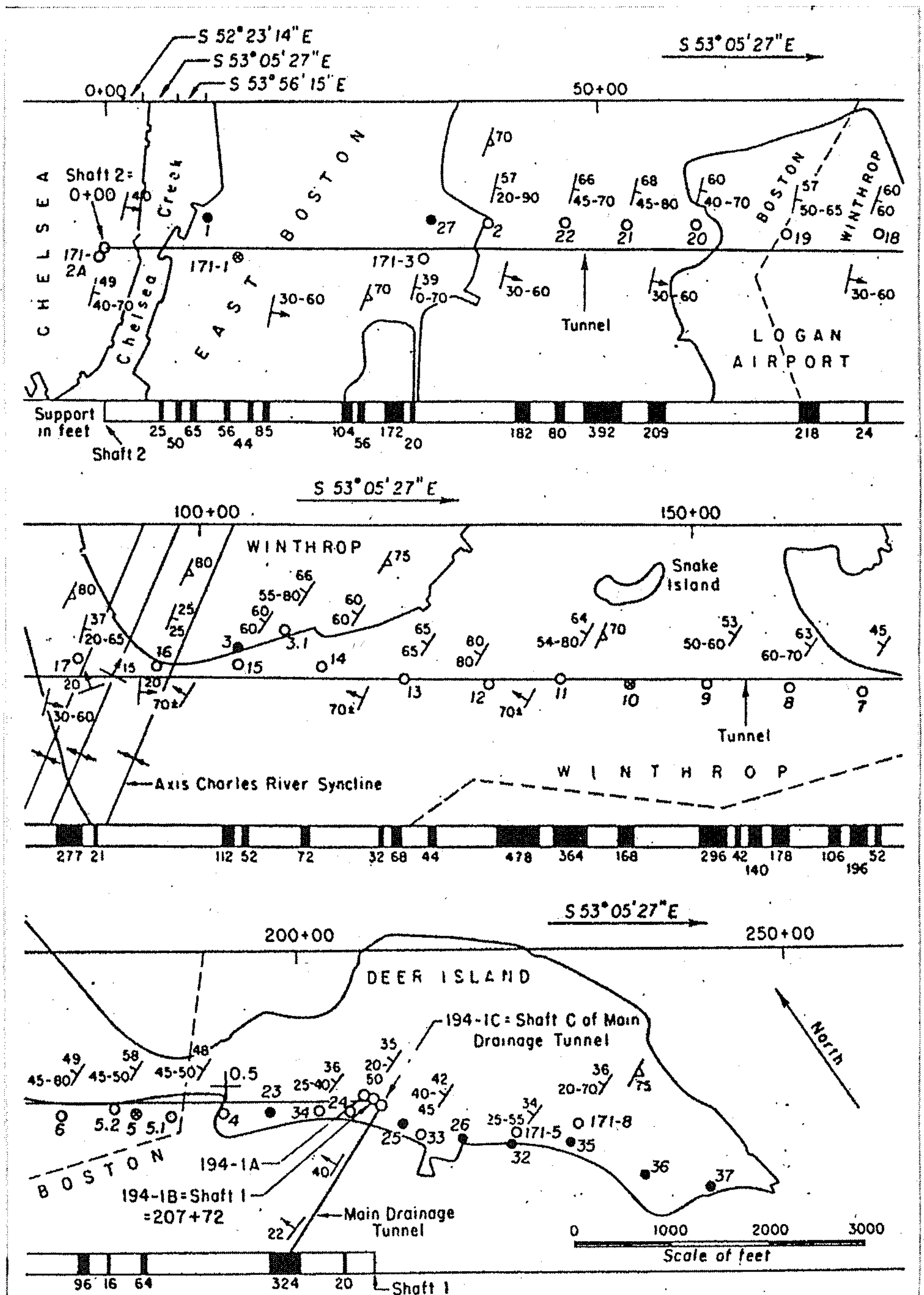


FIGURE 7-24. Map along the North Metropolitan Relief Tunnel showing attitudes from boreholes and section below with areas (and their widths) needing structural steel support marked in black.

cent of the recovered core. This shaly argillite might represent shear zones. The abundance of altered rock in this tunnel, unlike the other tunnels, was distributed fairly evenly throughout the length of the bore.

Many sections of this tunnel required lining and some places required structural steel support. The length of the lined sections suggests that altered strata ranged from as little as 3 to 30 meters (10 to 100 feet) or more in thickness. Between these lined sections are hard argillite and sandstone. Similar rock alteration did not occur in the contiguous western end of the Main Drainage Tunnel (Rahm, 1962). The many tunnel sections that required support would reflect both altered and faulted zones.

The strata strike to the northeast. Those strata in the northwestern part of the tunnel dip 30 to 60 degrees to the southeast and those in the southeastern part generally dip 60 to 70 degrees to the northwest, with lesser dips close to Deer Island. The changeover in dips, which occurs at the western edge of Winthrop, is considered the east-northeast-trending axis of the Charles River Syncline by Billings (1975). However, this axis is apparently the continuation of the fault at this "syncline" as found in the City Tunnel Extension.

About forty separate sections, 4.9 to 146 meters (16 to 478 feet) in length, required structural steel support, about twenty-four percent of the tunnel. Taddeus Medowski, the Senior Engineer (in Billings, 1975), considered it was due to intense fracturing of the rock, but Kaye (1967) thought most may have been built to support altered rock. Both causes undoubtedly exist and the alteration would be at least partially controlled by faults. The crumpled rock in the Charles River Fault Zone required 91 meters (298 feet) of support. The sections of support are probably a guide to the more disruptive faults.

Modern-Day Wastewater Tunnels

The MDC was reorganized as the MWRA in 1984 and charged with providing water and sewer service to the 2.5 million people of metropolitan Boston along with cleaning up the pollution in Boston Harbor. The MWRA, in its efforts to purge the waters of Boston Harbor and the area rivers, undertook a massive wastewater project beginning in the late 1980s and costing $3.8 billion. The program involved numerous improvements to the sewerage transport system to convey wastewater and storm water. It was designed to:

- connect any remaining separate outfalls into the main collection systems leading to the treatment facilities at Deer Island at the north and Nut Island at the south of the harbor;
- carry the wastewater northward beneath the harbor from Nut Island via an Inter-Island Tunnel to Deer Island where a major facility would treat all the sewage; and,
- discharge the treated effluent seaward through a long Deer Island Outfall Tunnel to mix with ocean waters (see Figure 7-1).

Improvements onshore included a Braintree-Weymouth Tunnel to better connect the south shore communities to the primary treatment plant on Nut Island, an additional Wellesley Tunnel to the west to prevent overflow into rivers leading to the harbor and a combined sewage overflow (CSO) storage tunnel at Dorchester Bay to prevent overflow of untreated storm water directly into the harbor.

Extensive exploration programs were undertaken in order to characterize the geology for the design of the shaft, the tunnels and diffuser section for the Deer Island Outfall and Inter-Island and Braintree-Weymouth tunnels in the Boston Harbor area. Preliminary design borings were carried out in the summer and fall of 1988, with the detailed borings being completed the following year. A detailed geophysical program was also carried out to better determine the quality of the rock along the proposed alignments and in the potential far-offshore diffuser locations near the end of the outfall. After assessing the data from the detailed design exploration program, the alignments were finalized.

The depths selected for the two tunnels carrying the sewerage to Deer Island were based on the initial geophysical survey information. The survey for the outfall tunnel indicated that there was bedrock low just to the east of

Deer Island and the tunnels were designed to pass two tunnel diameters below the lowest elevation of this bedrock low. The geophysical program also indicated that there was a low-velocity zone in the northern section of the proposed diffuser area. The low-velocity area was core drilled and found to be almost entirely "kaolinized" argillite. The geophysical survey for the Inter-Island Tunnel indicated that there was an area of low-velocity material to the west of Peddocks Island. Due to these studies, the northern extent of the diffuser area was eliminated and a jog made in the Inter-Island Tunnel alignment.

As expected, the majority of the rock recovered from the exploration was Cambridge Argillite, but intrusive rock was also an important component. Igneous sills intruded along bedding planes, dikes along fracture planes and irregularly shaped intrusive bodies that followed various features are abundant in the Boston Basin (Rahm, 1962) and were also observed in explorations for the tunnels. These observations found that about twenty-eight percent of the rock encountered in the City Tunnel is basalt and diabase (Tierney *et al.*, 1968), and about ten percent of the rock excavated at Porter Square are igneous intrusions and altered basalt (Dill, 1986). The outfall alignment passes "The Graves," an island made up of a large diabase sill that lies about 7.5 kilometers (4.5 miles) east of Deer Island. Kaye (1986) estimated that the sill at The Graves may be in the order of 91 meters (300 feet) in thickness. Borings also recovered felsite. The preliminary exploration program recovered the following percentages of the various units along the alignment at the expected tunnel depths of the three tunnels:

- argillite — 71.3 percent
- sandy argillite — 11.3 percent
- altered argillite — 5.5 percent
- igneous intrusive — 8.6 percent
- volcanic rock — 3.3 percent

The rock strengths for the argillite are very similar to those recorded from other tunnels in the Boston Basin, such as the MBTA Red Line Extension and the Dorchester Tunnel. Testing of the Inter-Island Tunnel samples resulted in similar results, whereas the results on samples from the shafts on both Deer and Nut islands yielded higher average unconfined compressive strengths of 146,169 kilonewtons per square meter (21,200 pounds per square inch) for the argillite and 182,573 kilonewtons per square meter (26,480 pounds per square inch) for the diabase. Considerable rock testing was done for the exploration programs for the Deer Island Outfall, Inter-Island and Braintree-Weymouth tunnels. The other tunnels had separate exploration programs.

Inter-Island Tunnel. The Boston Harbor Project's Inter-Island Tunnel extends from Deer Island south for 7.7 kilometers (25,160 feet) to the Nut Island headworks (see Figures 7-1 & 7-25). The alignment runs south to just off Peddocks Island and then turns to the southeast to the tip of Nut Island. The tunnel was driven with a TBM and completed at the end of the drive with a 4.3 meter (14 foot) diameter cast-in-place lining (Caspe & Williamson, 1995). The configuration of the lining was actually "D-shaped" in order to embed two 36 centimeter (14 inch) sludge lines into the west wall of the tunnel. The excavation began beneath Deer Island in July 1992 and was completed in November 1995 and the liner finished in late 1997. The tunnel, reached by shafts at both ends, was designed to have a minimum of 21 meters (70 feet) of rock cover and slope northward from elevation –62.5 meters (–205 feet) MSL at Nut Island to elevation –82.3 meters (–270 feet) MSL at Deer Island.

The tunnel penetrates Cambridge Argillite, diabase and basalt dikes and a few sills, and some thin greenish-gray and red felsite sills at the south end (see Figure 3-89). The rock is chiefly sandy argillite with some sections of interbedded argillite, tuff and tuffaceous argillite, as well as intervals of interbedded argillite, sandy argillite and sandstone with minor pebbly argillite. The rock is generally very good, although slickensides are very common and many faulted intervals 3 to 24 meters (10 to 80 feet) wide are present. The alignment of the Inter-Island Tunnel crosses the regional structural trend and, thus, has a greater risk of encountering varying condi-

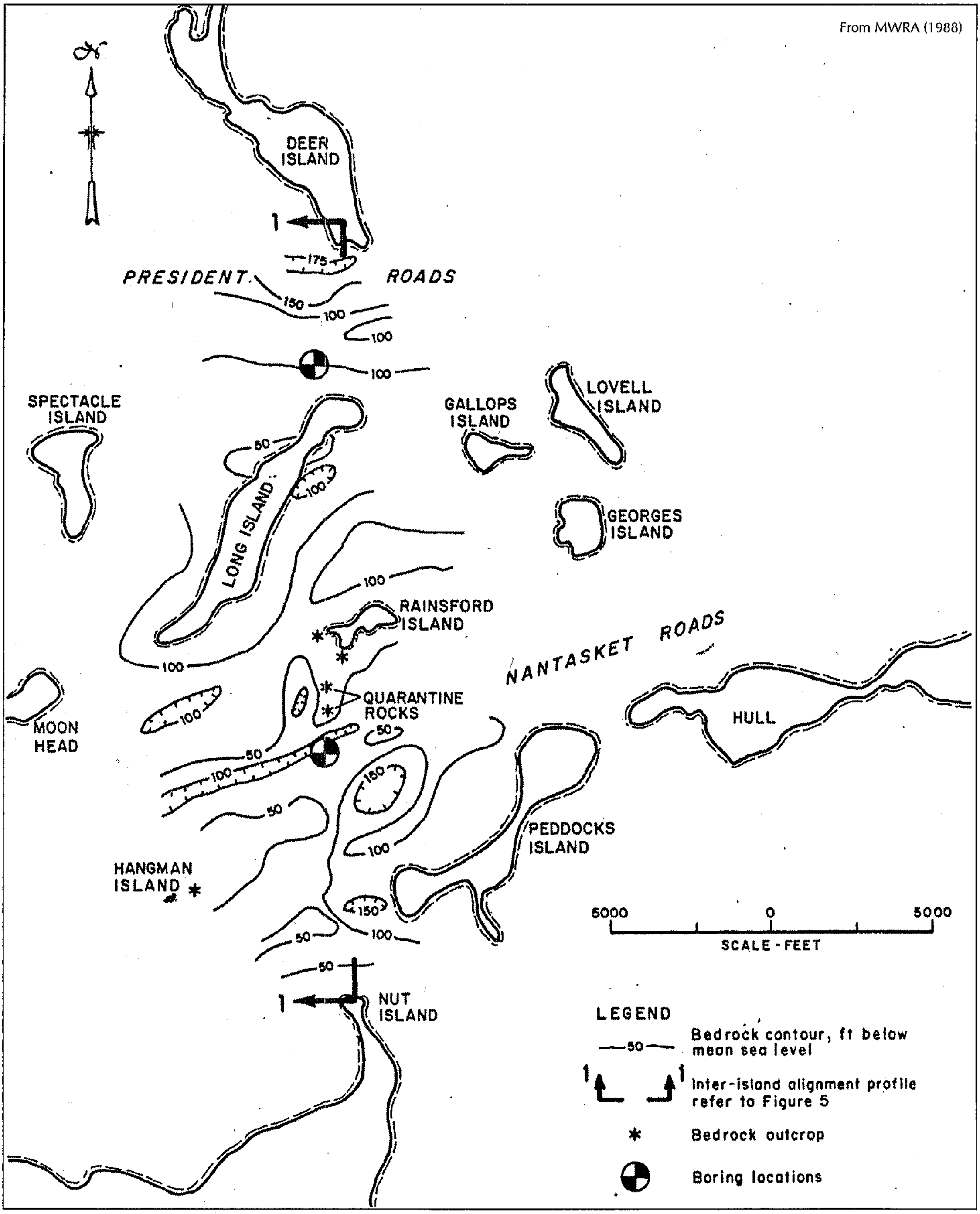


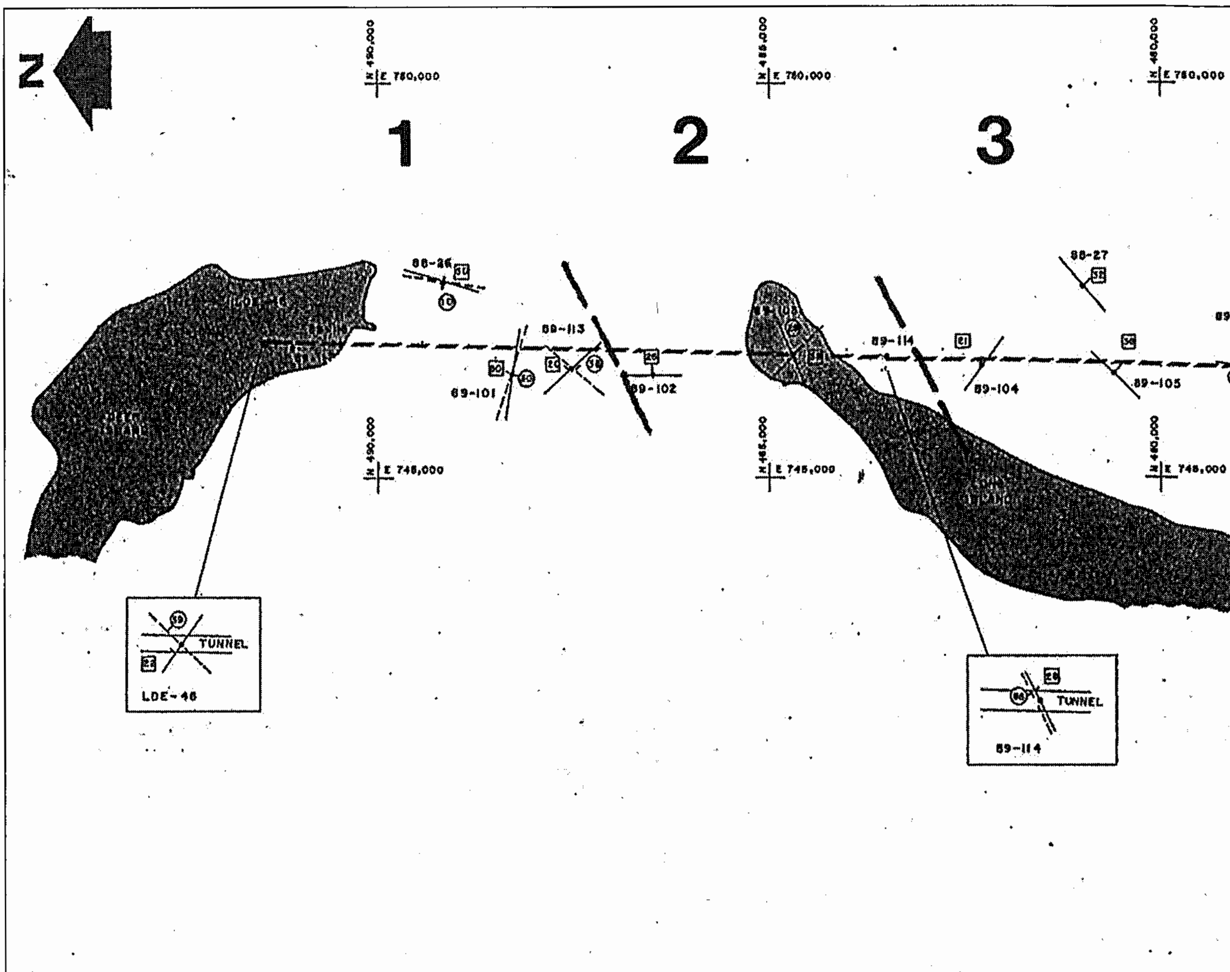
FIGURE 7-25. Bedrock surface along the route of the Inter-Island Tunnel.

tions as well as different lithologies of the Cambridge Argillite mapped along the tunnel alignment (see Figures 3-89 & 7-26). The attitude of the argillite is highly variable (see Figure 7-26), but between Deer Island and the south side of Long Island it generally strikes northwest with a northeast dip of 20 to 50 degrees, west of Peddocks Island it strikes northeast and dips 10 to 40 degrees south to southeast, and at Nut Island it strikes northeast with a northwest dip of 80 degrees (Sverdrup, 1990b). These three groupings generally reflect changes at fault zones, but many changes result from slumping during deposition. Variations in the lithology of the Cambridge Argillite also are seen along the tunnel (see Figure 7-26). At Deer Island most of the argillite below elevation –70 meters (–230 feet) MSL exhibits slump features and a large south directed slump was encountered in the tunnel north of Nut Island.

The tunnel's alignment crosses major faults of the basin projected through the alignment by Kaye (1984a), in addition to the evidence for very small- to moderate-sized faults seen in almost all rock core from boreholes (Sverdrup, 1990a). The easterly trending lows in the bedrock surface along the tunnel route reflect the faults (see Figure 7-25). The quality of rock found during exploration also apparently reflects the faulted areas (see Figure 7-27). A low-velocity zone and a northwest-trending bedrock trough, indicative of a fault across the south edge of Deer Island and a greater water inflow, was encountered there. Two other faults, which bracket Long Island, appear to have uplifted the island relative to either side to account for lithologic changes in the argillite.

An east-trending low seismic velocity zone identified in the exploration program coincided with the extension of the Squantum and Peddocks Island faults west of Peddocks Island that were identified by Kaye (1978) in his map (Weston Geophysical, 1989a & 1989b) of the Boston area (see Figure 1-34). An east-trending bedrock trough was indicated, but its depth was indeterminate prior to drilling because the seismic velocities of the till and soft bedrock overlapped. Exploration borings over a 1,220 meter (4,000 foot) interval found considerable highly fractured, medium to very-soft gray to white argillite and highly sheared diabase with higher water inflow (Sverdrup, 1990b; MWRA, 1996). The zone is characterized (Sverdrup, 1990a & 1990b) by the extreme development of slickensides, fault gouge, partings and lower rock quality designation (RQD). Although the tunnel alignment was altered in attempts to avoid the faulted zone, the tunnel drive encountered soft material off Peddocks Island. This zone is a major fault one, which extends about 122 meters (400 feet) between Stations 196+50 to 200+47 and required steel support. The northern side of the northeast-trending fault dips steeply to the northwest and the north half of the zone is highly broken altered gray argillite and gouge (Barosh, 1996b). The intact argillite in the northern edge of the fault zone dips about 20 degrees to the north.

Over the 300 meter (1,000 foot) length of tunnel north of this major fault zone, the rock is characterized by east-northeast striking, north 30 to 60 degree northwest-dipping argillite offset by near vertical, east-northeast striking faults and is cut by a few thick greenstone and light-colored dikes. The dips in the argillite change across the faults and dikes. For 245 meters (800 feet) of the tunnel south of the major fault, the gently to moderately south-dipping argillite was cut by 30 to 60 degrees north-dipping normal faults spaced 1 to 3 meters apart (3 to 10 feet). Slump structures are present at Station 210+00, about 291 meters (955 feet) south of the major fault zone. The dip of the argillite flattens to the south to Station 215+60 where it abruptly changes to a 45 degree north dip across an apparent slip on a slump. The bedding to the south is gently undulating with flat to moderate north, west, and south dips to Station 240+05 where a very dark gray dike 70 centimeters (2.3 feet) wide lies along an approximately 40 degree south-dipping fault. Farther south, the argillite is relatively undisturbed with 30 to 45 degree south dips to an abrupt change to vertical at Station 251+00 that is maintained to the shaft at Nut Island. The abrupt change appears to be due to a south-moving slump, as does the one at Station 215+60. The southern part of the argillite is seen to be well laminated in thin to very thin beds, which are commonly graded. Darker gray clasts, 8 to 15 centimeters (3 to 6 inches) long and elongated parallel to bedding, occur in one layer. Most if not all of the dikes intruded along faults, and many dikes are sheared and broken by later movement. The frequently reported veins of calcite and quartz in the rock along the alignment is similar to the Narragansett Basin, where such veins reflect extensional fault movement. The

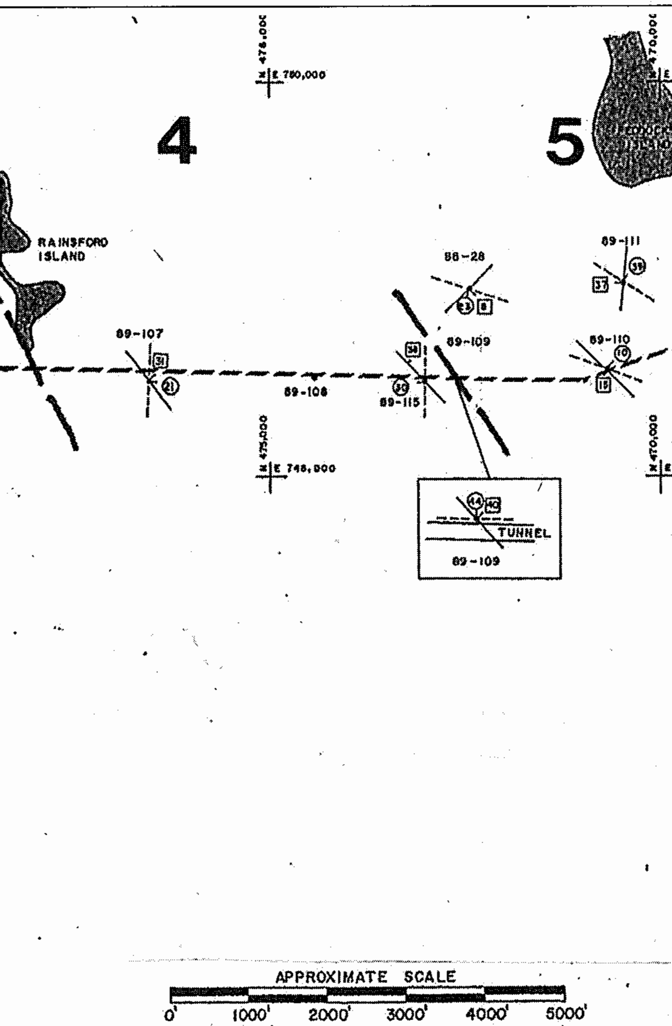


From Sverdrup (1990a)

FIGURE 7-26. Map showing subdivisions of the Cambridge Argillite and bedding attitudes from oriented core along the Inter-Island Tunnel across Boston Harbor.

structure south of the major fault is normal movement down to the north with rotation of the beds to the south. The slumps suggest that the movement started before the argillite was consolidated from soil into rock.

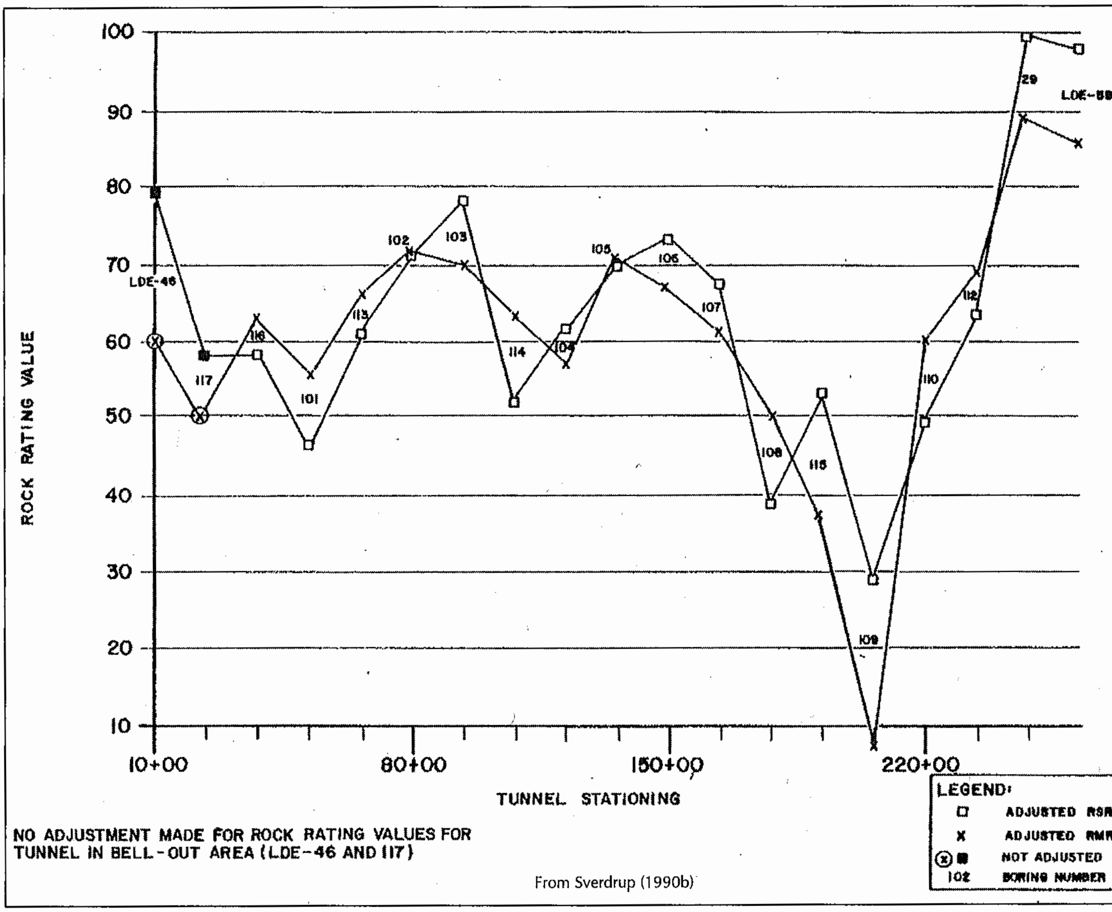
Problems in the tunnel construction resulted from the large fault zone, water inflow and a fire. The broken rock in the fault zone collapsed onto the TBM and caused it to become stuck. This stoppage required hand mining the soft and broken rock for about 30 meters (100 feet) in front of the machine to free it. The tunnel was advanced only 270 meters (900 feet) between May 1994 and June 1995 in crossing this fault zone. The rock fractures in the tunnel produced a larger quantity of groundwater than expected. The groundwater reached an inflow of 20 cubic meters per minute (5,300 gallons per minute) when the excavation was completed, thus requiring a special water treatment facility during construction (Fong *et al.*, 1998). The water inflow was generally between 0.3 to 0.75 cubic meters per minute (80 and 200 gallons per minute) in sections along the tunnel, but it was 0.75 to 3.8 cubic meters per minute (200 to 1,000 gallons per minute) in a 640 meter (2,100 foot) section south of Deer Island and in the major fault zone along with a large inflow through a pipe-like opening just north of the zone. A grouting



BORING No.	NUMBER OF POINTS USED TO DEFINE DIP AND STRIKE AT EACH BORING LOCATION	
	PRIMARY	SECONDARY
LDE-46	6	4
89-117	NONE	NONE
89-116	NONE	NONE
88-26	4	1
89-101	8	1
89-113	8	2
89-102	18	NONE
89-103	1	1
89-114	29	16
89-104	8	NONE
88-27	2	NONE
89-105	17	NONE
89-106	15	1
89-107	4	3
89-108	NONE	NONE
89-115	1	1
89-109	2	1
88-28	4	3
89-110	10	NONE
89-111	2	2
89-112	8	5
88-29	1	1
LDE-58	7	4

program was instituted to reduce this inflow to 4 cubic meters per minute (1,000 gallons per minute). A fire, which resulted from the ignition of a conveyor belt used to remove muck generated by the TBM, caused another delay, but all the miners escaped safely through an emergency shaft on Long Island. Hydrogen sulfide occurred in the rock excavated south of Deer Island and caused a minor problem during construction. In addition, clay-sized material was generated by the TBM excavation through the bedrock and occasionally clogged the cutter head on the TBM, causing delays at times throughout the length of the tunnel.

Deer Island Wastewater Treatment Plant. Deer Island originally was separated from the mainland to the northwest by the narrow Shirley Gut, a ship passage said to be wide enough to keep wolves from the deer that became very prolific (Wood, 1634). Currents gradually filled in the gut to the point where a road could be built crossing it (Snow, 1935), transforming the island to a peninsula (see Figure 7-18). Deer Island served as a site for a concentration camp, alms house, signal station, quarantine station and more recently a house of correction and a pumping station for the North Metropolitan Sewage District. The sewage received limited treatment and was discharged into Massachusetts Bay via short outfalls at the south end of the island. The island is now the site of the large MWRA Deer Island Sewage Treatment Plant, which is the centerpiece of the Boston Harbor cleanup (see Figure 7-19). The plant receives wastewater from the North Metropolitan Relief and Main



From Sverdrup (1990b)

FIGURE 7-27. Rock ratings along the Inter-Island Tunnel alignment.

Drainage tunnels from the west and the Inter-Island Tunnel from the south for treatment and then sends the treated water seaward through the Deer Island Outfall Tunnel and sludge back through the Inter-Island Tunnel for further treatment (see Figure 7-1).

Construction of the vast plant required almost all previous structures be removed and a near leveling of the island, along with very extensive exploration. The island was investigated by an extensive network of boreholes, which provide an exceptional three-dimensional view of the geology and its stratigraphy (Goldberg-Zoino Associates, 1983; Metcalf & Eddy, 1990a & 1990b). Simply put, the island was formed of drumlins overlapped by marine clay and capped by organic sediments. A large east-trending drumlin, which reached about 34 meters (111 feet) MSL in height and formed the southeast end, was separated by a lowland from a small and narrow about 21 meter (70 foot) MSL high southeast-trending one to the north, with the whole surrounded by a broad shoal (see Figure 8-28). The east end of the main drumlin was incised by a south-trending channel. Argillite is found at depths of –14 to –24 meters (–47 to –80 feet) MSL in the central part and drops off to about –30 meters (-100 feet) MSL at the southwest shore (see Figures 7-29 & 7-30). A 3 meter (10 foot) plus layer of gravel and cobbles between the till and argillite found in one boring at the west side of the main drumlin is apparently part of the similar deposit discovered at the southeast edge of the island (Figure 3-76) and may represent an esker or early glacial retreat deposit. The till is incised by channels filled by marine clay in the lowland and along the northeast side, which overlaps the till on the southwest (see Figure

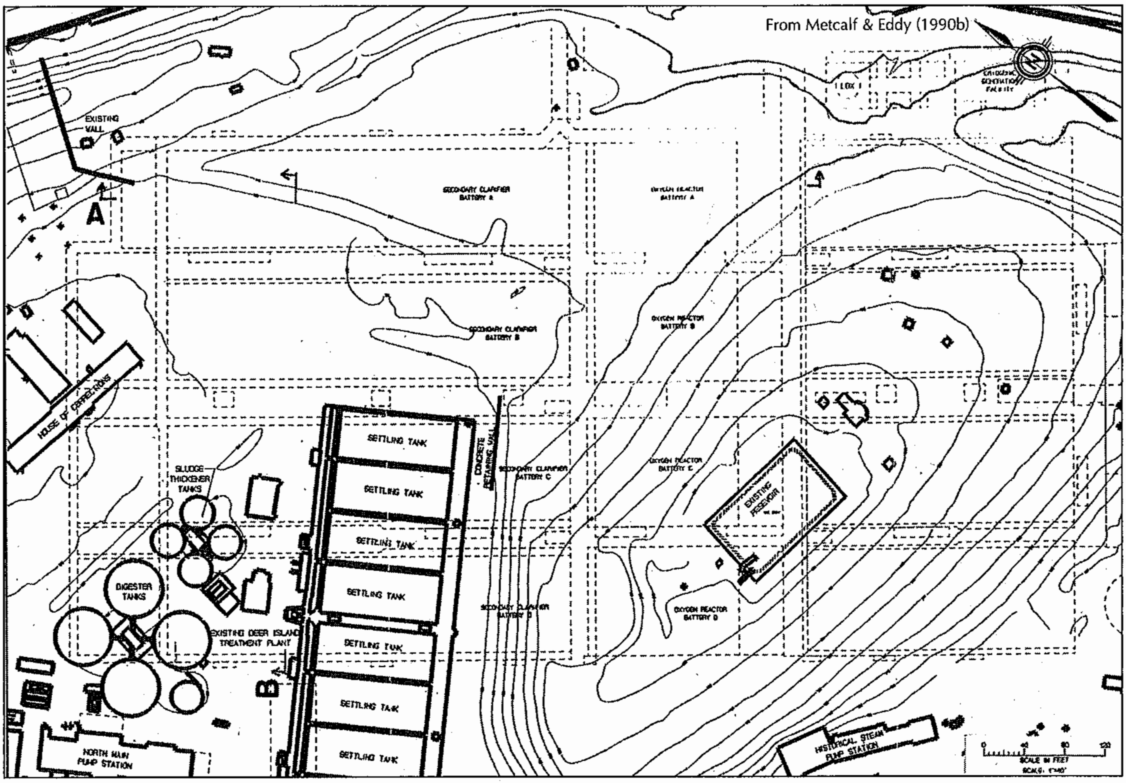


FIGURE 7-28. Central Deer Island prior to leveling, showing the central drumlin and a portion of the northern one and the location of sections.

7-31). The clay reaches 14 meters (45 feet) in thickness in a channel in the lowland and over 18 meters (60 feet) in the overlap at the southwest shore. In places, the channels cut through the till into the argillite at –14 meters (–45 feet) MSL elevation. Those channels in the lowland slope eastward along the northeast shore. The top of the gray marine clay reaches about 1.2 meters (4 feet) MSL in elevation onshore and it has a yellow oxidized cap just offshore to the southwest. A local channel in the clay itself in the center of the lowland has a fill of upper outwash. An irregular layer of brown silty to sandy clay, silt and peat 0 to 9 meters (0 to 30 feet) thick covers the marine clay areas and in places may extend to over 6.1 meters (20 feet) MSL in elevation. Some of this material fills shallow channels in the marine clay and most (if not all) represent the organic deposit, which overlies the marine clay off the southwest shore. Very locally sand and gravel, which extends up to about 3.7 meters (12 feet) MSL elevation and overlies the organic deposit, may be beach sediment.

A fractured fault zone found at the southern shore apparently continues northeastward to form a low-velocity zone near the Deer Island Outfall Tunnel. However, too little bedrock was explored to locate any additional faults onshore.

Deer Island Outfall Tunnel. The outfall tunnel from the Deer Island Treatment Plant extends 15.3 kilometers (9.5 miles) in a northeasterly direction into Massachusetts Bay and is the largest ocean outfall tunnel in the United States (see Figures 7-1 & 7-32). The tunnel has a maximum capacity of 5.8 million cubic meters per day (1.27 billion gallons per day) in conveying the secondary treated effluent to an area in Massachusetts Bay where currents allow the effluent to mix well with ocean water. The effluent is discharged into the bay through a diffuser system, which consists of fifty-six vertical pipes to the sea floor over the last 1,677 meters (5,500 feet) of the tunnel, the

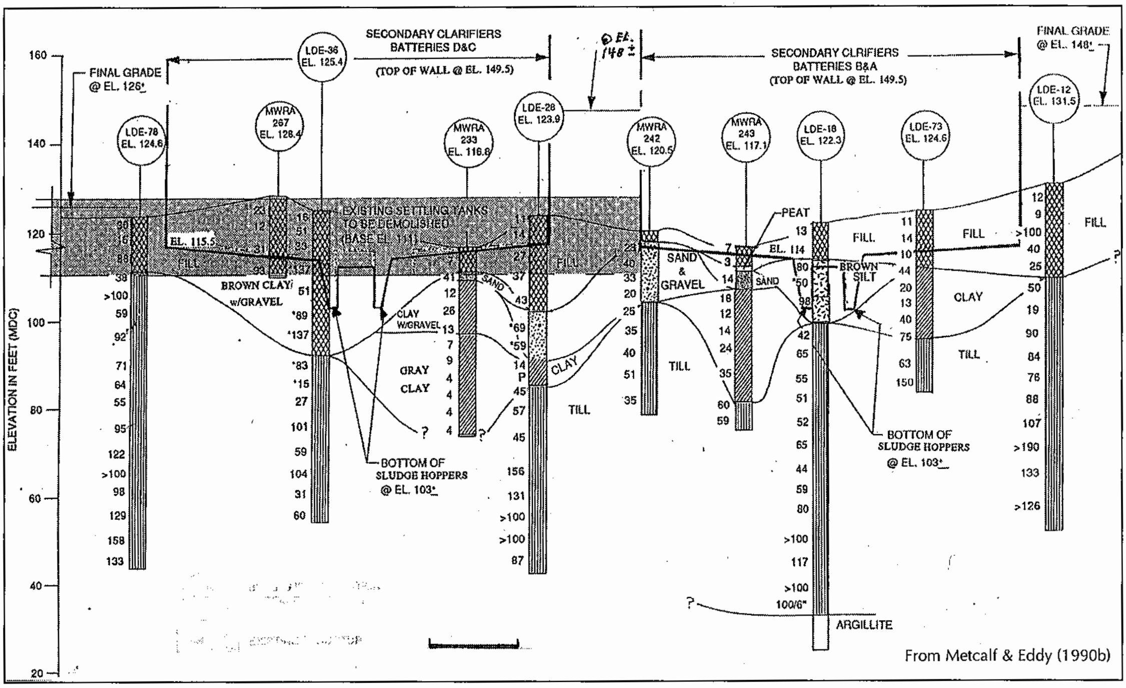


FIGURE 7-29. Southwest-northeast section across central Deer Island between the central and northern drumlins showing small marine clay-filled channels. (Location B is shown in Figure 7-28.)

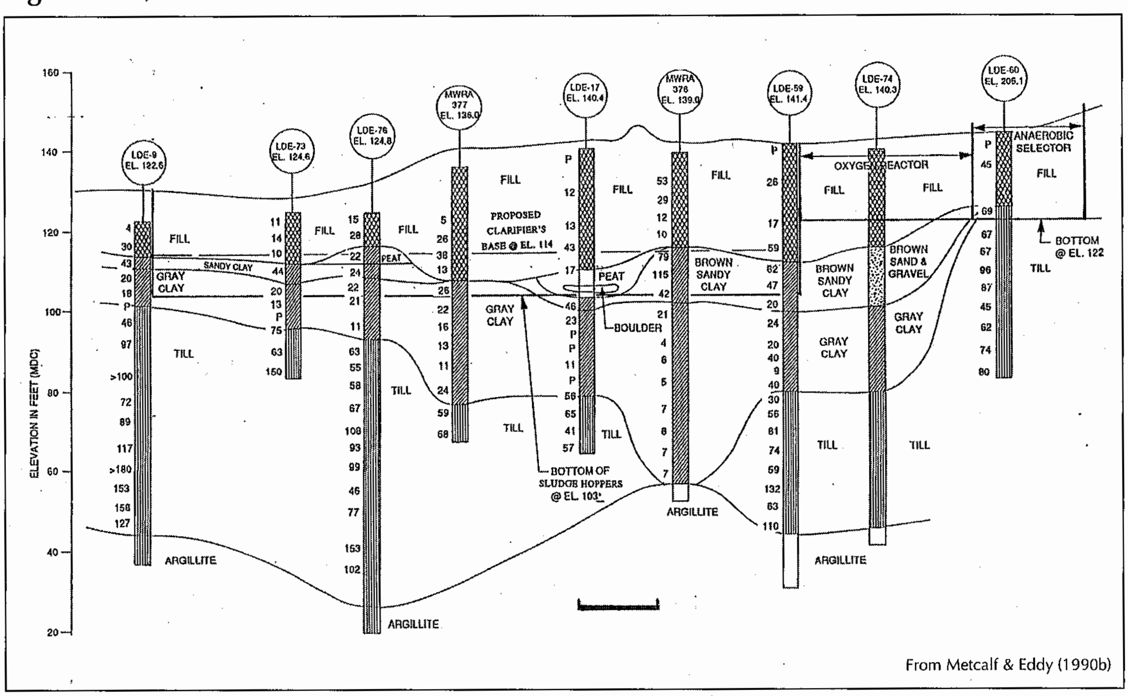
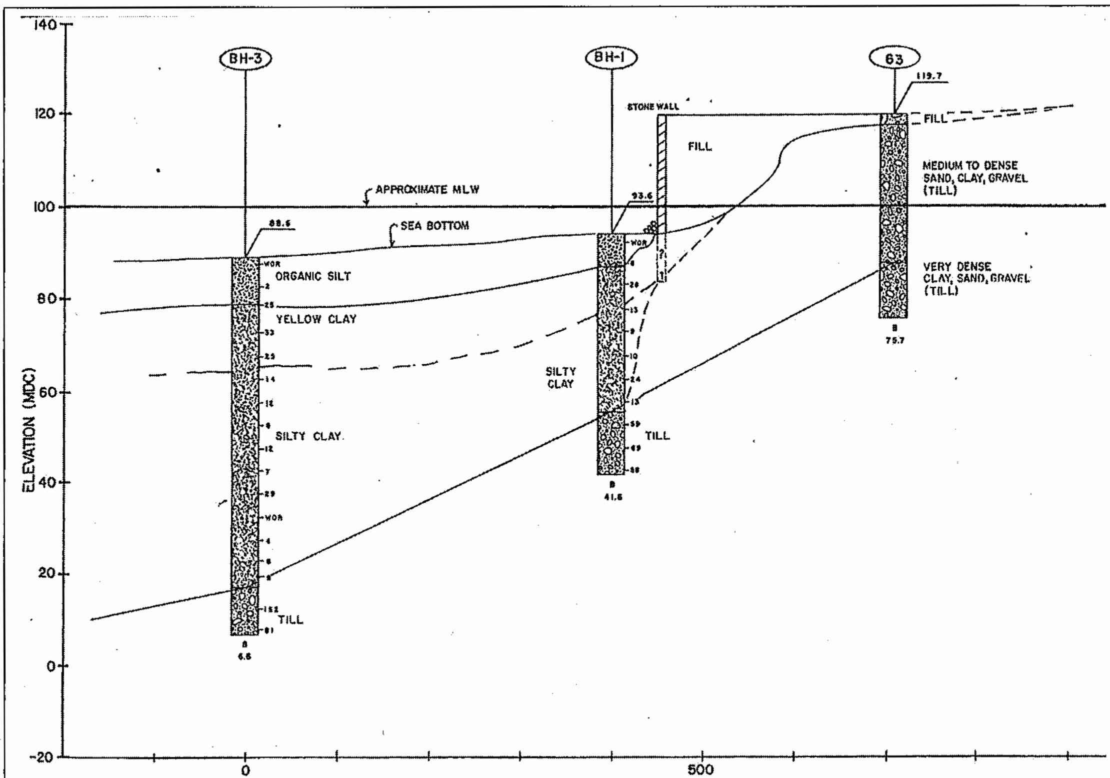


FIGURE 7-30. Northwest-southeast section across central Deer Island between the northern flank of the north drumlin and the eastern flank of the middle drumlin showing marine clay filled channel in the till (view northeast). (Location A is shown in Figure 7-28.)



From Goldberg-Zoino Associates (1983)

FIGURE 7-31. Northeast-southwest section at the southwest shore of central Deer Island near the old piers showing the marine clay with an oxidized top and overlying organic deposit lapping onto the till (view northwest).

top of which is 30 meters (100 feet) below the sea floor. Excavation began July 1992 and was completed in 1998, and the outfall started operating in September 2000. The tunnel is drilled 8.08 meters (26.5 feet) in diameter by a Robbins TBM, which was purchased specifically for this project and was left buried beyond and below the tunnel level at the end of its drive. A segmented concrete liner was installed behind the TBM as it moved forward and, thus, limited the amount of geologic data that could be obtained from direct observation of rock that was drilled through. The tunnel excavation cost $390 million, which was about 10 percent of the total harbor wastewater treatment project.

The tunnel alignment parallels the regional trend of the Boston Basin and extends eastward into an area of northwest-trending bedrock lineaments (see Figures 3-72 & 7-33). The tunnel lies within the Cambridge Argillite, which includes a few tuffaceous beds of the formation, along with diabase and lesser basalt, andesite and felsite dikes and sills — all of which are covered by marine clay and other surficial deposits (see Figures 7-34 & 7-35). The bedding in the argillite is generally 1 millimeter to 8 centimeters (0.04 to 3.2 inches) and is normally very tight, but the rock proved more fractured than predicted. This blocky ground slowed the TBM and caused a high water inflow that reached an extremely high volume of 19,000 to 21,000 liters per day (5,020 to 7,030 gallons per day) in some reaches of the tunnel.

Some borings were drilled during tunnel location planning, exploring a fan-shaped area east of Deer Island for possible tunnel routes. The top of the argillite rose from nearly elevation –18 meters (–60 feet) MSL east of the island to about elevation –12 meters (–40 feet) MSL 1.6 kilometers (1 mile) farther and then

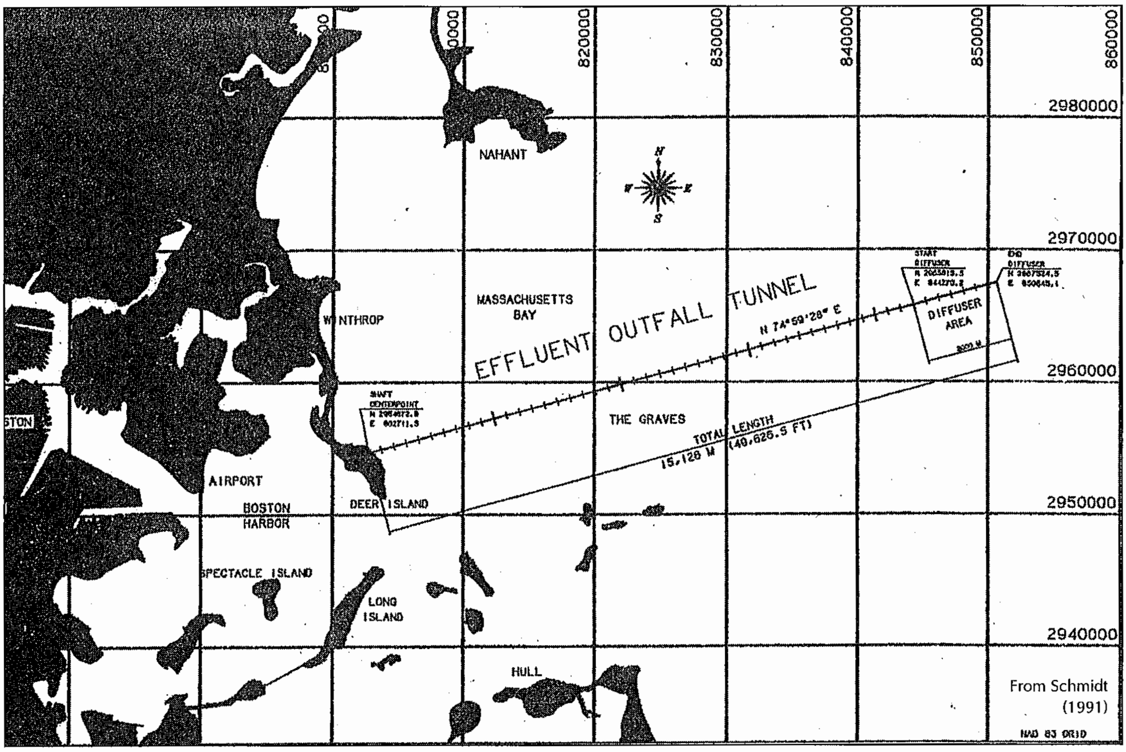


FIGURE 7-32. Map showing the location of the Deer Island Outfall Tunnel.

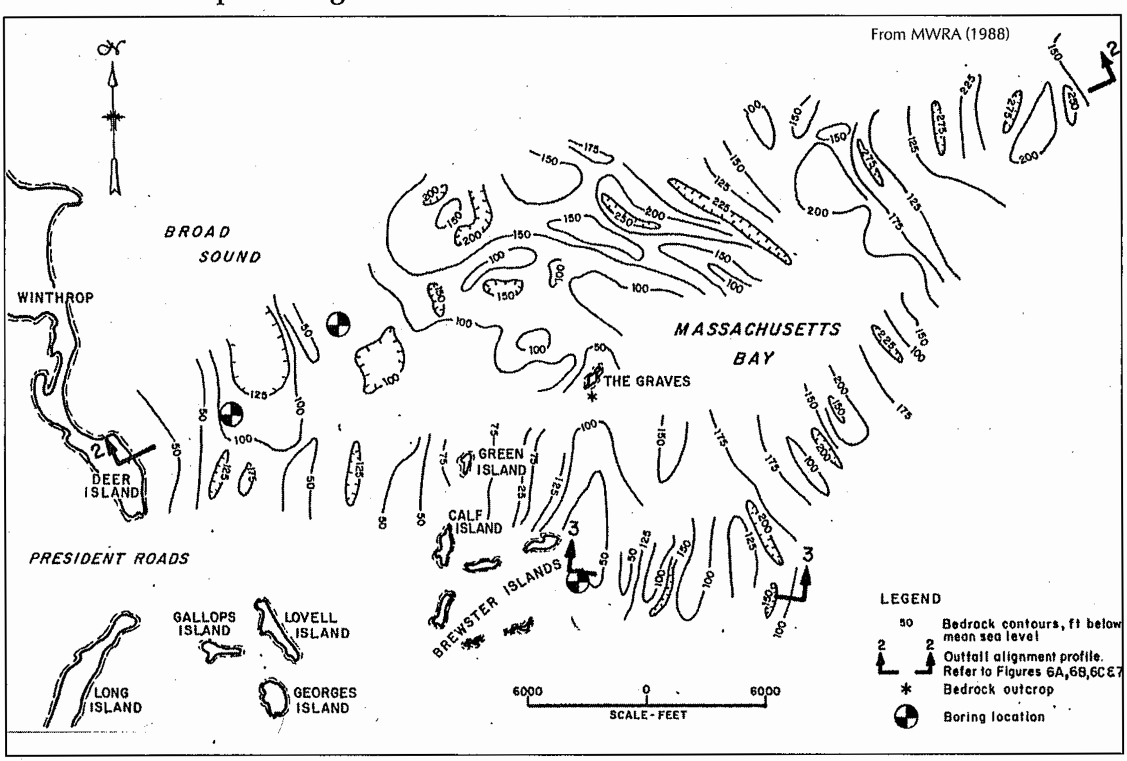


FIGURE 7-33. Bedrock surface along the route of the Deer Island Outfall Tunnel.

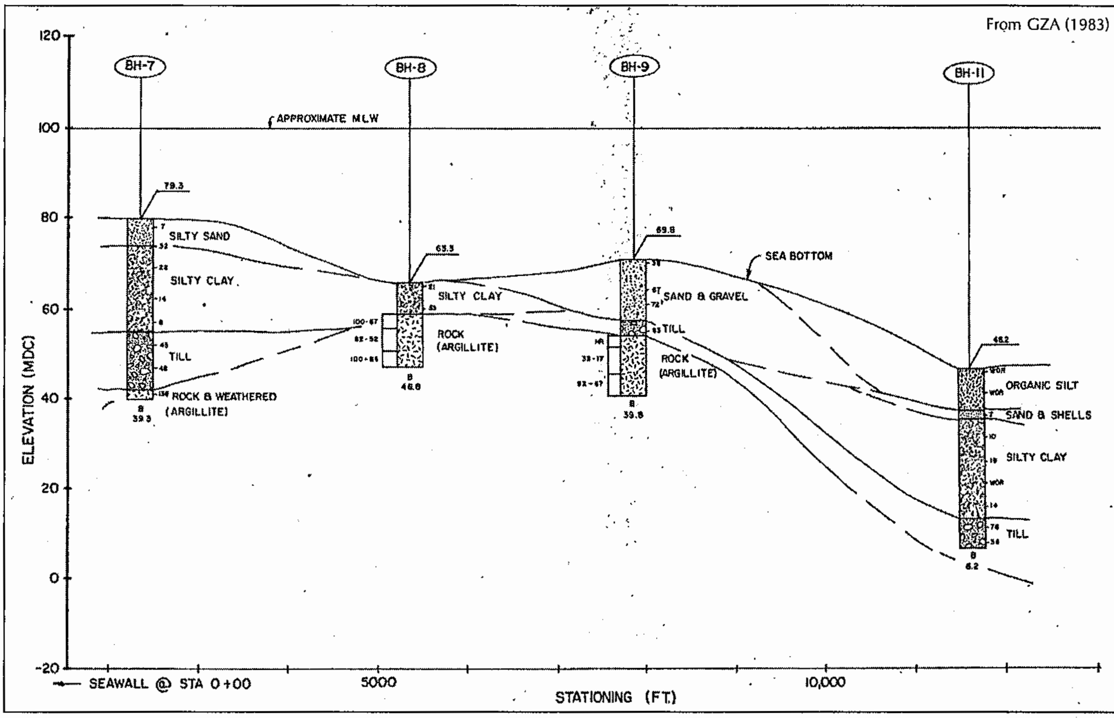


FIGURE 7-34. Surficial geology interpreted from borehole data along the western end of the Deer Island Outfall Tunnel.

dropped below elevation –27 meters (–90 feet) MSL 3.7 kilometers (2.3 miles) east of the island (Goldberg-Zoino Associates, 1983) (see Figures 7-33 & 7-35). The thickness of the overlying till is extremely variable, but its surface generally reflects the bedrock surface (see Figure 7-35). The overlying marine clay also is missing locally on the rise and thickens again to over 9 meters (30 feet) thick at the eastern-most boring. An overlying silty sand and sand and gravel 0 to 3.6 meters (0 to 12 feet) thick may be a beach or bar deposit, but could be related to the organic deposit, which is present to the east. These borings do not show the presence of the lower outwash as at Deer Island and the upper outwash also may be absent.

Marine geophysical surveys indicated a highly irregular bedrock surface (see Figure 7-36) and a low-velocity zone extending northeastward from the south end of Deer Island parallel to the basin structure and in the proposed route for the tunnel (Weston Geophysical, 1988). This zone projects into the fault zone found at the south end of Deer Island in the exploration for the Inter-Island Tunnel. The route had to be adjusted around the low-velocity zone, but other possible structures also are indicated. A zone of northwest-trending topographic features in the bedrock surface probably indicates that there is a zone of cross faults (as occurs on land) and other local trends are present. Some of these potential faults would be responsible for the high water inflow. The range of velocities encountered in the bedrock reflect the changes caused by different rock types and their degree of fracturing.

Braintree-Weymouth Tunnel. The $200 million Braintree-Weymouth relief facilities project was undertaken to correct chronic sewer surcharge, and backup and overflow problems in six towns at the south side of Boston harbor (see Figure 7-1). The 3.7 meter (12 foot) diameter tunnel extends northward 4.6 kilometers (2.9 miles) from the former Sprague Energy site along the Fore River at Route 3A in Weymouth to Nut Island where it ties into the Inter-Island Tunnel. This tunnel carries the wastewater from the MWRA's new pump station at the Sprague site via a

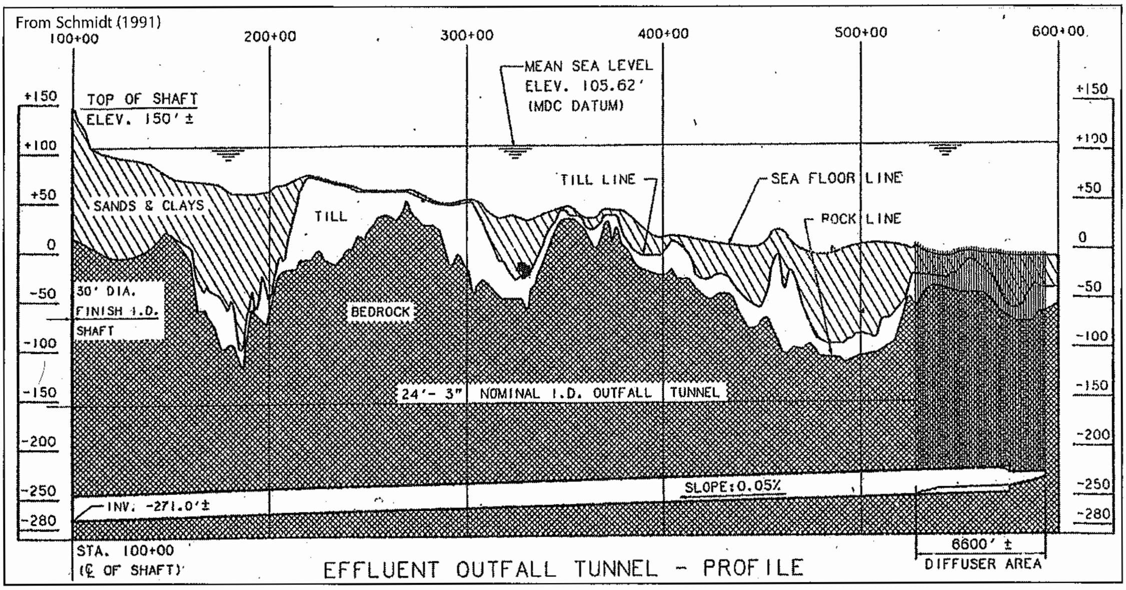


FIGURE 7-35. Geologic section along the Deer Island Outfall Tunnel.

connection at the base of the Nut Island shaft to the treatment plant on Deer Island. This tunnel also returns sludge to the MWRA fertilizer plant located along the Fore River in Quincy (see Figure 7-37). The sludge and wastewater flows are through separate ductile iron pipes.

The tunnel has several rather shallow segments, but does descend as deep as 76.2 meters (250 feet). It has a main North Weymouth Shaft (see Figure 7-38) near the south end and access shafts at either end. The 940 meter (3,000 foot) long portion south of the main shaft was excavated by drill and blast, and the remaining 3,660 meters (12,000 feet) to the north by a TBM. The tunnel was backfilled with concrete after two 1 meter (3.3 foot) diameter wastewater pipes and five smaller ones were installed. This $73 million portion of the overall Deer Island Project began in June 1999 and was completed March 2003. The tunnel has directionally drilled siphons through surficial material under Fore River. Directional drilling was used for two north-northwest-trending, nearly 1.2 kilometer (3,900 foot) long 1 meter

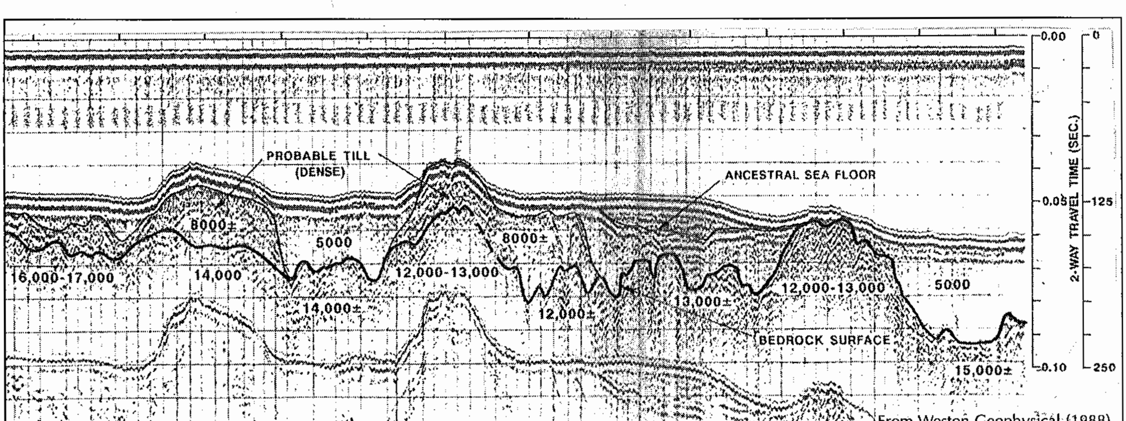


FIGURE 7-36. Typical north-south geophysical profile near the outer Deer Island Outfall Tunnel.

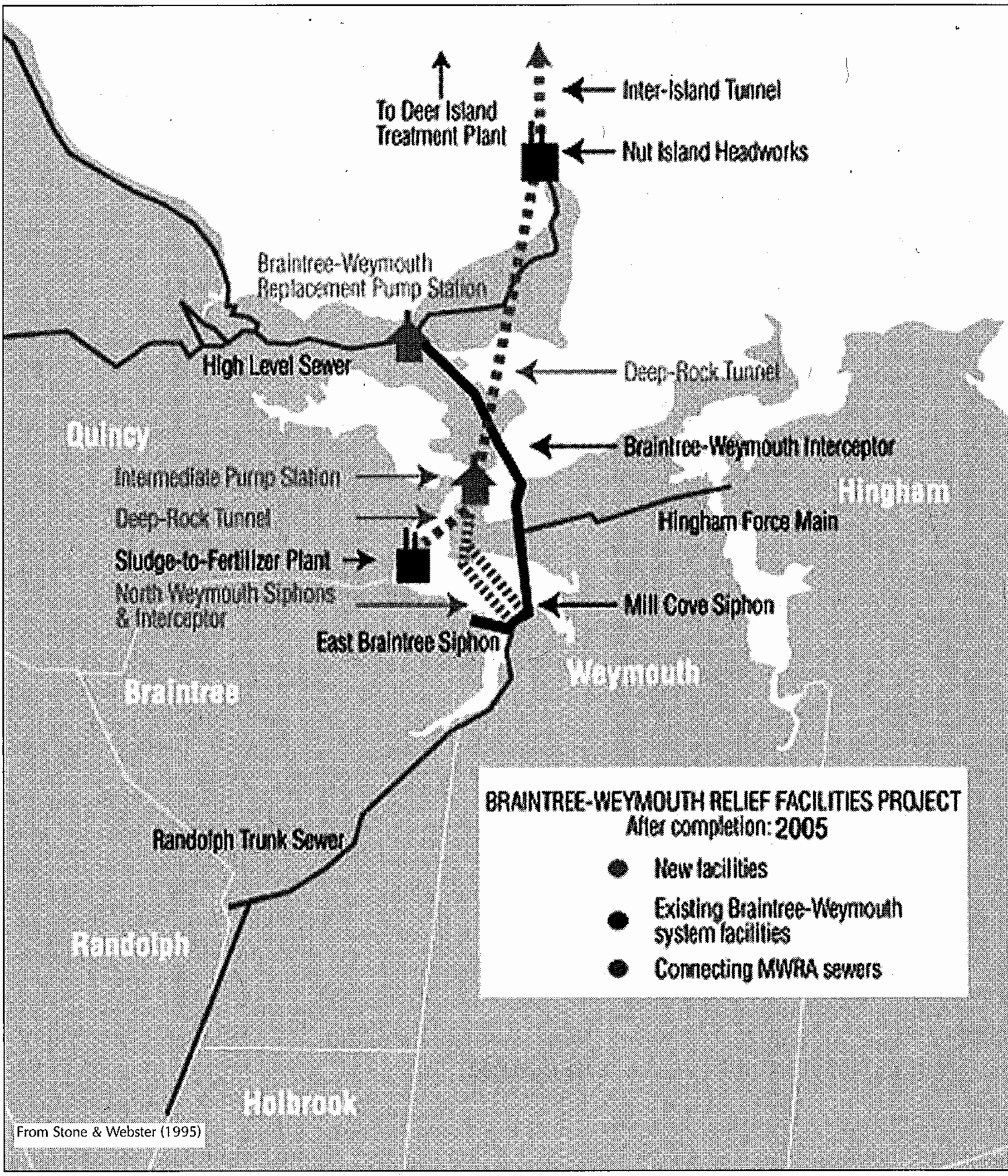


FIGURE 7-37. Map of the Braintree-Weymouth Tunnel and associated structures.

(36 inch) diameter siphons 18 meters (60 feet) under the Fore River. These siphons are connected to the tunnel via a new pump station by a 1.5 meter (60 inch) diameter interceptor (Angelo, 2004). The combined siphons were probably the longest and largest diameter of such horizontal bores in the world. This work began in September 2000, but its completion was delayed until 2004 by an access problem.

Exploration for the Braintree-Weymouth Tunnel and mapping of partial sections of the tunnel (see Figures 3-53, 7-37 & 7-38) reveal the geology at the southern edge of the Boston Basin (Stone & Webster, 1995; Deere *et al.*, 2004). The bored portion consists of two sec-

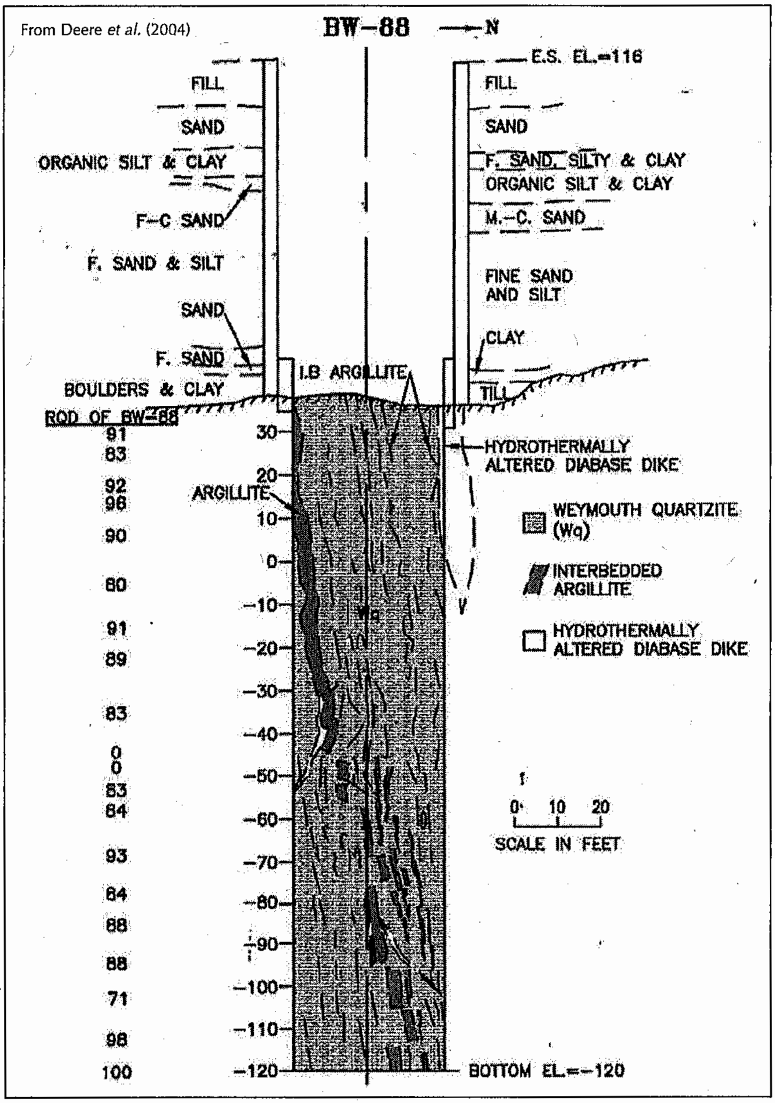


FIGURE 7-38. Section of the North Weymouth Shaft of the Braintree-Weymouth Tunnel.

tions of Cambridge Argillite separated by a east-west-trending fault zone containing a sliver of Roxbury Conglomerate, which crosses the middle of Hough's Neck as shown by LaForge (1932) and confirms his Rock Island Fault. Many mafic dikes, some of which are hydrothermally altered, cut the tunnel alignment. The beds dip between 60 degrees north and vertical. The borings and tunnel mapping to the south along the alignment of the Fore River, which separates the island from the mainland, show severely fractured rock at the faulted border of the basin with the Cambrian Weymouth Formation, marking the Southern Boundary Fault of LaForge (1932). The rock of the rest of the southern end of the tunnel consists of narrow alternating bands of Weymouth Formation quartzite and Quincy Granite with both faulted and intruded contacts.

Both the Rock Island Fault and the Southern Boundary Border Fault Zone trend west-northwest. The Southern Boundary Border Fault Zone is formed of north-dipping thrust faults. These faults, along with the rest of the tunnel, are cut by numerous northwest-trending faults and a few north-northwest and north-northeast-trending ones. Closely spaced northwest-trending faults cut the southern end of the tunnel. Billings (1976a) had reinterpreted the Roxbury slice in the Rock Island Fault Zone as a "Hough's Neck Anticline" (see Figure 1-33). He described a volcanic flow rock in the Roxbury as a "melaphyre," which was thought to represent the older rock unit at the core of the anticline. The flanking conglomerate was assumed to be younger and to form the limbs of an overturned anticline. However, the tunnel data demonstrate the Roxbury Conglomerate is the older unit and does not form an anticline (Stone & Webster, 1995).

During tunnel construction, a cave-in occurred in the Cambridge Argillite that formed a 7.6 meter (25 foot) tall chimney in one zone of highly fractured bedrock, which required substantial support (Deere *et al.*, 2004). A side wall in argillite also collapsed due to the slippage of a wedge bounded by two shear zones and a zone of highly fractured sandstone in the Cambridge Argillite, which also caused the jamming of the TBM. In addition, fractured quartzite of the Weymouth Formation in the main shaft required more support and work to stop excessive water inflow.

Exploration across Fore River for the siphons shows that the Quincy Granite-Weymouth Formation contact is near the south side of the river (see Figure 7-39), but the low point in a channel cut into the argillite is at about elevation –43.6 meters (–143 feet) MSL, and is nearer the north side of the river (Metcalf & Eddy, 2003). In between, the RQD in the borehole cores is usually zero and indicates that a broad zone of faulting is present.

Till is about 21 meters (70 feet) thick on the south side of the Fore River and thins to 3 to 6 meters (10 to 20 feet) over the bedrock in the river. The till is overlain by sand on the north side of the river. The bedrock channel under the river and over the till is filled with marine silt, sand and clay, and capped by a wider deposit of organic clay. The sand and gravel of the till on the south side appears to be a buried esker (Martin, 2009). The siphons lie mostly in the esker and marine deposits. Only very thin till remains to the north in the 24 meter (80 foot) thick surficial section at the main shaft of the tunnel (Deere *et al.*, 2004), where it is overlain by sand and silt, organic silt and clay, and sand and fill (see Figure 7-39). At this location, the position of the marine clay appears to be represented by sand and silt that represents a near-shore facies. To the north at the Intermediate Pump Station, the clay is overlain by a thin channel-fill of gravel, which may be a distal upper outwash deposit (see Figure 7-40). This deposit is overlain by a complex sandy organic deposit.

Wellesley Extension Interceptor Sewer Tunnel. The 11 kilometer (6.8 mile) long, 1.5 meter (5 foot) diameter pipe of the Wellesley Extension Interceptor Sewer Tunnel in western Dedham was designed to end sewer overflows into the Charles River from Newton, West Roxbury, Brookline and Dedham (see Figures 7-1 & 7-41). This very shallow tunnel had to overcome several challenging construction conditions, which resulted in problems, especially east of the Charles River where the tunnel passes through a hill of both bedrock and glacial sediments in an urban setting. In this area, the 480.5 meter (1,576 foot) long bedrock portion was excavated by drill and blast via a portal on the west, plus a 107 meter (350 foot) portion of mixed face with sand. The 336 meter (1,100 foot) section of surficial material to the east was drilled by a small diameter TBM (Almeraris & Peyton, 1991). The drill-and-blast bedrock portion varies from roughly 3 to 4.5 meters (10 to 15 feet) in diameter. The tunnel runs parallel to and within 4.6 meters (15 feet) of an existing sewer tunnel and under six buildings with as little as 7 meters (23 feet) of vertical clearance (Almeraris & Peyton, 1991).

The western end of the tunnel trended N77°W through a section of bedrock at a great bend of the Charles River, just southwest of the Boston Basin in Dedham. This portion of the tunnel lies within the Late Proterozoic batholitic complex (see Figure 3-53), which consists of an interfingering contact zone of the Dedham Granodiorite and Westwood Granite, which is the border phase of the Dedham, with an older hornblende diorite, and is cut by greenstone dikes and Early Jurassic diabase dikes (Barosh & Woodhouse, 1990 & 2001). Similar greenstone dikes cut Cambrian strata near both the north and south borders of the Boston Basin, but are not found to cut the Late Ordovician granites.

Rock along the tunnel is highly fractured by closely spaced faults and tectonic joints that were mapped in detail (see Figure 3-53). Numerous faults with a spacing of 3 to 4.6 meters (10 to 15 feet) cut the rock. These faults form several fault sets, some of which controlled the dikes and part of the interfingering of the plutonic granitic rock. The area lies at the edge of a broad northwest-trending fault zone, which controls the river bend, and is just south of the east-northeast trending border fault of the Boston Basin (Kaye, 1980a). Surprisingly, relatively few faults of these trends are found in the tunnel. The faults most commonly found trend northeast and north-northeast. The youngest are north-trending near-vertical faults, some of which are intruded by the diabase, which has local shears and gouge due to fault reactivation. These faults

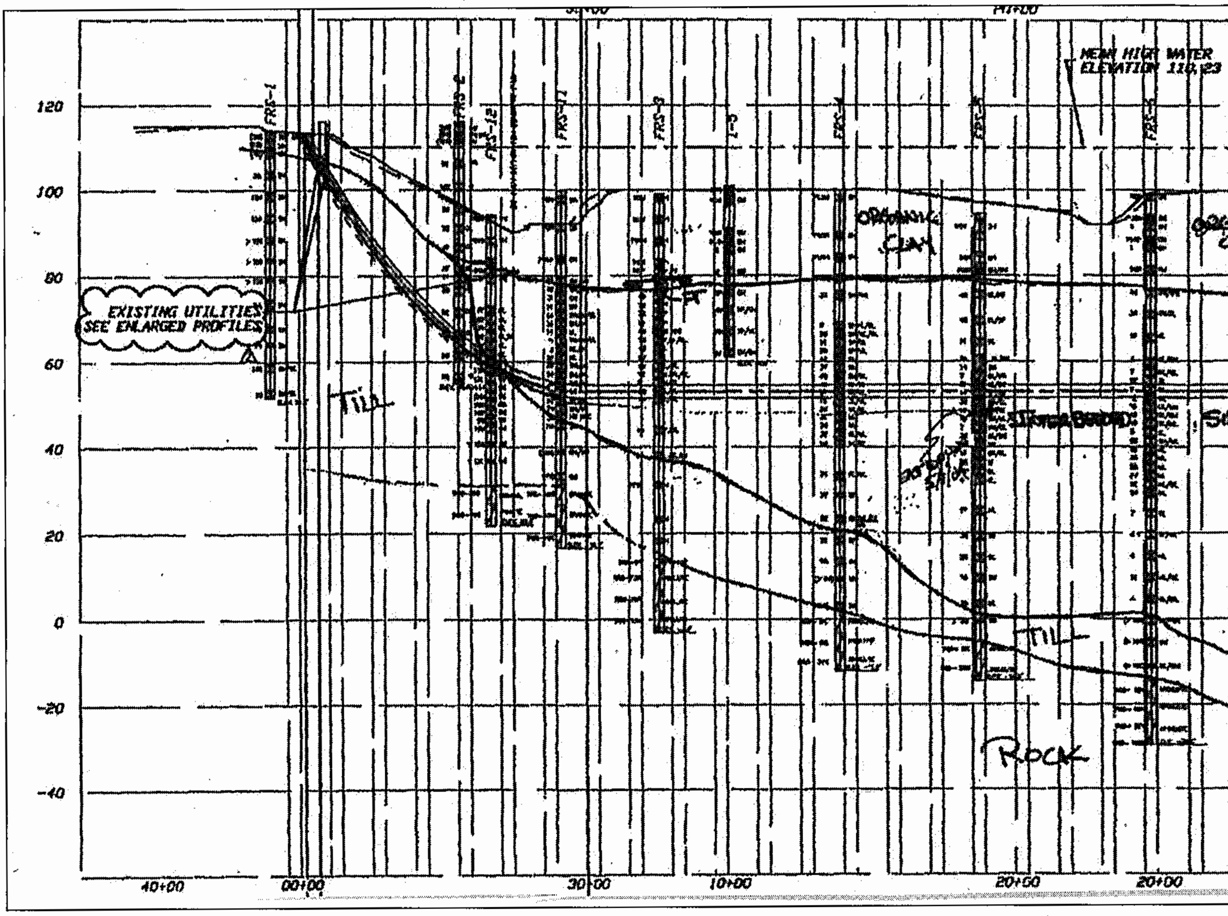
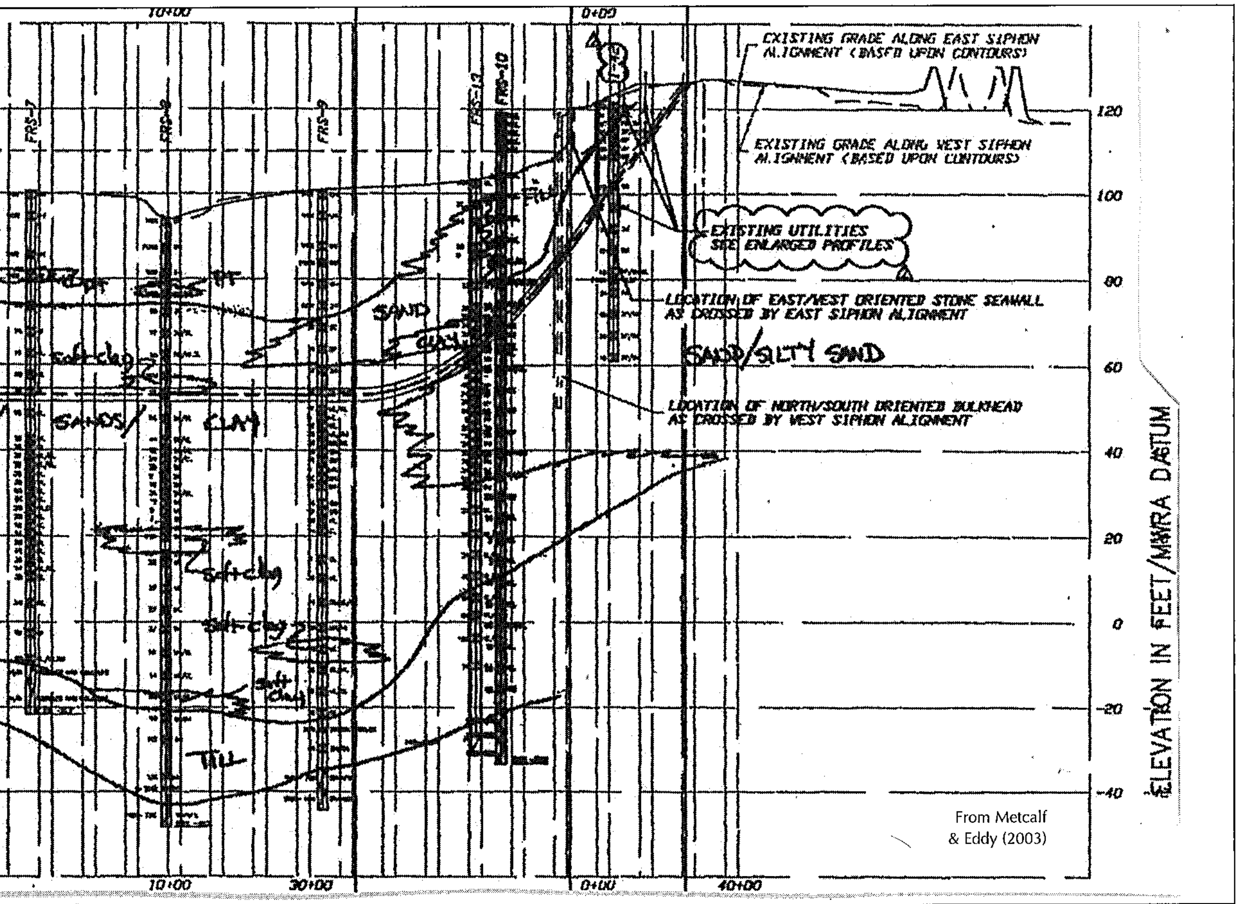


FIGURE 7-39. Section through Fore River for the Fore River siphons.

form the most open zones. Highly varied and closely spaced joint sets are ubiquitous and frequent and are related to faulting, except for the columnar joints in the diabase. The combination of joints and faults cut the rock into blocks 0.3 meters (1 foot) across, but fortunately most fractures are at a moderate to high angle to the tunnel alignment. The use of rock bolts and mesh controlled most of the problem areas.

The tunnel section east of the Charles River ran into a series of difficulties according to Levy (1993). The noise and vibrations from the excavation forced limits on the working hours that extended the length of project to the dismay of nearby home owners. High water inflow occurred (chiefly where the mixed face bedrock-overburden was intercepted) and required constant pumping. The water flowed just above the rock surface through sand and gravel. Fuel oil also dripped into the tunnel along a reactivated vertical north-trending fault bordering a Jurassic dike. The oil apparently flowed from a leaking tank in a nearby basement. Disturbances said to be from the excavation resulted in oil contamination of a water well that then was replaced by city water. The most serious problem occurred in the surficial till, sand and silt, which was drilled by a small-diameter TBM. However, it was stopped by a boulder and had to be dismantled and lifted out through an unplanned excavation, which necessitated extensive grouting and the purchase of a house. Almost all the problems arose from having to work at a shallow depth in a developed neighborhood.

Other problems occurred farther west, where the borings had indicated that gravel



From Metcalf & Eddy (2003)

was to be excavated, but the zone turned out to contain numerous 1.3 to 2 meter (4 to 6 foot) diameter boulders, which greatly increased the difficulty of excavation and cost.

North Dorchester Bay Combined Sewer Overflow (CSO) Storage Tunnel. The North Dorchester Bay CSO Storage Tunnel (also called the South Boston CSO Storage Tunnel) extends from the Conley Terminal near Castle Island in a sinuous fashion southwestward (see Figure 7-42) along the shoreline of South Boston and Dorchester for a distance of 3.4 kilometers (2.1 miles). It is a soft ground, concrete-lined tunnel with a finished 5.2 meter (17 foot) diameter and a crown elevation –9 to –10.5 meters (–30 to –35 ft) MSL. The $225 million project opened in July 2011 (MWRA, 2011). It stores storm water from seven intercepted existing outfalls along Pleasure Bay and Carson Beach and carries it to the terminal for pumping to the MWRA headworks at Columbia Point and thence to Deer Island for treatment. The downstream mining shaft is located at the Conley Terminal and the upstream equipment removal shaft is located at the former Bayside Expo Center. There are three other intermediate shafts and all are constructed down to bedrock. The tunnel was constructed using an earth pressure balance TBM. Tunneling started in January 2008 and finished in September 2008, slightly ahead of schedule. It traversed mostly through sand of the lower outwash and the marine clay (Parsons Brinckerhoff, 2006a & 2006b).

The argillite surface is at elevation –32 meters (–106 feet) MSL at the northeast end and climbs to near elevation –14 meters (–45 feet) MSL before mid-tunnel, where it remains with about a 4.5 meter (15 foot) relief for the rest of its length. The overlying till forms a blanket 1.5 to 6 meters (5 to 20 feet) thick, with no indication of a drumlin or two tills being present. No overlying glaciomarine deposit was recognized from the test borings. Sand of

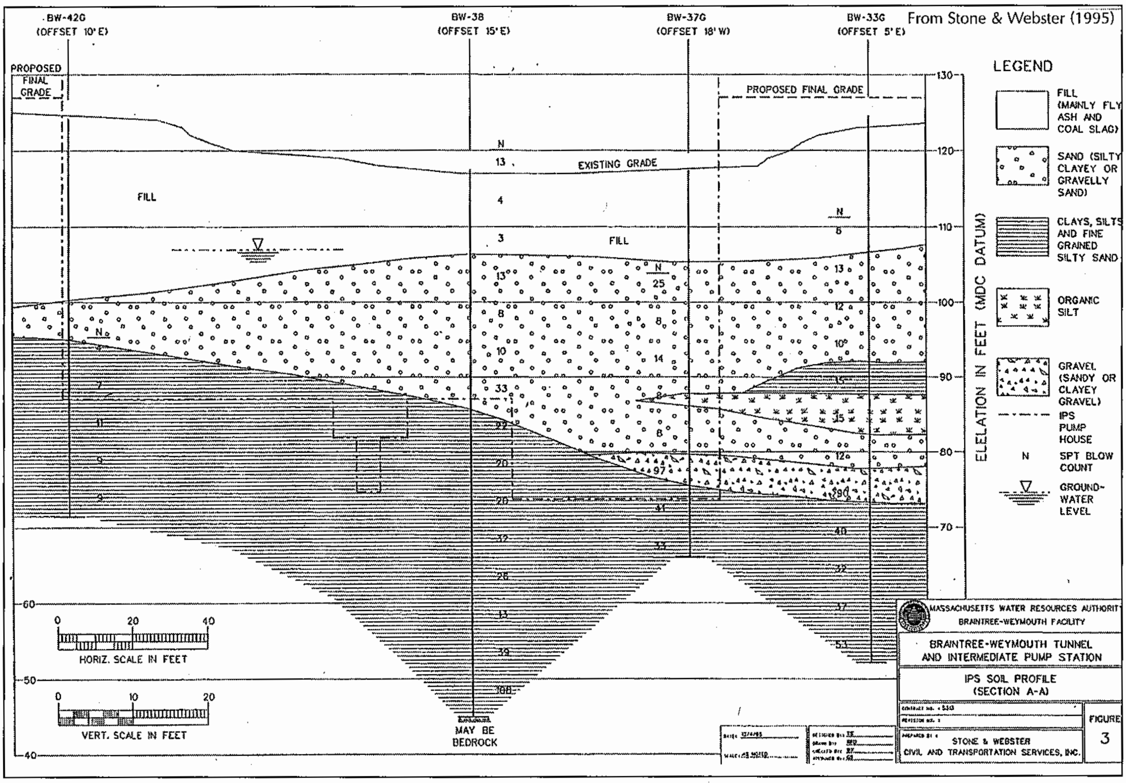


FIGURE 7-40. North-south section through the Intermediate Pump Station above the Braintree-Weymouth Tunnel, west of King's Cove, Weymouth.

the lower outwash above the till is generally thin and may be absent, but is 4.5 to 18 meters (15 to 60 feet) thick in a mound at the south end of Pleasure Bay. The mound separates the overlying marine clay at the north end from that of the rest of the tunnel length. Some thin gravel lenses are scattered in the sand and a thick one is present at the southwest side of the mound. The oxidized surface of the overlying marine clay has three channels cut into it along the northern half of the tunnel. The upper outwash filling the channels is composed of sand, except for the gravel fill of the northeastern one and thin clay lenses at the top. These Pleistocene layers appear to dip to the southeast. Organic sediment usually forms an irregular capping 1.5 to 6 meters (5 to 20 feet) thick, but is very often locally missing. Associated with the organic deposit

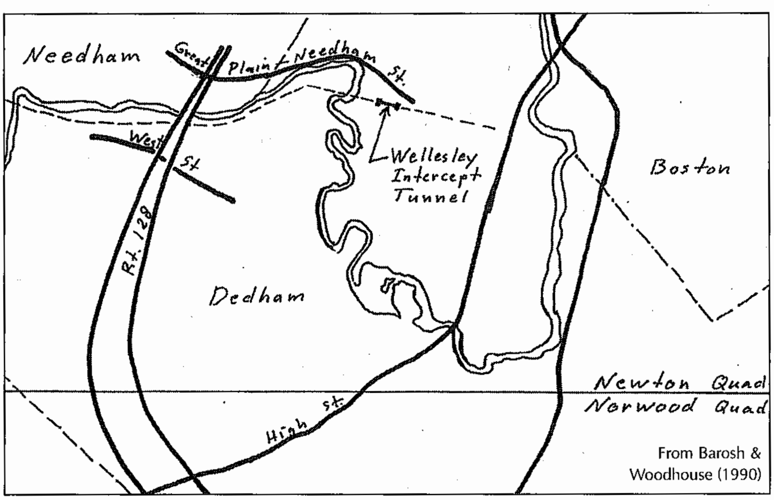


FIGURE 7-41. Map showing the location of the Wellesley Sewer Extension Tunnel in northern Dedham.

FIGURE 7-42. Map of the North Dorchester CSO Storage Tunnel Project. (Courtesy of the MWRA.)

are many lenses of sand, which apparently represent banks from tidal currents or small beach deposits. A continuous fill from less than 1.5 to 7.5 meters (5 to 15 feet) in thickness overlies the tunnel.

No serious water inflow occurred. A polymer was injected through the TBM cutter head to absorb water as the TBM shield passed by. Water was thus sealed out as the tunnel liner was installed and the annulus between the shield and liner was subsequently grouted around the perimeter. Minor inflow of water-sediment mixture occurred only three times as the procedure was adjusted or turned off for a while.

Water Diversion Tunnels

Spring flooding along rivers is a natural annual event that was of some benefit to New England farmers since the grasses that grew along the floodplains formed important pastures, but such floods were a serious problem in developed areas where buildings fronted on waterways. The problem of excess spring rainstorms or summer thunderstorms and hurricane waters is usually handled by runoff control dams and diversion. However, this solution is not always possible in an urban setting. Streams and rivers along which towns were settled were usually narrowed by injudicious filling in order to gain property, thereby both increasing flood problems and limiting solutions. Diverting floodwaters through tunnels was one way to solve the dilemma. These tunnels are built along with a system of surface trenches and pipes to convey the flow to them. Early examples were the shallow Stony Brook Conduits built in the nineteenth century to help relieve flooding in the Stony Brook watershed that covers much of the southwestern side of Boston (see Figures 3-1 & 3-4). Problems associated with these conduits have caused considerable environmental damage. The Malden and Town Brook tunnels (from the north and south sides of the Boston Basin, respectively) are modern examples of deeper rock tunnels for water diversion.

Stony Brook Conduit. Stony Brook ran from Turtle Pond in the Stony Brook Reservoir in West Roxbury, through Hyde Park, Roslindale, Jamaica Pond to the Muddy River in the Fens and into the Charles River (see Figure 3-4). Its clear waters that ran through parts of Jamaica Plain and Roxbury enticed two dozen breweries to locate along its banks, but flood and sewage problems resulted and necessitated the building, from 1851 to 1866, of a shallow cut-and-cover conduit. This conduit was the first of a series to carry excess storm water flows northward to the Charles River. Filling in the Back Bay required an extension just west of the Fens. A large flood that occurred in February 1867 (as well as others in the 1880s) demonstrated that a larger conduit was needed. About 15 centimeters (6 inches) of rain fell during a three-day storm in February 1886 that resulted in water rising over 2 meters (6 feet) on the meadows, flooding 1,620 dwellings and affecting over 3,300 families. A new conduit was designed to handle normal flood water, but not such as that from the 14.2 centimeters (5.63 inches) of rain that fell on adjacent Waltham in three hours on August 21, 1860 (Francis *et al.*, 1886).

The new 1,385 meter (4,542 foot) long conduit was built from 213 meters (700 feet) above Centre Street to end at the Fens, rather than at the Charles River (see Figure 7-43). It picks up the drainage of Stony Brook, Canterbury Brook, Bussey Brook and Goldsmith Brook. A water diversion through a rock ridge to the Neponset River was considered, but it was rejected because of cost. The new 5.2 meter (17 foot) wide by 4.6 meter (15 foot) high, largely brick conduit was constructed from 1888 to 1889 by cut and cover, with a 1.5 meter (5 foot) fall in grade down to the average high tide. The conduit was cut into Roxbury Conglomerate at its upper end to the head of Halleck Street and over mud for 168 meters (550 feet) in Parker Street where wood pilings were needed for support. The tunnel replaced 1,951 meters (6,400 feet) of the old, smaller conduit, which was later cut off to change from a water tunnel into a combined sewage and water conduit.

Between 1867 and 1906, Boston spent over $3 million on these and other improvements. More money was needed when the conduit was replaced by an 11 kilometer (7 mile) long, 3.7 meter (12 foot) diameter concrete pipe in 1934. The conduit still operates under Parker and Gurney streets in Roxbury and under the MBTA Commuter Rail and Orange Line subway structure. The combined sewage and storm water in the conduit continued to have many overflows into the Charles River. A $45 million project was undertaken between 2000 and 2006 to separate the combined flows to send only the relatively clean storm water to the Charles River and the wastewater to Deer Island. This project required 22,561 meters (74,000 feet) of new storm drains. Now sewage overflows rarely occur.

Malden Tunnel. The 1,605 meter (5,266 foot) long Malden Tunnel was built in the 1950s beneath Malden as part of a system to relieve flooding along Spot Pond Brook (see Figure 7-1). It extends southward through Malden near Malden Square (Billings & Rahm, 1966) and slopes from elevation –84 meters (–276 feet) MSL at the north entrance shaft to elevation –87 meters (–286 feet) MSL at the south shaft. The bedrock cover ranges in thickness from 23 to 76 meters (75 to 249 feet). The 3.8 meter (12.5 foot) finished diameter drill-and-blast tunnel was constructed from 1957 to 1958.

The northern part of the tunnel passes through the Lynn Rhyolite and the southern part passes through the Cambridge Argillite

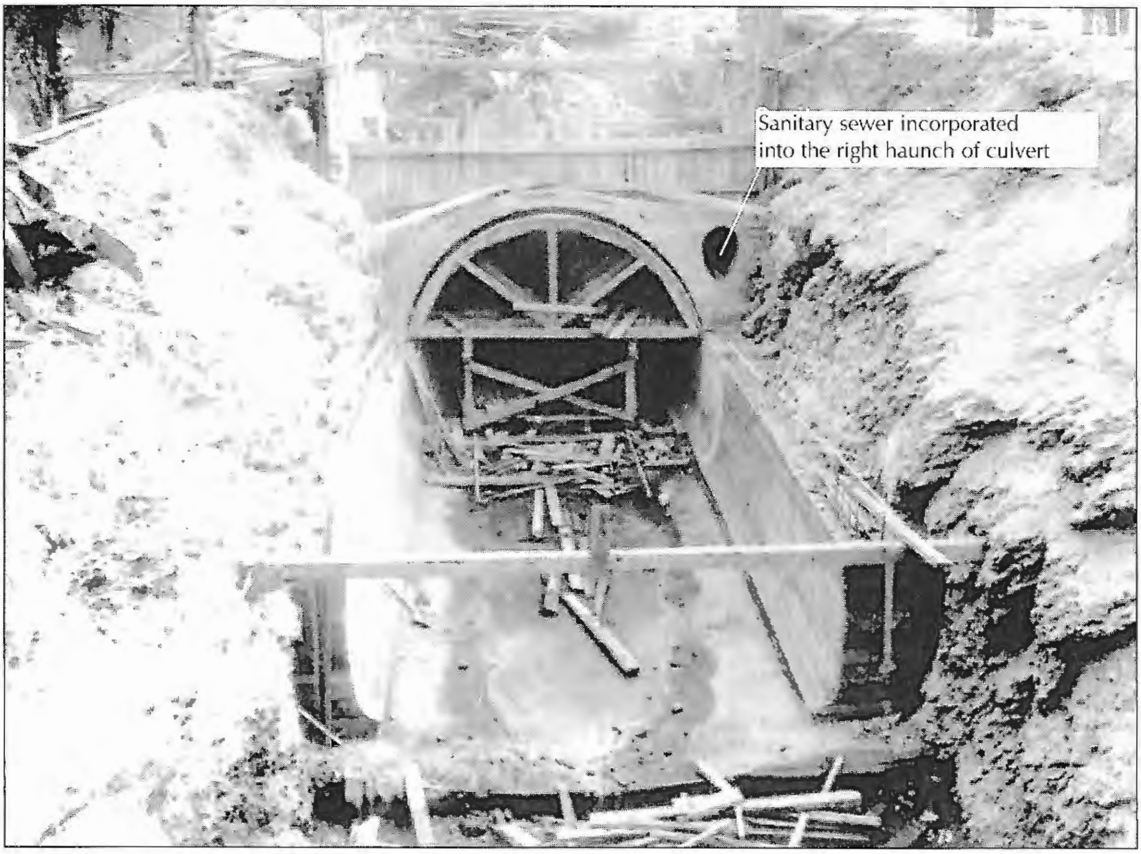


FIGURE 7-43. View of the Stony Brook Conduit being constructed at Forest Hills about 1905, apparently in the Roxbury Conglomerate. (Courtesy of the Boston Water and Sewer Commission.)

and sills and dikes of diabase, with the contact formed by the Northern Boundary Fault of the Boston Basin (MDC, 1956a & 1956b; Billings & Rahm, 1961 & 1966; Billings, 1965). The Lynn Rhyolite consists of felsitic flow-banded lava and an overlying tuff-breccia that are locally separated by thin lenses of porphyry and tuff. These strike to the northeast and usually dip 15 to 20 degrees to the northwest. The very thin-bedded and laminated Cambridge Argillite displays cyclic beds and cross-beds, indicating a source of sediment from the south. Very subtle differences in shades of gray and bedding allowed it to be divided into ten units. The argillite strikes northeast and generally dips 40 to 65 degrees south, but steepens toward the boundary fault and is slightly overturned adjacent to it. Altered and unaltered diabase dikes and altered sills form about eight percent of the tunnel and these are concentrated in the argillite. The dikes are very steep and about parallel to the border fault. The surficial deposits above the tunnel alignment were mapped by a series of boreholes (see Figure 3-104), but had no real bearing on tunnel construction.

The Ordovician Lynn Rhyolite is thrust southeasterly along the Northern Boundary Fault (see Figure 7-44) over the argillite of the Boston Basin (LaForge, 1932). The dip of the fault is 55 degrees north in the tunnel, but borings indicate that the dip flattens at depth (Billings & Rahm, 1966). Billings and Rahm (1966) estimated that the stratigraphic throw exceeded 3,000 meters (10,000 feet) and the net slip at least 4,570 meters (15,000 feet). Gouge, breccia and silica veins are reported absent in the tunnel at the fault zone, but were seen on the surface by Barosh. The fault is associated with close jointing in the argillite for 540

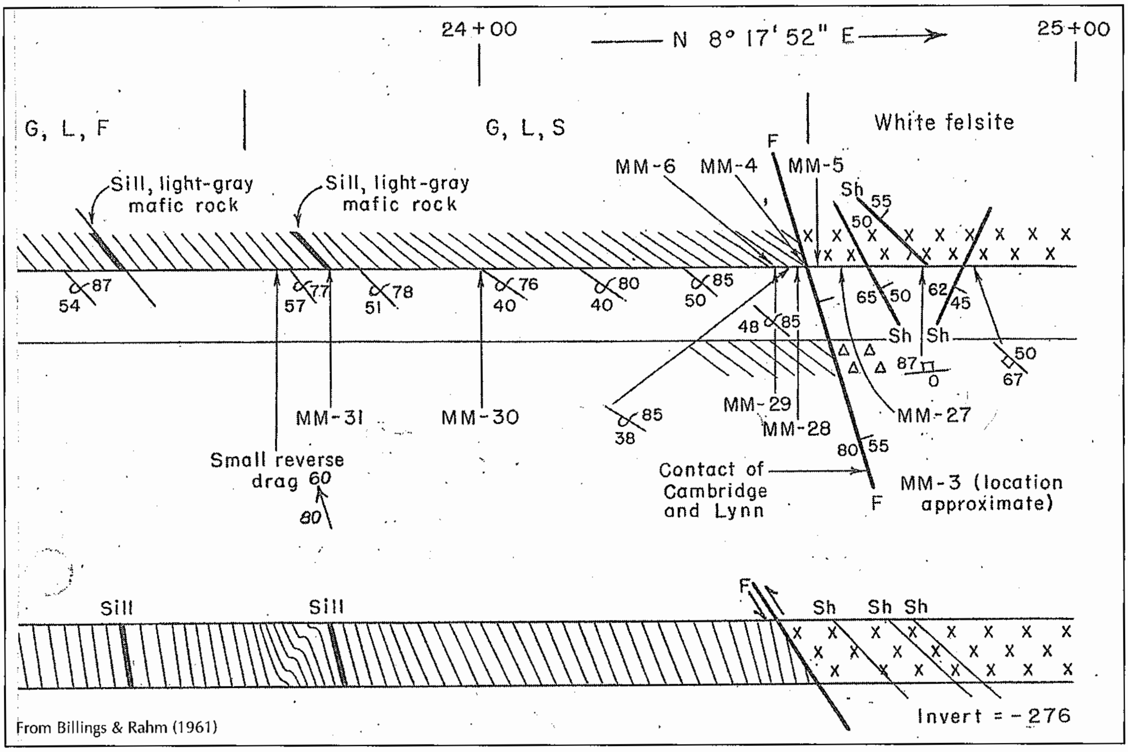


FIGURE 7-44. Portion of the Malden Tunnel crossing the Northern Border Fault of the Boston Basin, forming the contact between the Cambridge Argillite on the south with the Lynn Rhyolite on the north. This section is from along the west wall of the tunnel shown at the bottom (view west) and map view of the west wall data shown on the top.

meters (1,771 feet) south of the fault and for 262 meters (861 feet) north of it in the Lynn Rhyolite. The water inflow into the tunnel when being constructed in this zone was excessive. This broken zone required structural steel for ground support; fifty-two percent of the tunnel needed steel support (Billings & Rahm, 1966).

No faults were mapped in the argillite, but the dikes almost certainly follow faults as they do elsewhere in the Boston Basin. The dikes at the edge of the overturned zone apparently mark the faulted border of drag beneath the Northern Boundary Fault. A zone of roughly parallel faults, called shears by Billings and Rahm (1966), lie north of the boundary fault. However, farther to the north most of the faults dip steeply to the south. At least some of the faults have normal movement, although they still trend east-west. These faults are probably younger ones controlled by the border of the Boston Basin.

Town Brook Tunnel. The Town Brook Tunnel passes beneath the center of Quincy near the southern boundary of the Boston Basin at the east end of the Blue Hills (see Figure 7-1). The frequent flooding over several years in the later nineteenth century along Town Brook in Quincy prompted the mining of this water diversion tunnel underneath the brook, along with improvements to culverts and the Old Quincy Dam in its headwaters. The 4.4 meter (14.3 foot) excavated diameter tunnel extends 1.24 kilometers (4,060 feet) in a northeast direction (about N53°E) and is fitted with a grouted pre-cast concrete-pipe liner 3.8 meters (12.5 feet) in diameter. Flood water from the brook enters a 5.2 meter (17 foot) diameter intake shaft and flows through the tunnel at a depth of about 56 meters (180 feet) under Quincy Center to rise up through a 5.8 meter (19 foot) diameter outlet shaft near the shore (see Figure 7-45). The first 49 meter (160 foot) section from the outlet shaft was mined by drill and blast, and the rest was excavated through rock by a TBM. The tunnel work for the U.S. Army Corps of Engineers cost $24 million. The repairing of the culverts upstream and reconstruction of the Old Quincy Dam (which now lies in Braintree), along with an earth filled dike along the north shore of the reservoir, increased cost by about $15 million. The tunnel construction started November 1993 and was completed by January 1995.

The top of the rock along the tunnel alignment varies in depth (see Figure 7-45) between about 6 meters (20 feet) MSL to –30 meters (–100 feet) MSL for a relief higher than that of the surface (U.S. Army Corps of Engineers, 1986). The low point lies in a north-trending trough that passes south of Hancock Street and reaches below elevation –40 meters (–130 feet) MSL (Metcalf & Eddy, 1980). The thickness of the overburden above the tunnel ranges from 4.6 meters (15 feet) to 38 meters (125 feet). Till up to about 14 meters (45 feet) thick fills the trough, but is thin to absent elsewhere. A thin patchy dense sandy silt to silt 3 to 5.5 meters (10 to 18 feet) thick lies above and beneath a sand and gravel unit, 3 to 24 meters (10 to 80 feet) thick, which forms most of the glacial deposit. Heterogeneous fill forms a generally 1.3 to 3 meter (4 to 10 foot) thick cap, and increases to about 9 meters (30 feet) locally. At the northeastern end near the Town River Bay where the top of the rock is at an elevation of about –15 meters (–50 feet), the overburden section differs. At that location, about 9 meters (30 feet) of a deposit of silty fine sand and silt, with clay in the lower part, is present between the rock and the surficial sand and gravel layer. This layer is about 6 meters (20 feet) thick and covered by organic silt and peat that varies from 1.4 to 3.7 meters (4.5 to 12 feet) in thickness.

The bedrock tunnel intersects the intrusive contact of the Late Ordovician Quincy Granite with the Cambrian Argillite of the Weymouth Formation and the fault contact with the Cambridge Argillite lies at the northeast end of the tunnel. The southwestern 797 meters (2,615 feet) of the tunnel is in granite and the northeastern 441 meters (1,445 feet) is in argillite. The contact zone lies (see Figure 7-45) approximately at tunnel Station 14+45 (U.S. Army Corps of Engineers, 1986; Lachel & Associates, 1996). The Weymouth Formation at the northeast end is light bluish-gray and the remainder appears light to dark-gray. It locally contains interbedded tan, light greenish-gray and white limestone, calcareous sandstone and quartzite. Previously, Kaye (1983d) noted calcareous nodule zones in the light- to medium-gray bedded argillite typical of the Weymouth, which he thought was affected by contact metamorphism. The Weymouth strata are laminated locally. The Quincy Granite is medium to coarse-grained and light-red, pinkish-gray, yellowish-gray and banded white and black in color.

The nature and geometry of the contact is complex, with small to large xenoliths of argillite within the granite and dikes of granite in the argillite. The argillite is altered to hornfels and shows some fracturing at the contact, which strikes to the northwest and dips steeply to the southwest. The granite becomes medium- to fine-grained near the contact.

The granite has numerous joints, but generally has a very high RQD (U.S. Army Corps of Engineers, 1986). It is offset by both relatively small shear and brittle faults. The latter may be calcite-filled or quartz-filled breccia zones. Many fractures have clay, calcite, quartz and chlorite veins. In addition, altered argillite seams, which are throughout the granite, ranged from several centimeters to 1 meter (a few inches to several feet) in thickness that strike N65°W and N80°W, with dips of 63 degrees northeast and 58 degrees northeast, respectively. At least some of these veins and seams are along faults. The RQD of the argillite is variable and much of it is poor to very poor due to close to very closely-spaced joints, and sheared, slickensided and brecciated fault zones.

The exploration program indicated that there were (U.S. Army Corps of Engineers, 1986):

> "two major fracture zones within the site. The first, located within the granite east of the inlet shaft, consists of a highly fractured breccia zone rehealed with quartz and with occasional slickensides. The second zone, located within the argillite west of the outlet shaft, is several hundred feet wide and consists of very highly fractured and slickensided shattered rock" (see Figure 7-46).

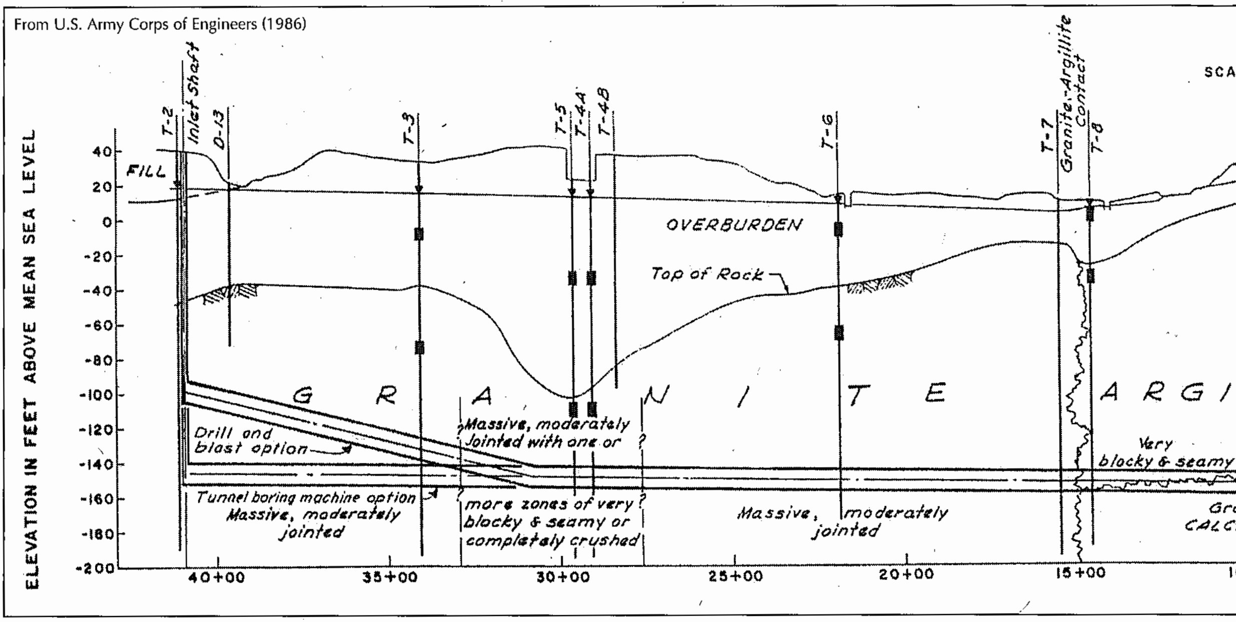


FIGURE 7-45. Section of the Town Brook Tunnel showing contact of Quincy Granite and Cambridge Argillite (view northwest along the northeast-trending tunnel).

However, these zones were reported as lesser breaks during the construction of the tunnel and caused no unusual problems (Lachel & Associates, 1996). Their mapping during construction revealed many important details. The southern fracture zone has mylonite, re-cemented quartz and vugs, and this fracture zone controls the low sag in the bedrock surface above the tunnel. The northern faulted zone separates northeast from southwest dips in the argillite and is most prominent as a 4.5 meter (15 foot) wide disrupted zone between Stations 1+15 to

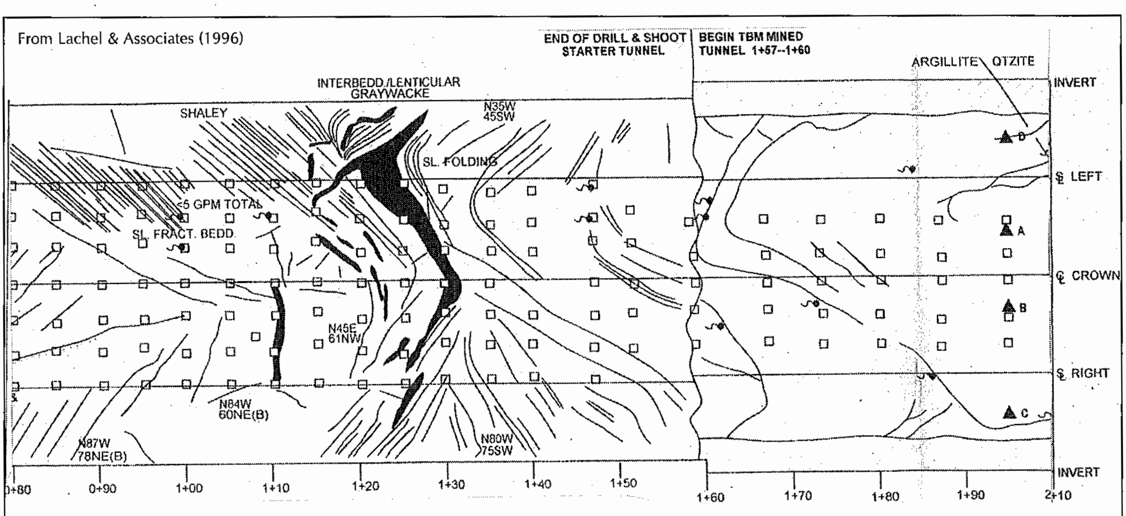
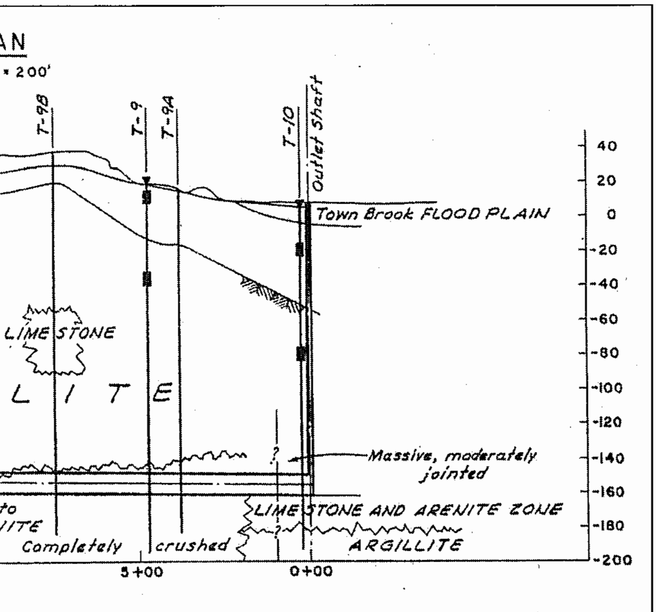


FIGURE 7-46. Detailed map of the Town Brook Tunnel near northeast end (Stations 0+80 to 2+00) showing bedding and shear zone in Cambridge Argillite with cavity (black) and lesser amount of observed data in the TBM portion of the tunnel.



1+30 (see Figure 7-46). To the northeast and in the outlet shaft, the attitude strikes 58 degrees north to 88 degrees west with a dip of 60 to 85 degrees northeast. To the southwest, the attitude strike also is to the northwest , but the dip is 40 to 75 degrees southwest. This strike is described as a fold by Lachel & Associates (1996), but the geometry indicates that it is a fault.

Overall, the jointing is moderate. The dominant joints in the granite strike between N5 to 35°E and N57 to 78°W, with dips of 35 to 85 degrees southeast and 43 to 72 degrees northeast, respectively. Two dominant joint sets seen in the argillite in the oriented core from the borings both strike northeasterly with one dipping to 60 to 85 degrees southeast, and the other 40 to 45 degrees northwest, but the dominant joint sets in the outlet shaft strike N10 to 49°E and N20 to 75°W, with dips of 70 to 85 degrees northwest and 45 to 75 degrees southeast, respectively (Lachel & Associates, 1996). The dominant joint attitude in the inlet shaft is northwest with a steep southwest dip.

Fewer areas needing support were found than expected. Additional rock bolts and wire mesh were needed at one location near the northeast end of the tunnel and another location in the faulted zone in the argillite. In the weathered granite rock, closely-spaced jointing and an argillite seam required additional bolts and mesh at several areas. The water inflow at the completion of the outlet shaft reached 0.8 cubic meters per minutes (200 gallons per minute), of which only 0.06 cubic meters per minute (15 gallons per minute) was from the overburden, which had been essentially sealed off. Inflow in the tunnel section in argillite was generally insignificant except for a few local zones of 0.08 cubic meters per minute (20 gallons per minute) in the argillite. The granite section of the tunnel, however, produced a total of approximately 1.9 cubic meters per minute (500 gallons per minute) from over a hundred separate inflows, most of which were less than about 0.008 cubic meters per minute (2 gallons per minute), but there were nine sites with inflows up to 0.06 cubic meters per minute (15 gallons per minute). Subsequent overburden aquifer water problems developed because the tunnel resulted in sufficient dewatering of the overlying material to cause serious low water and even no water at times in the overlying Town Brook, which was once a significant spawning ground for smelt. This problem continues and, based on subsequent investigations, a plan was drawn up in 2011 to restore flows unnecessarily diverted to the tunnel.

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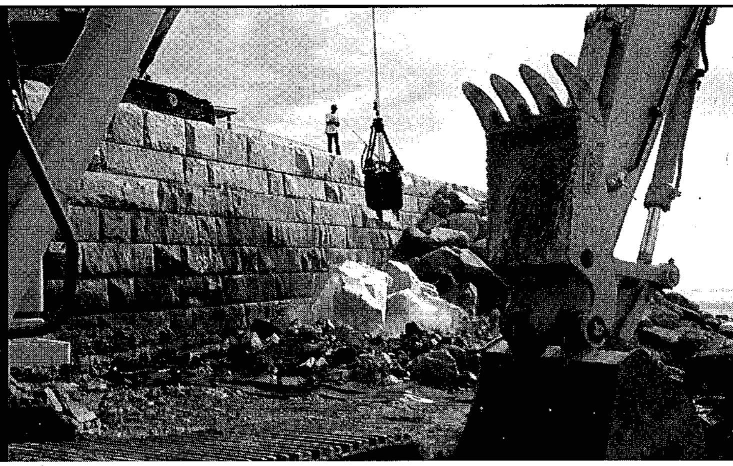

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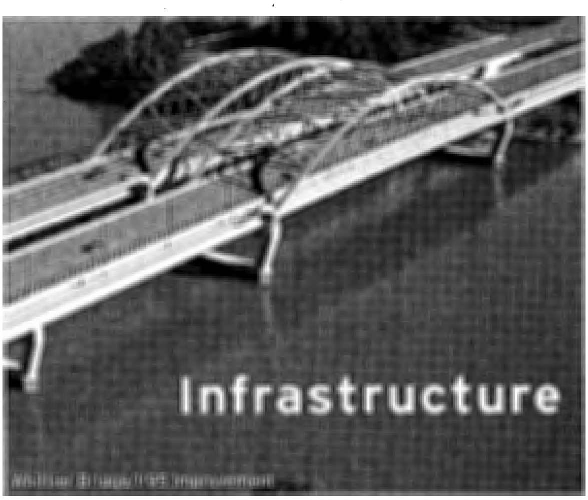

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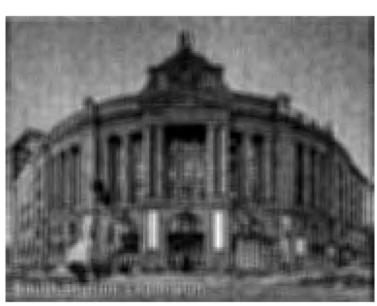

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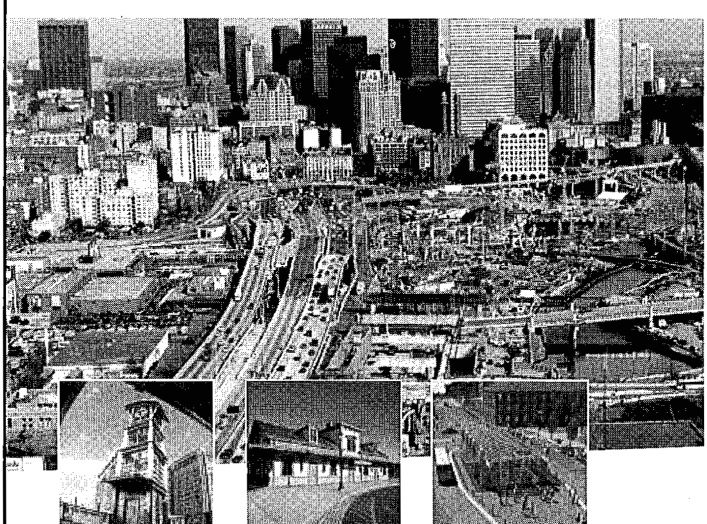

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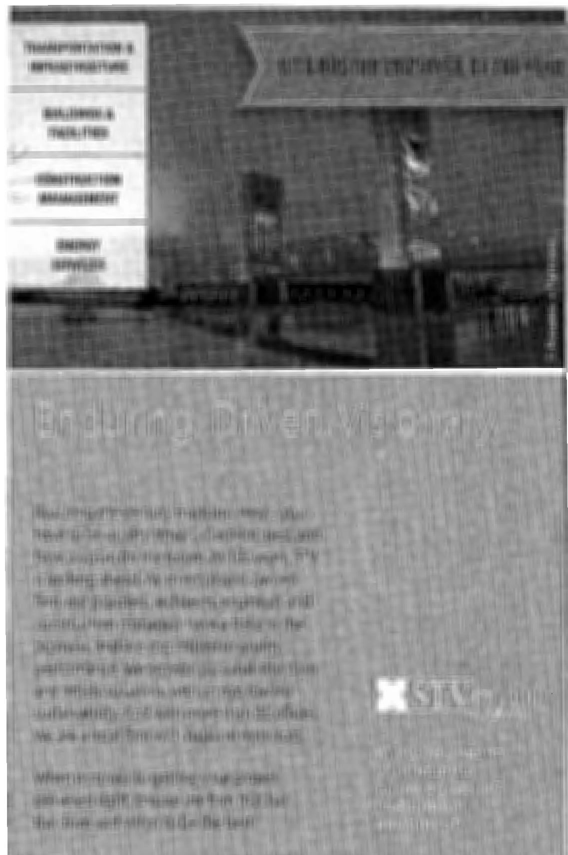

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FIGURE 1-16. Boston and the lower Charles River estuary showing marshes in 1775.

FIGURE 2-29. Fault slice of Late Triassic redbeds, the Middleton Basin, in the Bloody Bluff Fault Zone, bordering dark Late Proterozoic volcanic rock mined in the SanVal Quarry, Middleton.

FIGURE 3-13. Pebbly mudstone slump deposit, which has been called the "Squantum Tillite," in the Cambridge Argillite at Squaw Head, Squantum, Quincy.

FIGURE 3-14. Mattapan rhyolite found at the Tileston School, Mattapan Square, Dorchester.

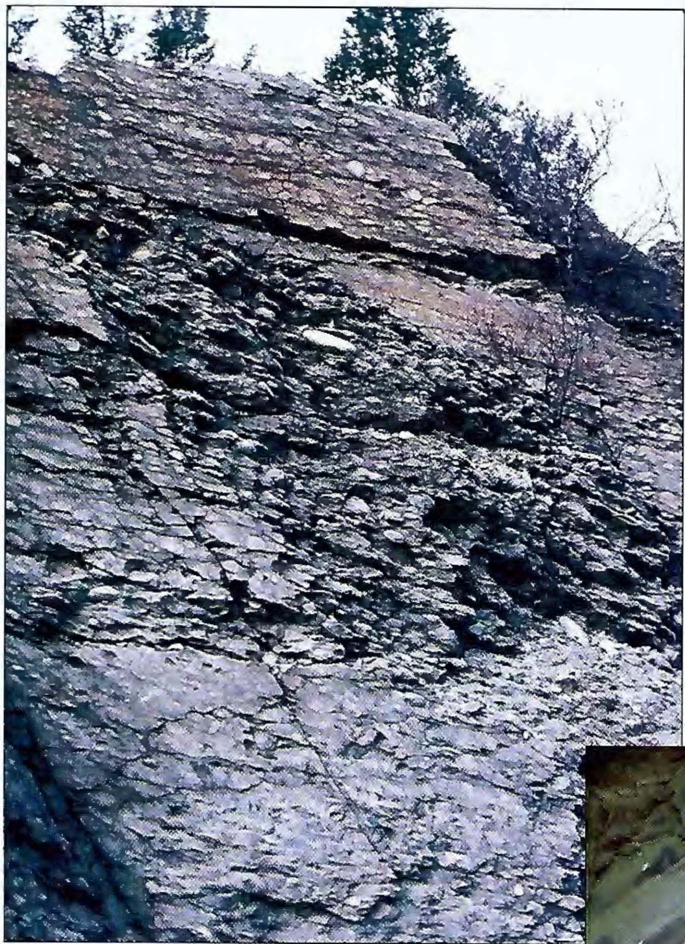


FIGURE 3-15. Roxbury Conglomerate at Route 128 (Interstate 95), south of Route 9, Newton.

FIGURE 3-17. Cambridge Argillite at the Somerville Quarry, Somerville.

FIGURE 3-18. Thin-bedded, laminated Cambridge Argillite on Grape Island.

FIGURE 3-19. Thin-bedded Cambridge Argillite capped by gently dipping diabase dike at Little Brewster Island.

FIGURE 3-20. Slump deposit of conglomerate with tuff block and Cambridge Argillite at Squaw Head, Squantum, Quincy.

FIGURE 3-21. Thin-bedded, laminated Cambridge Argillite with slump folds at Rainsford Island.

FIGURE 3-22. Contorted laminated mudstone bed slump in sandstone of the Cambridge Argillite at Squaw Head, Squantum, Quincy.

FIGURE 3-23. Siltstone and mudstone of the Lower Cambrian Weymouth Formation at Brewster Road in Quincy.

FIGURE 3-24. Argillaceous beds with brown cherty layers, Lower Cambrian Weymouth Formation at East Point in Nahant.

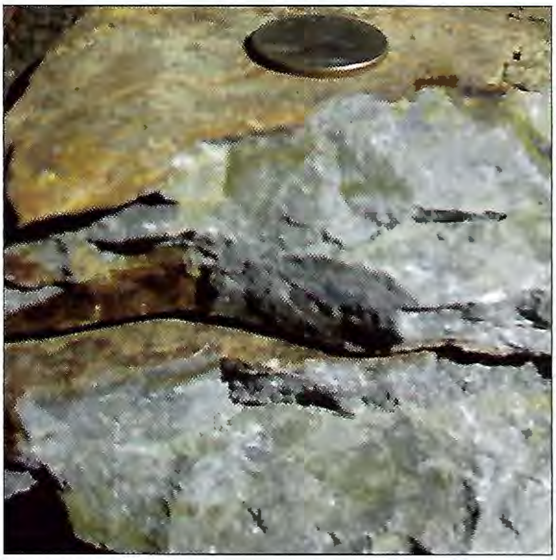


FIGURE 3-25. Middle Cambrian Braintree Argillite, slightly metamorphosed by Quincy Granite at Hallum Street in Milton.

FIGURE 3-26. Ordovician siliceous sandstone and siltstone clasts in Pennsylvanian conglomerate at Sachuest Beach in Middletown, Rhode Island.

FIGURE 3-28. Ash flow tuff of the Chickatawbut Road Flow Member of the Blue Hills Rhyolite at Blue Hills.

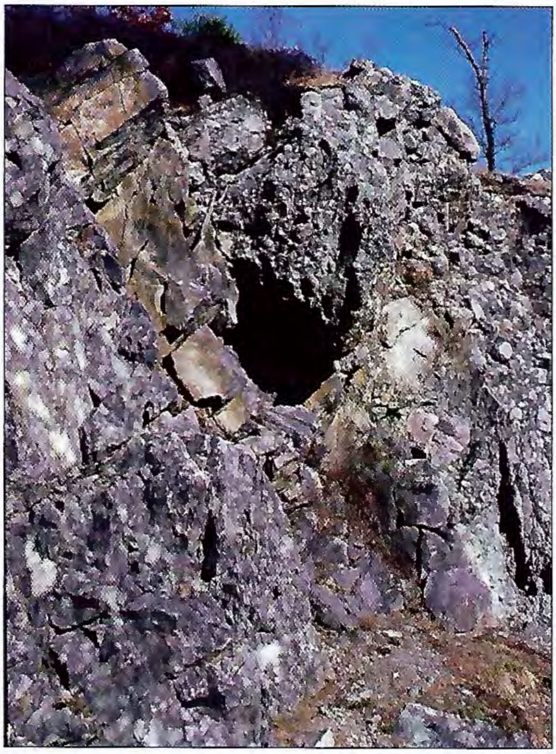


FIGURE 3-30. Pondville Conglomerate, upper right, overlying Blue Hills Rhyolite volcanic rock, left side, along an irregular contact in the Norfolk Basin on the north side of Route 128 in Milton.

FIGURE 3-31. A close-up view of Pondville Conglomerate just above lower contact, at Routes 128 and 28 in Quincy.

FIGURE 3-32. Red sandstone beds of the Wamsutta Formation, southbound lane of Route 24 just south of Route 128 in Randolph.

FIGURE 3-33. Amygdaloidal basalt of the Brighton Basalt (Melaphyre) at Wiltshire and Chestnut Hill streets in Brighton.

FIGURE 3-35. Nahant Gabbro cut by a nearly contemporaneous diabase dike that is offset at East Point in Nahant.

FIGURE 3-36. Nahant Gabbro, sheared with drag folds.

FIGURE 3-37. Quincy Granite closeup at the Granite Rail Quarry in Quincy.

FIGURE 3-39. Blue Hills Granite Porphyry at Blue Hills.

FIGURE 3-40. Curved greenstone dike cutting the Cambridge Argillite (on the right) at the southeast end of Calf Island.

FIGURE 3-41. Greenstone dike cutting Late Proterozoic Dedham Granodiorite on Route 128, near Exit 16, west of route 109 in Dedham.

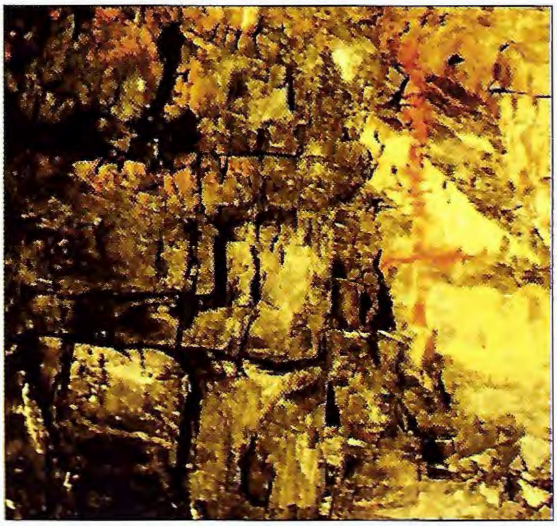


FIGURE 3-47. North-trending diabase dike with columnar jointing and with fault gouge along its border at the Wellesley Extension Intercept Tunnel in Dedham.

FIGURE 3-44. Gabbro dike from Porter Square Subway Station in Cambridge with fragment of granite. (Photo courtesy of Allen Hathaway.)

FIGURE 3-49. Kaolinized Roxbury Conglomerate at Blue Hill Avenue at Franklin Field in Dorchester.

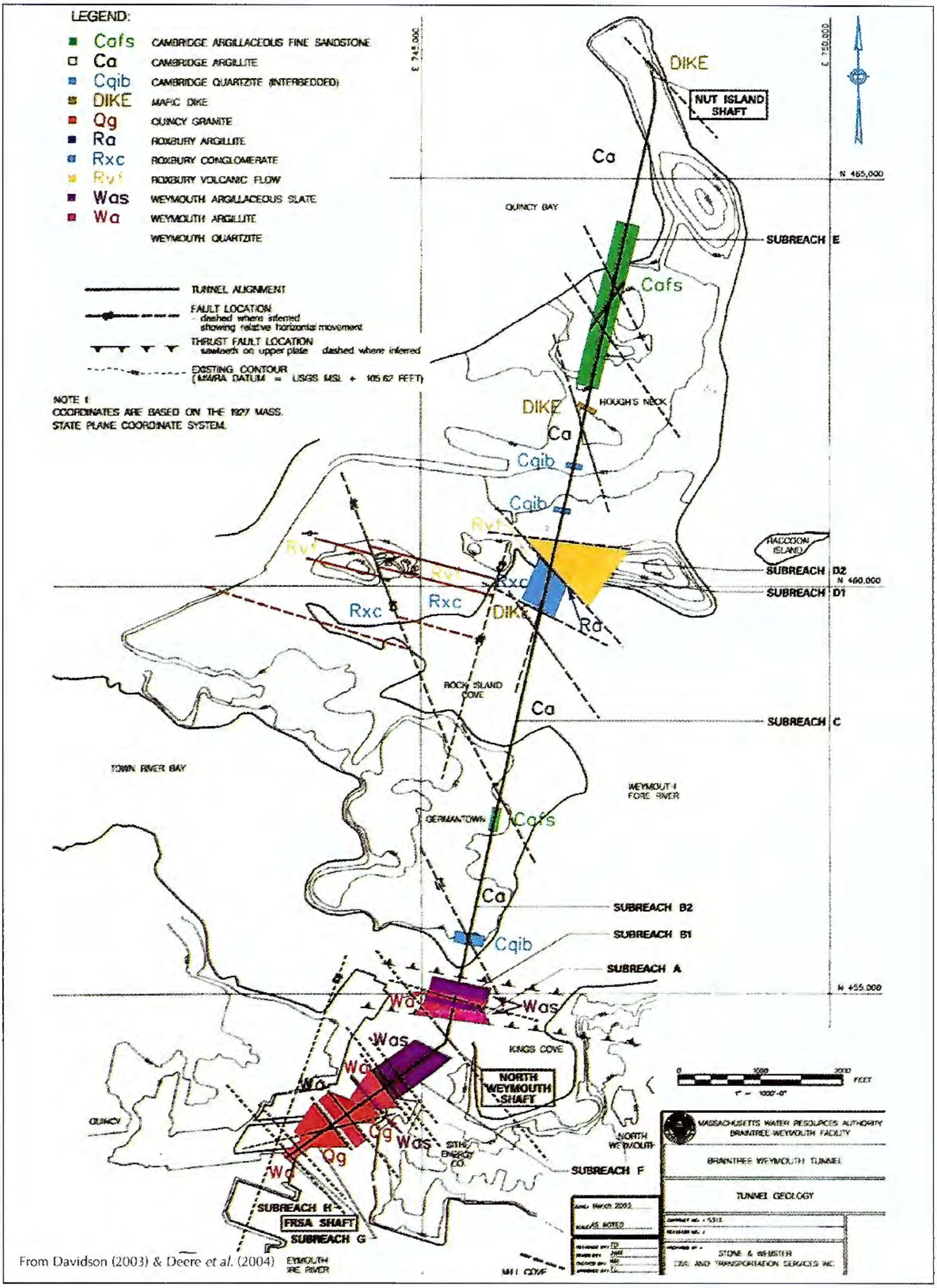


FIGURE 3-55. Geologic map of the Braintree-Weymouth Tunnel from Hough's Neck to Nut Island, Hingham.

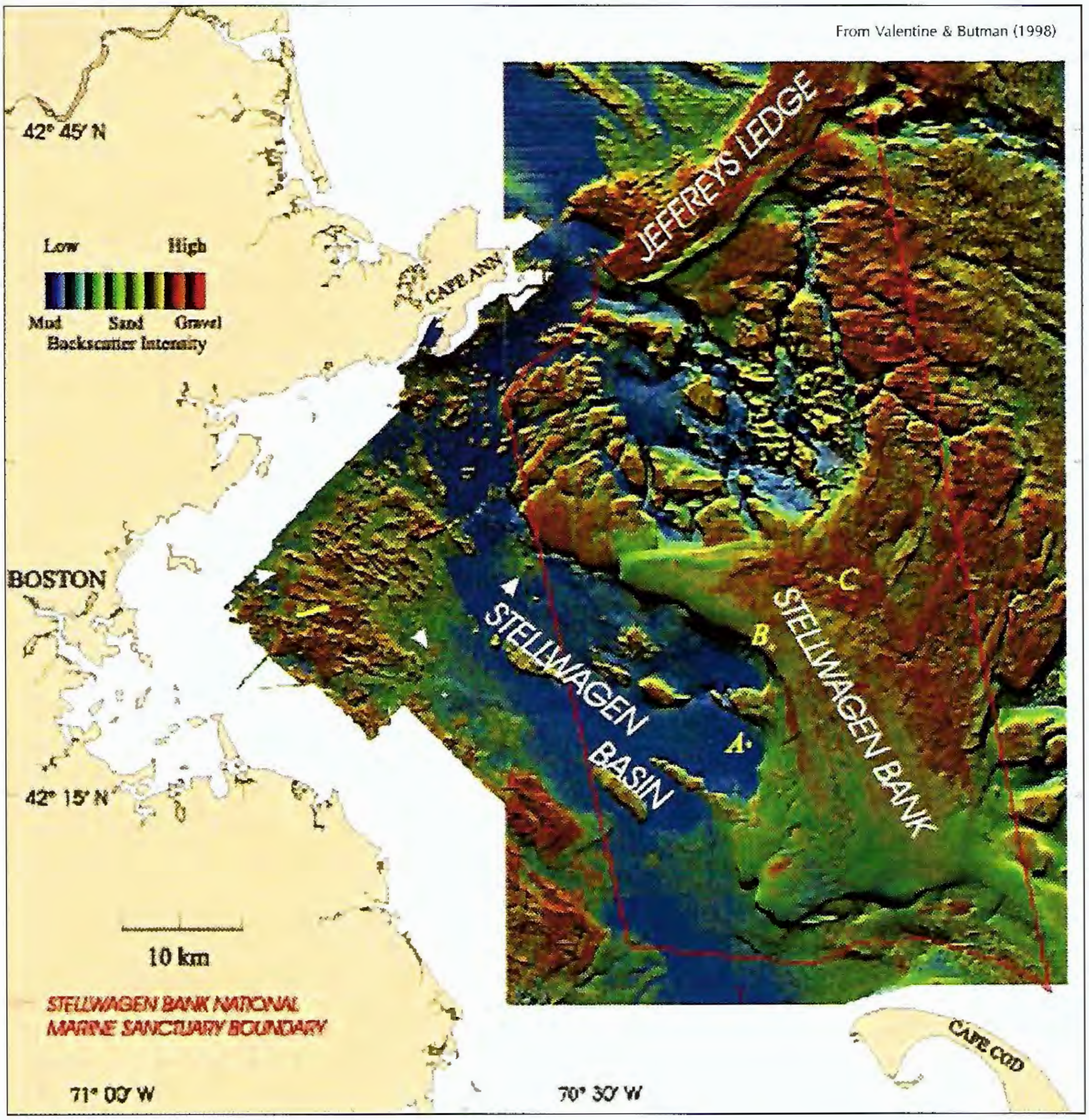


FIGURE 3-72. Sea floor topography from Massachusetts Bay to Stellwagen Bank.

FIGURE 3-77. Typical till at Great Brewster Island.

FIGURE 3-78. Great Brewster Island showing rougher and gullied lower till overlain by smoother upper till.

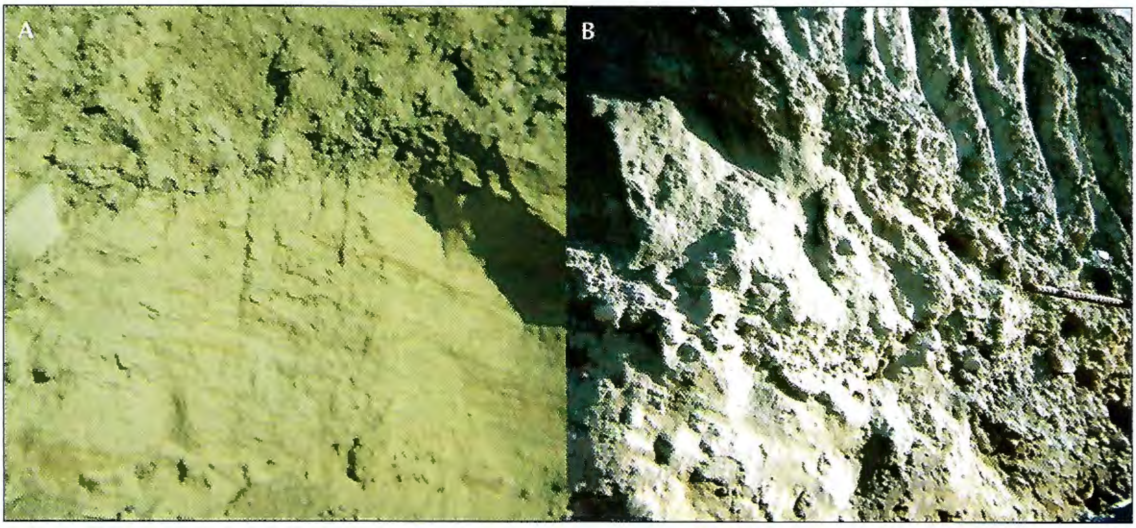


FIGURE 3-80. Photos of deltaic sand and gravel north of Beacon Hill, looking south at the face against Cambridge Street during the excavation for the Holiday Inn showing: (A) partly faulted stratified sand and gravel, and (B) tilted stratified sand and gravel, unconformably overlain by till.

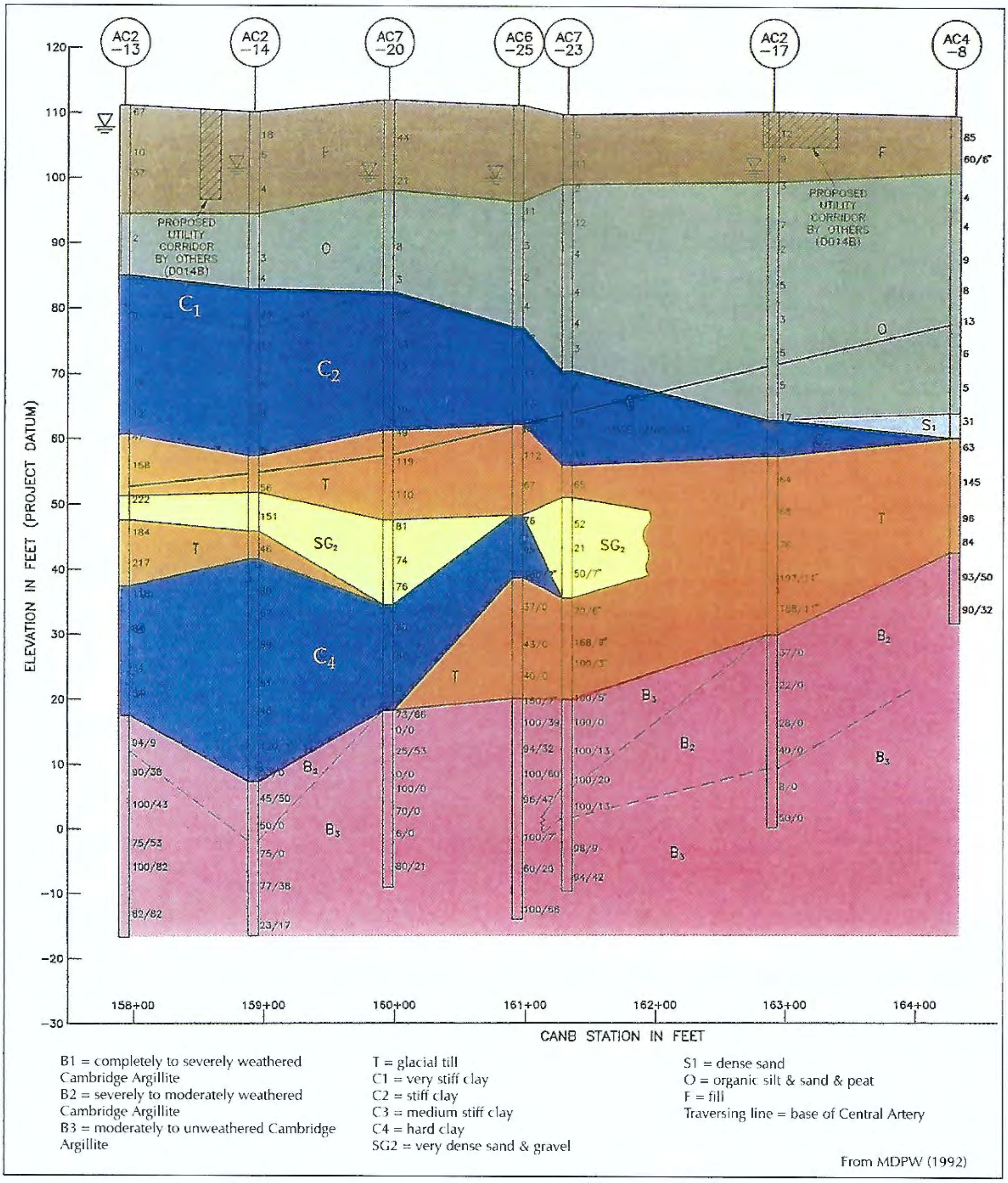
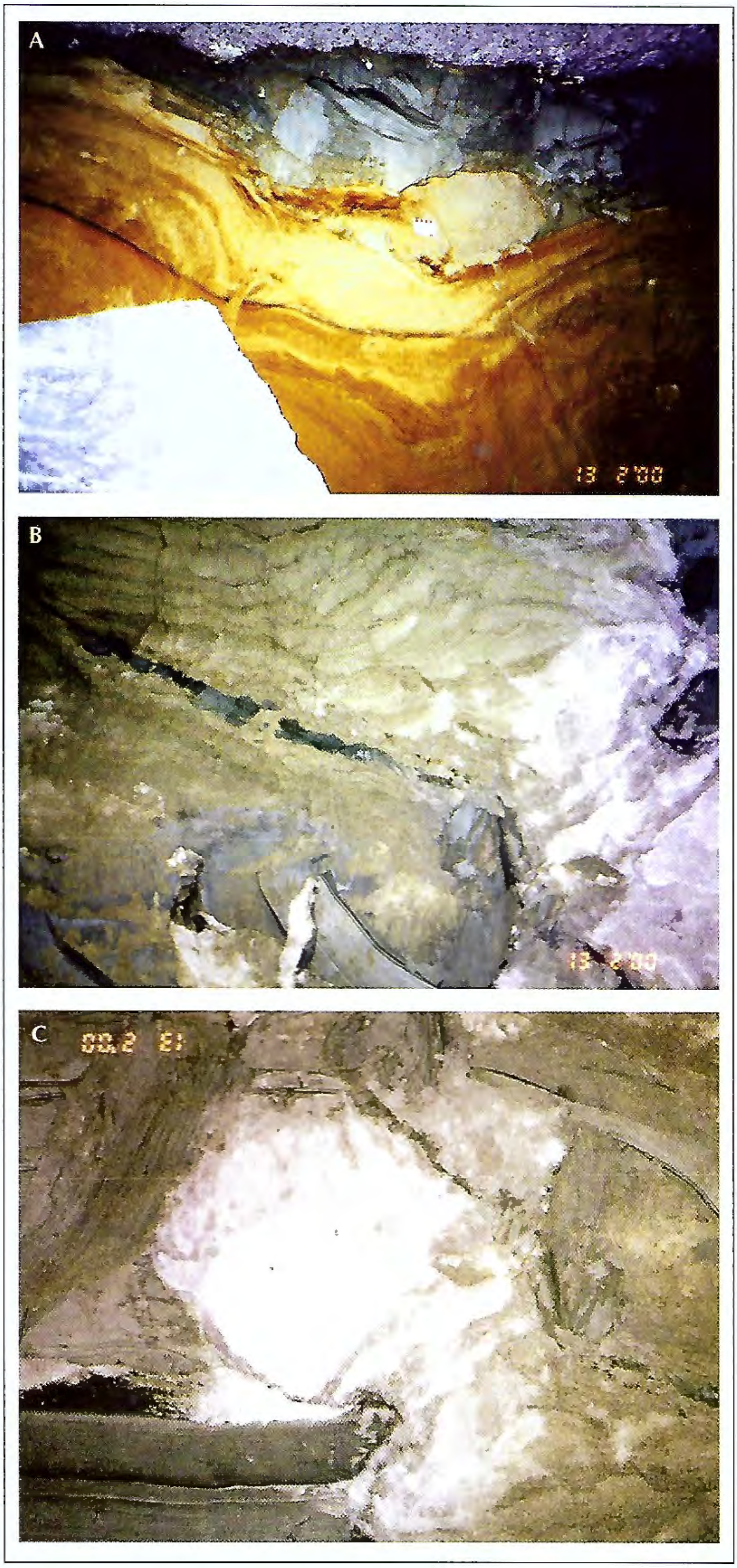


FIGURE 3-82. Geologic cross-section (from the southwest) along the Central Artery Tunnel between Valenti Way and Causeway Street (east slurry wall, stations 158+00 to 164+00) showing an apparent clay and sand filling of a channel cut through the lower till and later covered by upper till and partially thrusted between the upper and lower tills, which here are undifferentiated.

FIGURE 3-84. Excavation for garage at Millennium Place, Tremont and Boylston streets, on the southeast corner of Boston Common in 2000, showing (A) banded blue clay on lower left complexly faulted against blocks of stratified sand, (B) graded-bedded fine-grained sand on upper right thrust over sand with clay seams along small thrusts on lower left (which also shows teeth marks of the backhoe in the lower part of the photo), and (C) banded orange and buff stratified sand with brecciated blue clay above.



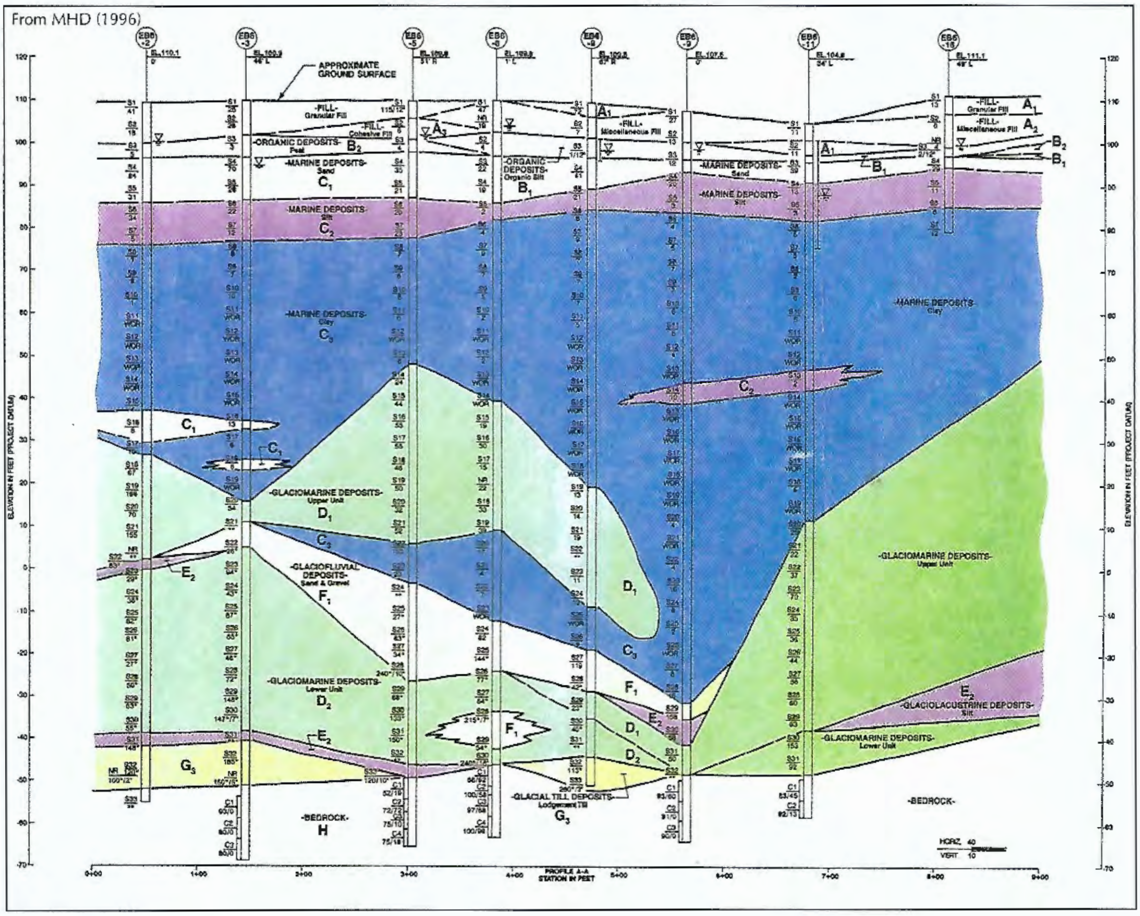


FIGURE 3-92. Variations of the glaciomarine deposit in section (north view) along the Central Artery/Tunnel Project, beneath Airport Access Road off the northwest corner of Logan Airport and west of MBTA Airport Station. Similar redeposited glaciomarine sediment (D_1) is also in the lower marine clay (C_3) in a channel above the lower outwash (F_1).

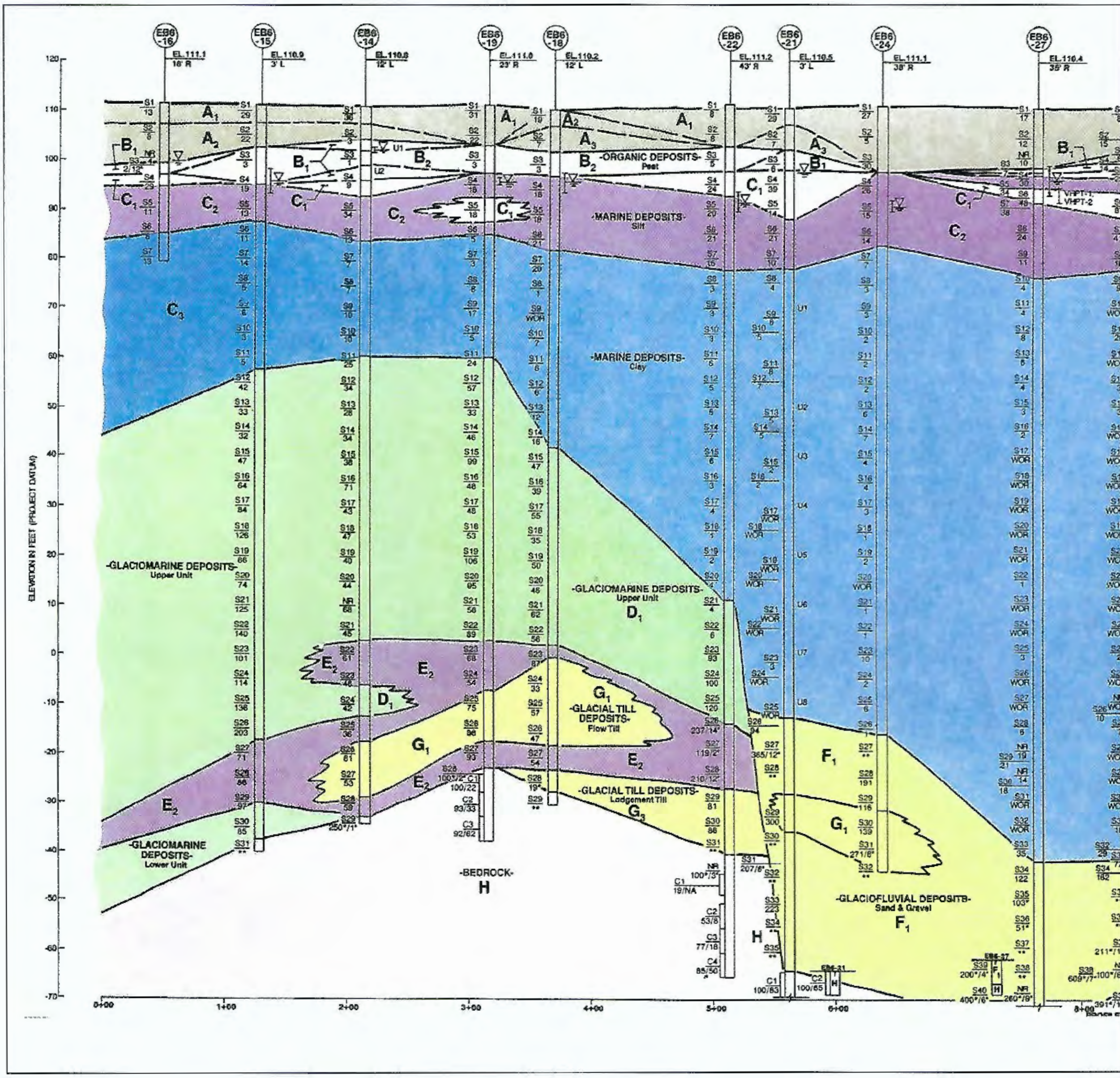
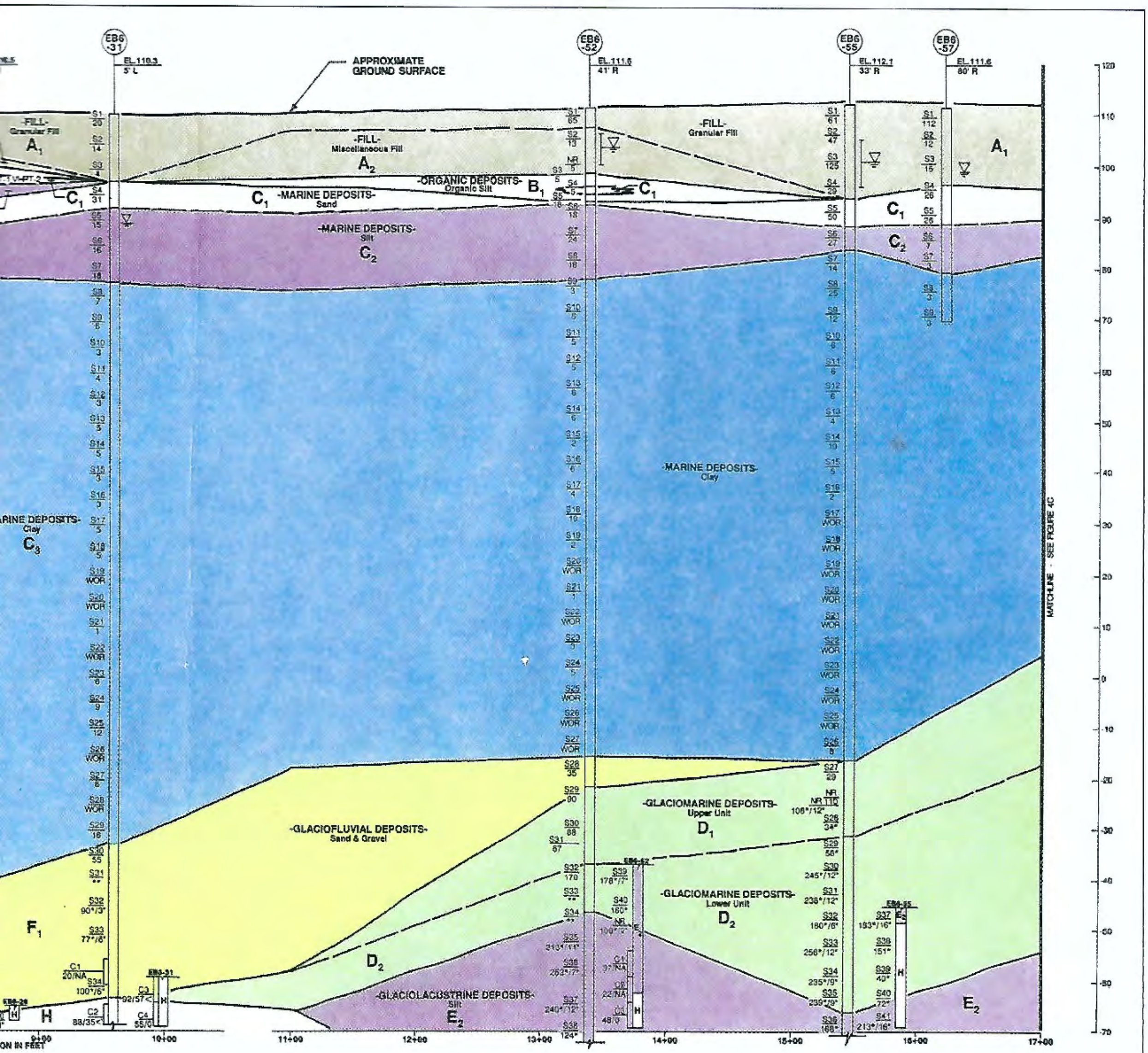


FIGURE 3-93. Section from the Central Artery/Tunnel Project beneath Route 1 adjacent to MBTA Airport Station showing complex facies relations within the glaciomarine deposits resting on lower



From Haley & Aldrich (2010)

till and bedrock that are cut by a deep channel with lower outwash and marine clay fill, view northwest. The units labeled glaciolacustrine silt and enclosed till are facies of the glaciomarine deposit.

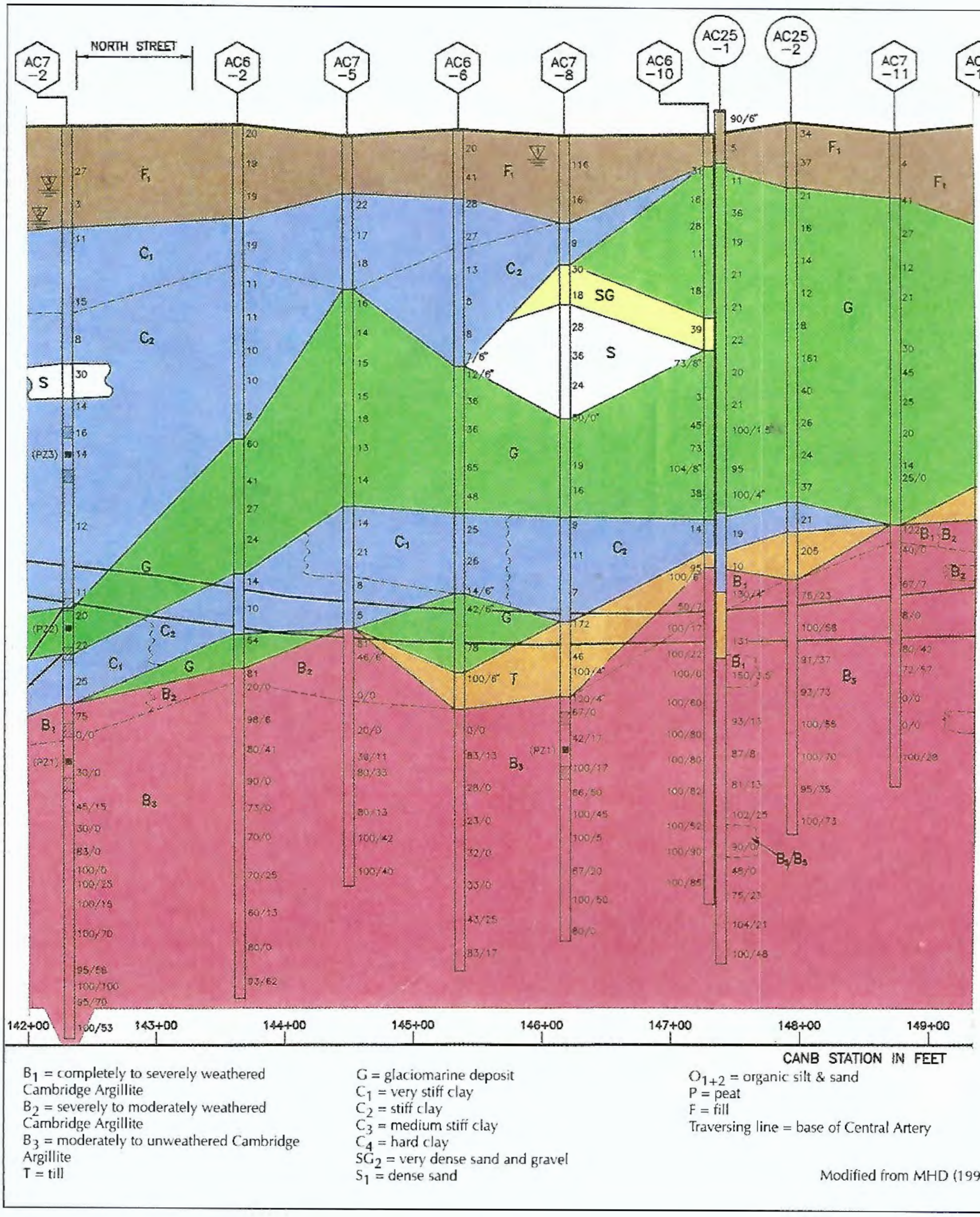


FIGURE 3-94. Section along the Central Artery between North Street and North Washington Street (west tunnel wall; stations 142+00 to 150+00) showing glaciomarine deposit interbedded with and overlain by marine clay above thin till, which are undifferentiated; view southwest.

FIGURE 3-96. Gray marine clay under the shovel, covered by reddish-brown organic silty sand in the foreground. (Photo courtesy of Bradford Miller.)

FIGURE 3-97. Marine clay rubble in excavation, including large boulders. (Photo courtesy of Bradford Miller.)

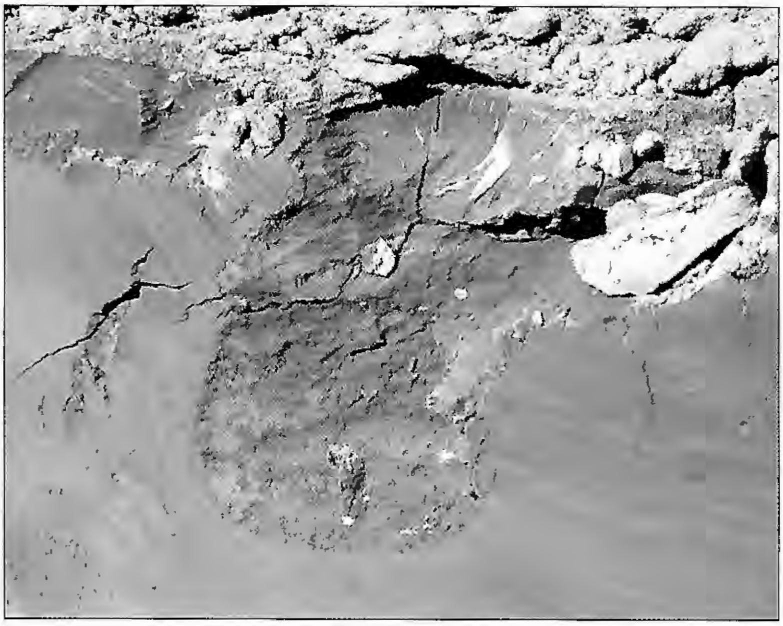
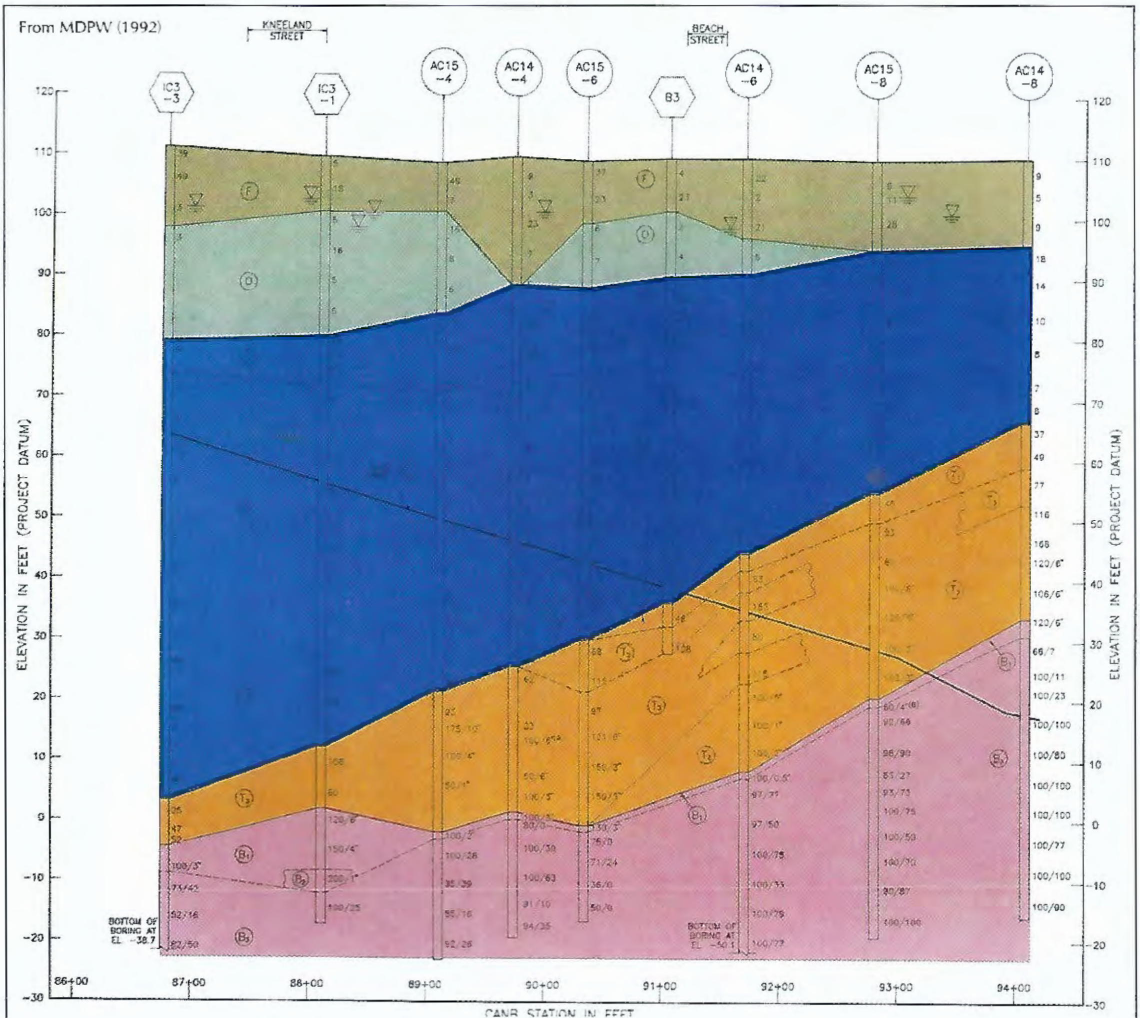


FIGURE 3-107. Reworked clay over the weathered top of marine clay. (Photo courtesy of Bradford Miller.)

FIGURE 5-5. Aerial view of Boston view on May 18, 2012. (Courtesy of lesvants.com.)



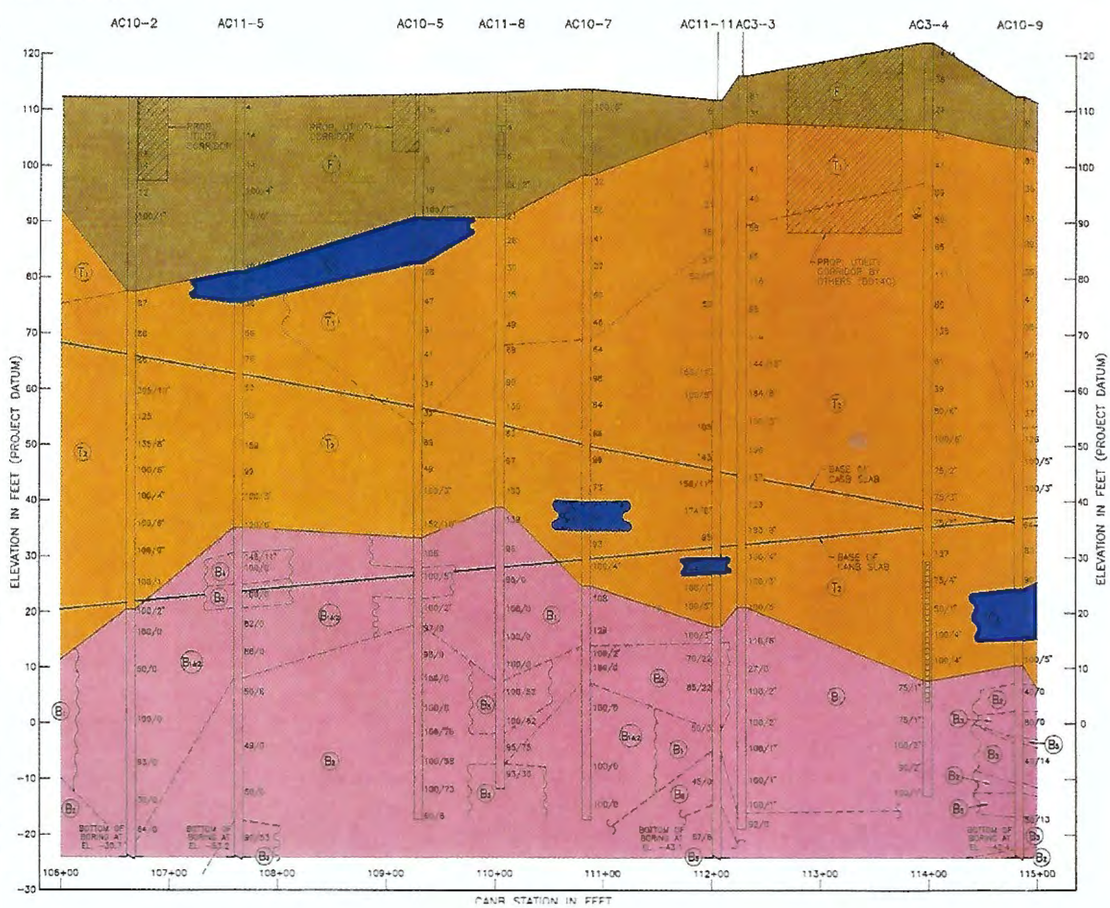
B1 = Completely to severely weathered Cambridge Argillite
B2 = Severely to moderately weathered Cambridge Argillite
B3 = Moderately to unweathered Cambridge Argillite

T1 = Dense cohesive till
T2 = Very dense cohesive till
T3 = Granular till
G = Glaciomarine deposit
C1 = Very stiff clay
C2 = Stiff clay

C3 = Medium stiff clay
C4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-27. Section along the Central Artery west of South Station (middle slurry wall between stations 87+00 and 94+00) showing the marine clay overlapping the south side of the Fort Hill drumlin (view west).

From MDPW (1992)

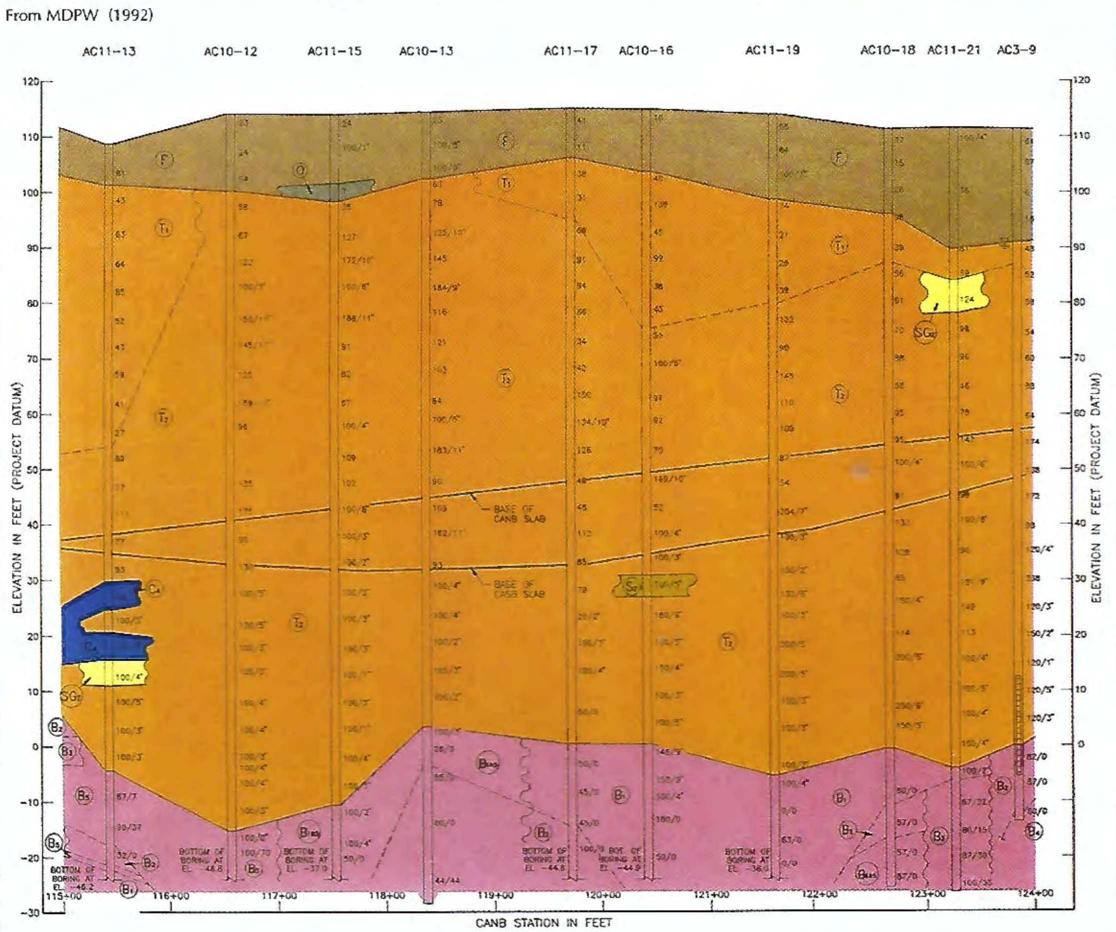


B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-28. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 106+00 and 115+00 (view west to southwest).

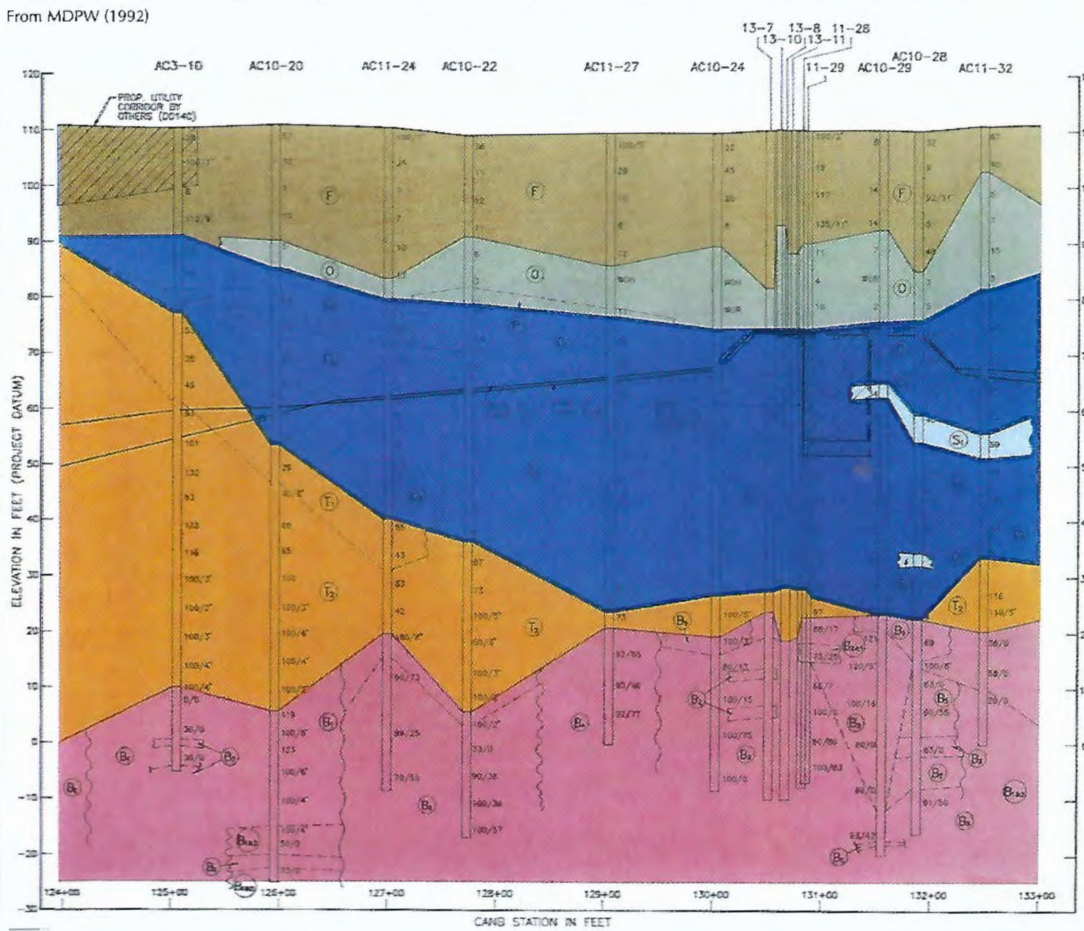


B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-29. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 115+00 and 124+00 (view west to southwest).



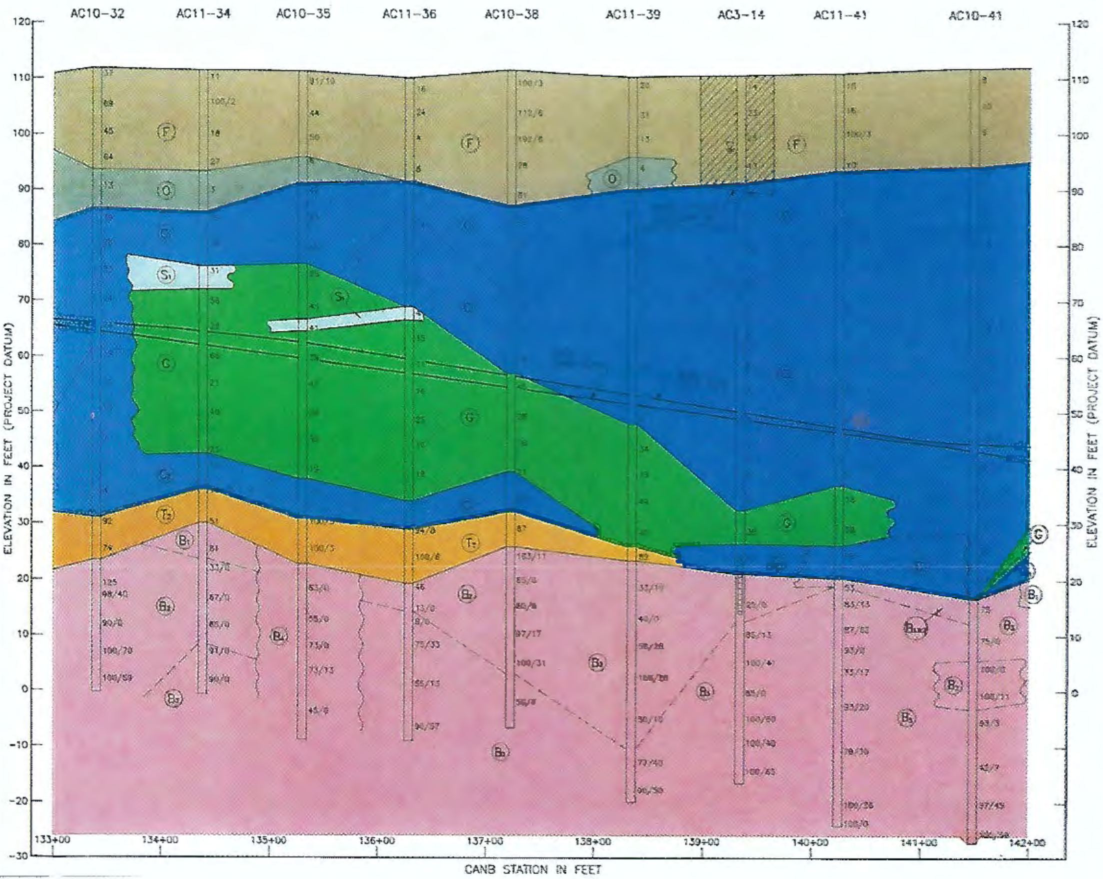
B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-30. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 124+00 and 133+00 (view west to southwest).

From MDPW (1992)



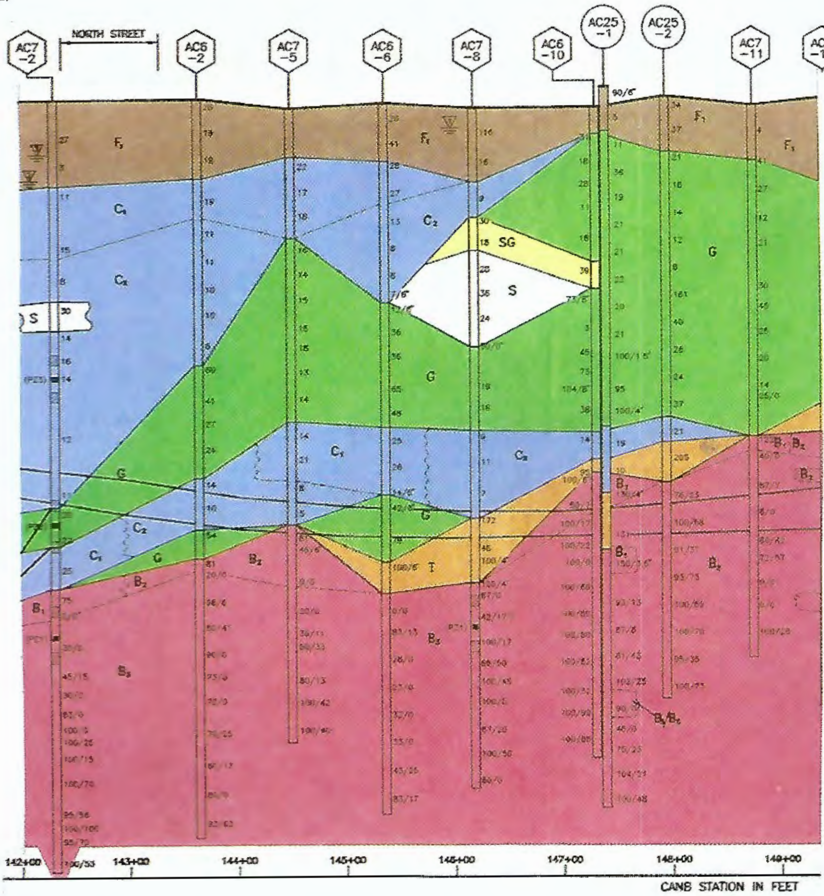
B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-31. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 133+00 and 142+00 (view west to southwest).

From MDPW (1992)

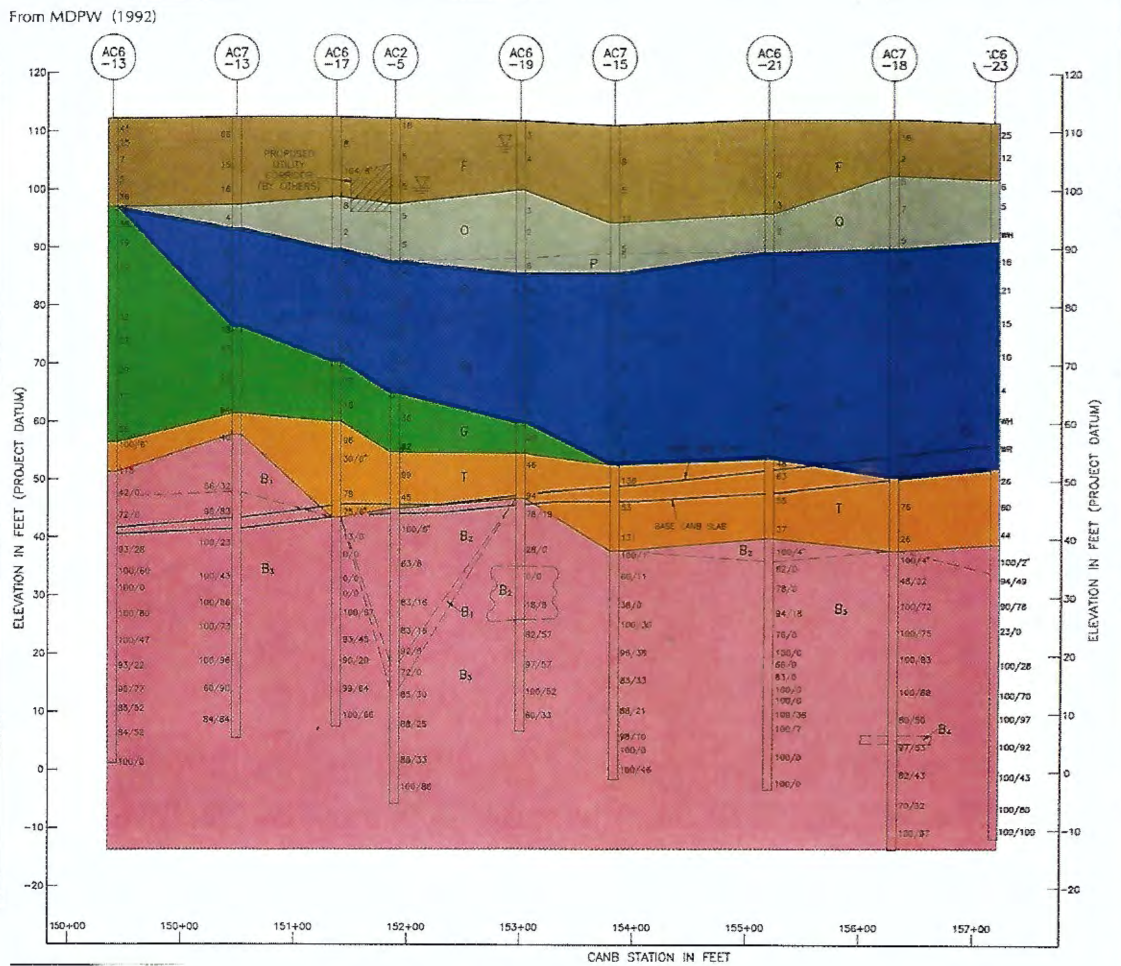


B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

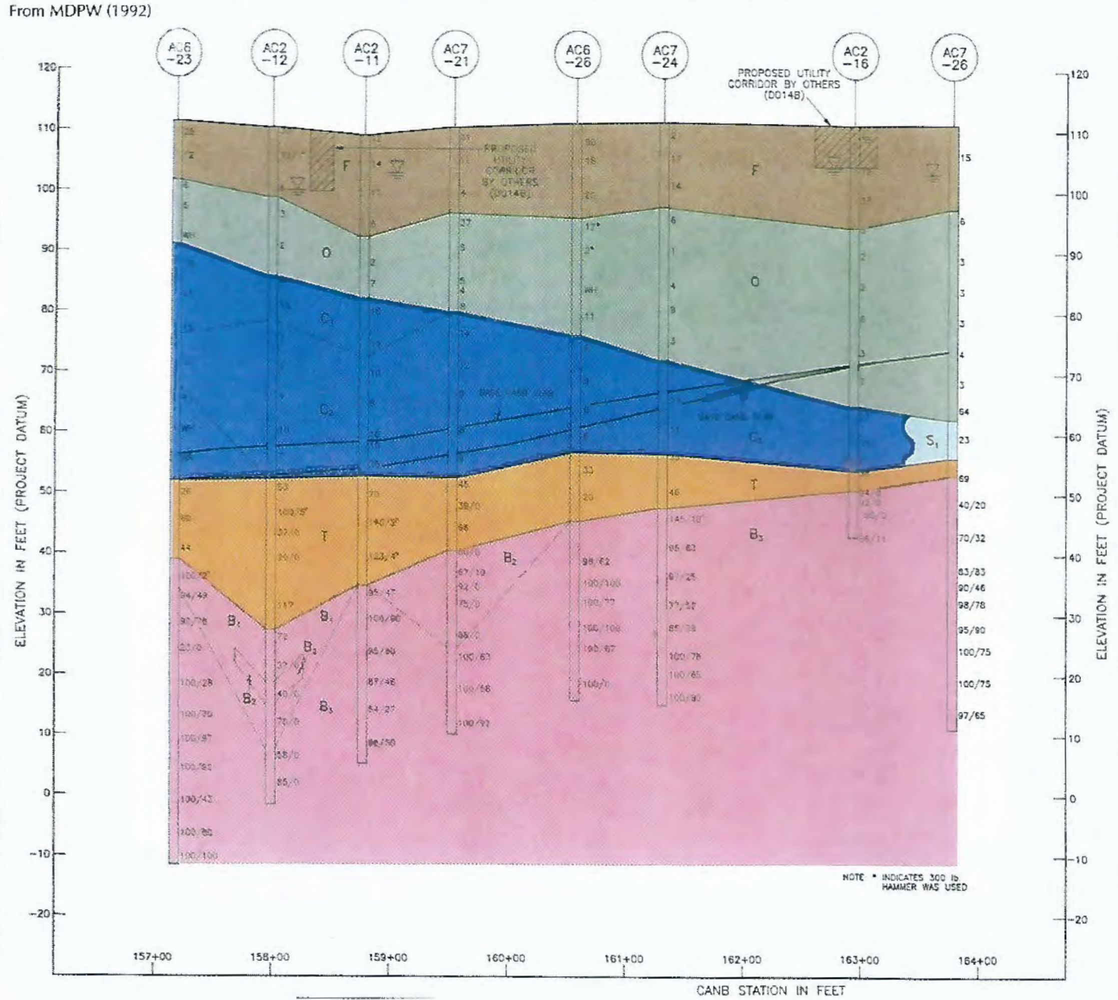
FIGURE 6-32. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 142+00 and 150+00 (view west to southwest).



B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite
T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-33. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 150+00 and 157+00 (view west to southwest).

From MDPW (1992)



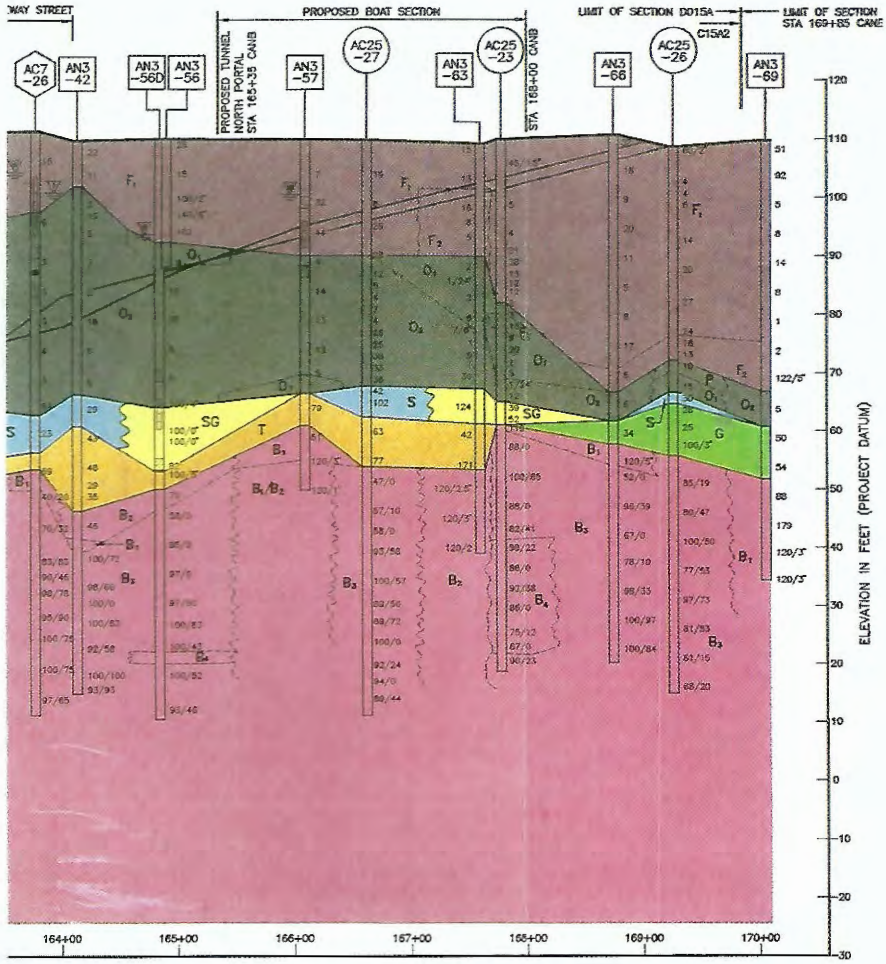
B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay

C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-34. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 157+00 and 164+00 (view west to southwest).

From MDPW (1992)



B_1 = Completely to severely weathered Cambridge Argillite

B_2 = Severely to moderately weathered Cambridge Argillite

B_3 = Moderately to unweathered Cambridge Argillite

T_1 = Dense cohesive till

T_2 = Very dense cohesive till

T_3 = Granular till

G = Glaciomarine deposit

C_1 = Very stiff clay

C_2 = Stiff clay

C_3 = Medium stiff clay

C_4 = Hard clay

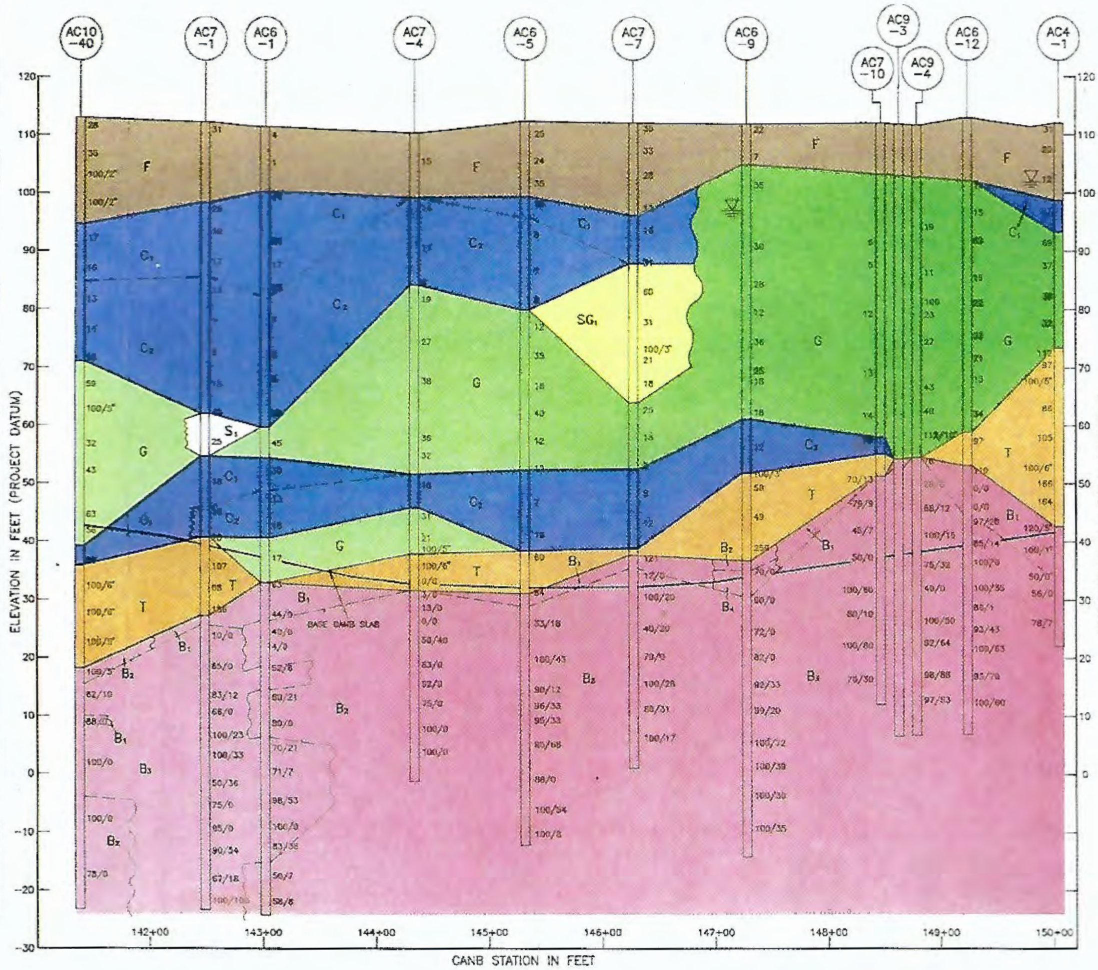
O = Organic silt & sand

F = Fill

Traversing lines = base of Central Artery Tunnels

FIGURE 6-35. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 164+00 and 170+00 (view west to southwest).

From MDPW (1992)



B_1 = Completely to severely weathered Cambridge Argillite
B_2 = Severely to moderately weathered Cambridge Argillite
B_3 = Moderately to unweathered Cambridge Argillite
T_1 = Dense cohesive till
T_2 = Very dense cohesive till
T_3 = Granular till
G = Glaciomarine deposit
C_1 = Very stiff clay
C_2 = Stiff clay
C_3 = Medium stiff clay
C_4 = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

FIGURE 6-36. Section along the Central Artery Tunnel between North and Cross streets (east slurry wall Stations 142+00 to 150+00) showing the lower outwash sand and the gravel filling channel in the glaciomarine deposit and both covered by marine clay.