# 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.*

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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

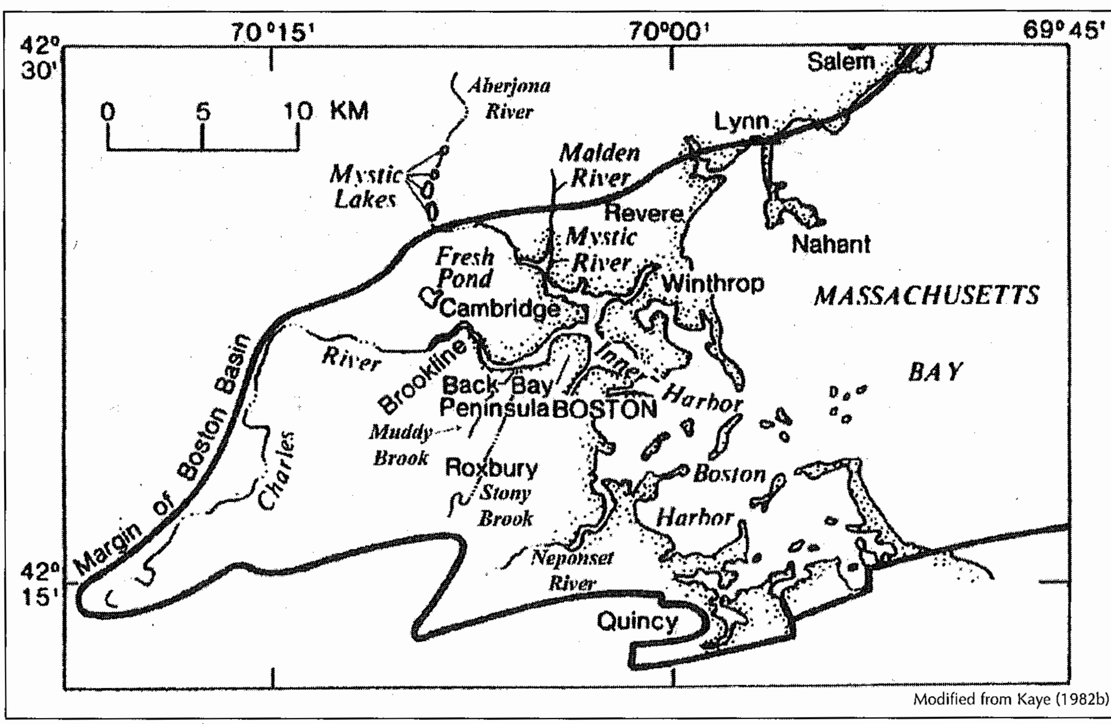



**FIGURE 3-1. Outline of the Boston Basin and its major rivers and streams.**

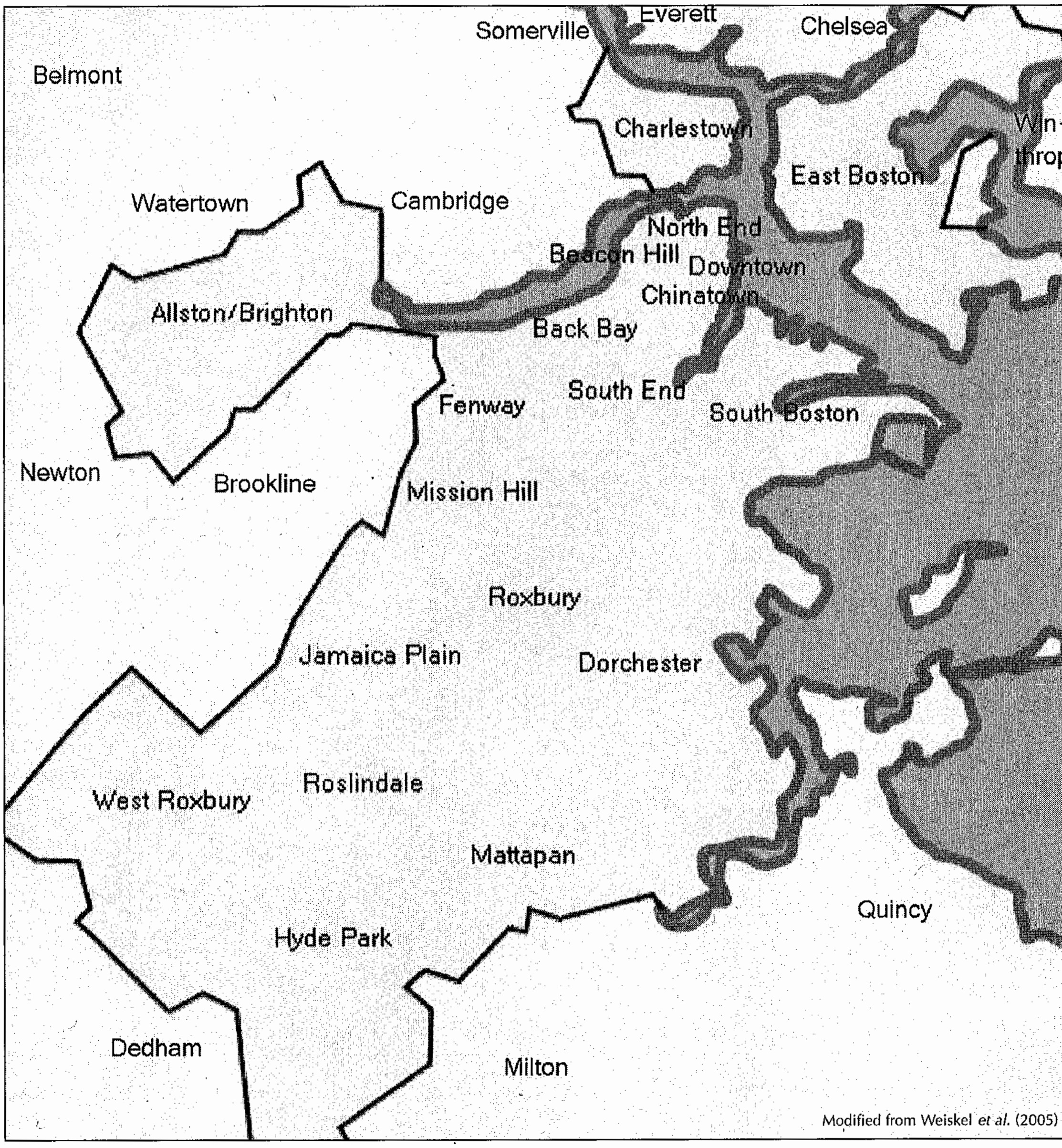



**FIGURE 3-2. Boston and adjacent towns in the Boston Basin.**

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-

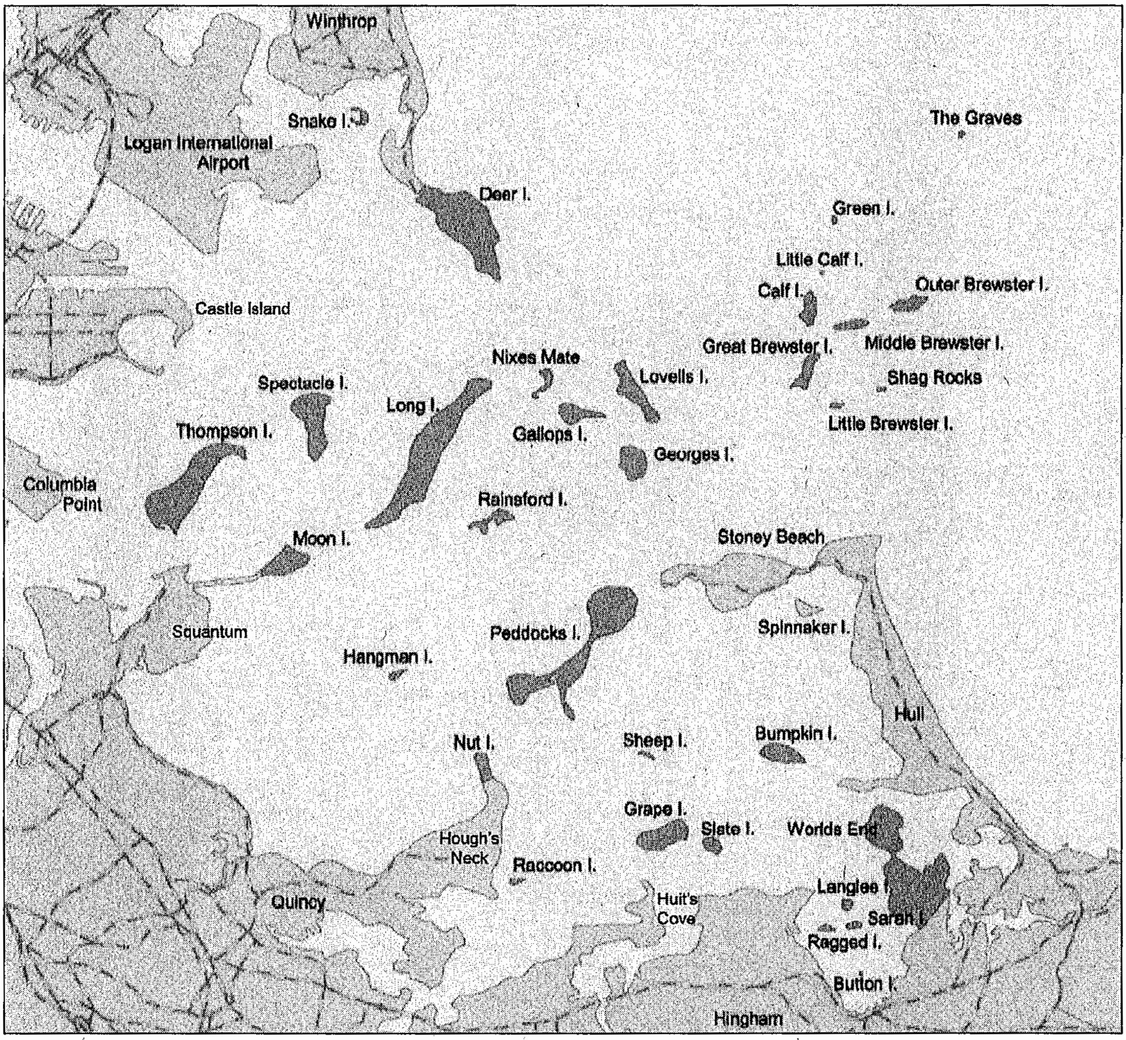



**FIGURE 3-3. Map of Boston Harbor and islands. (Courtesy of the National Park Service.)**

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 &

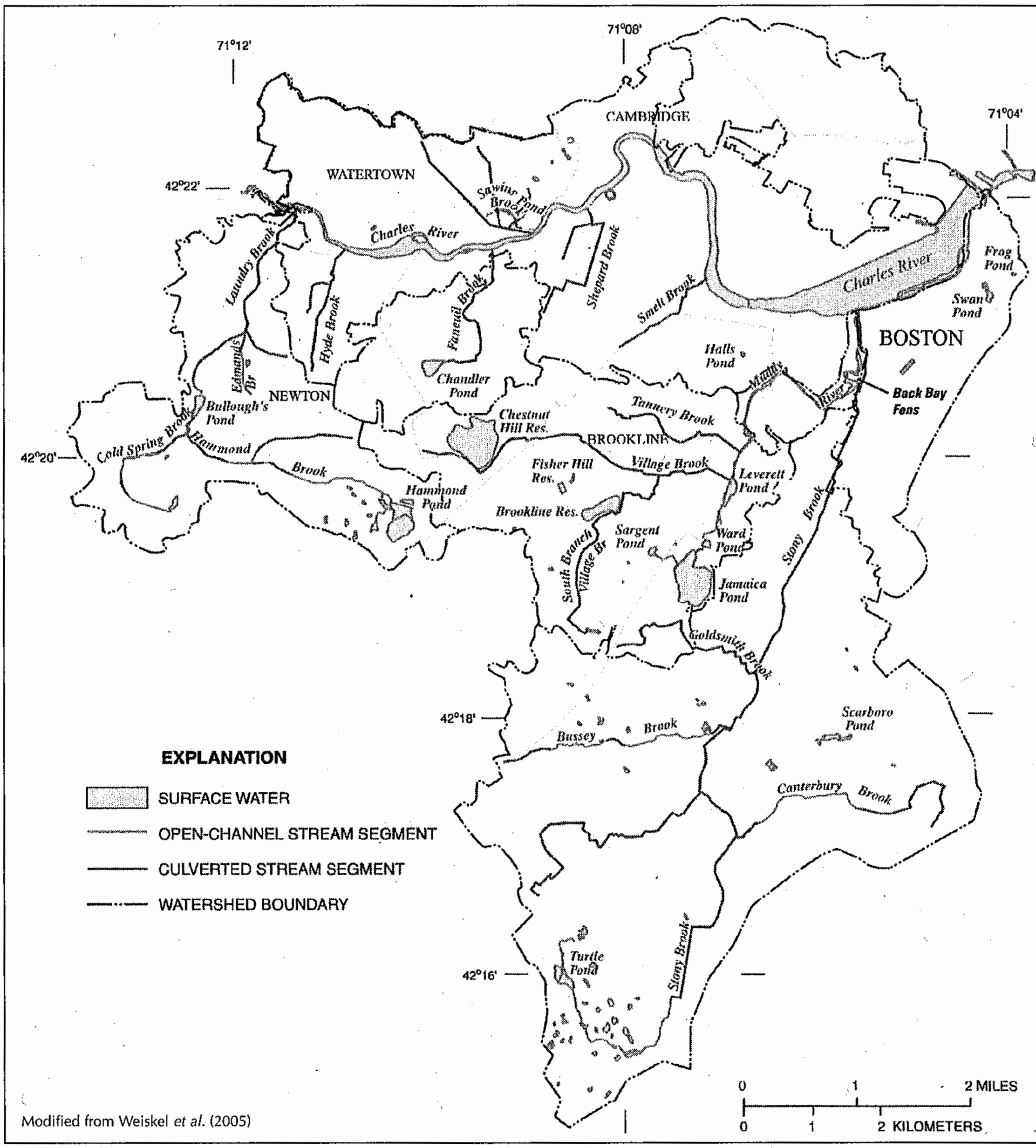



**FIGURE 3-4. Map showing rivers and streams in the lower Charles River watershed.**

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-

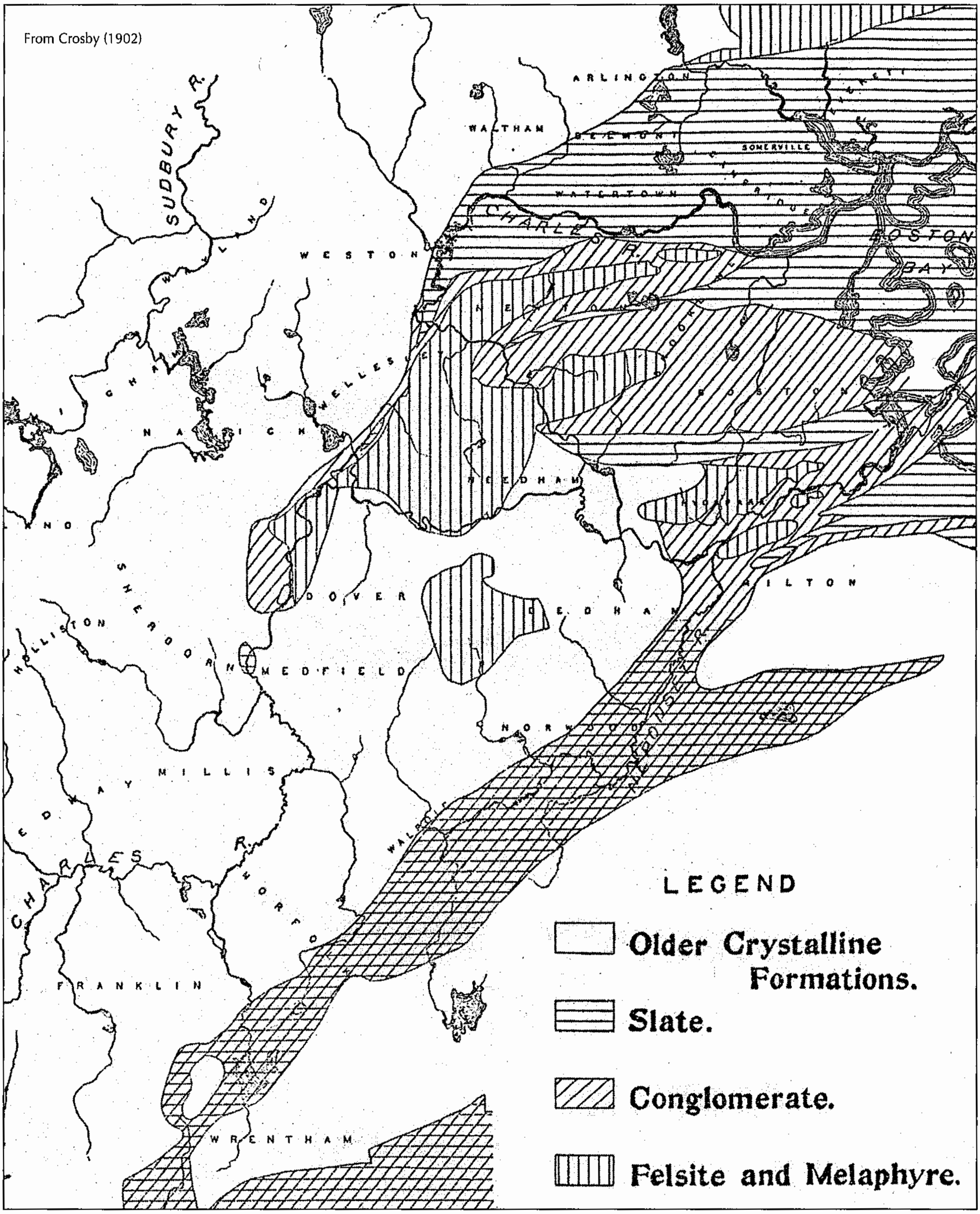



**FIGURE 3-5. Generalized distribution of the lithologies of basin fills and overlap in the region around Boston. Mixed lithologies are shown by the superposition of patterns.**

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).

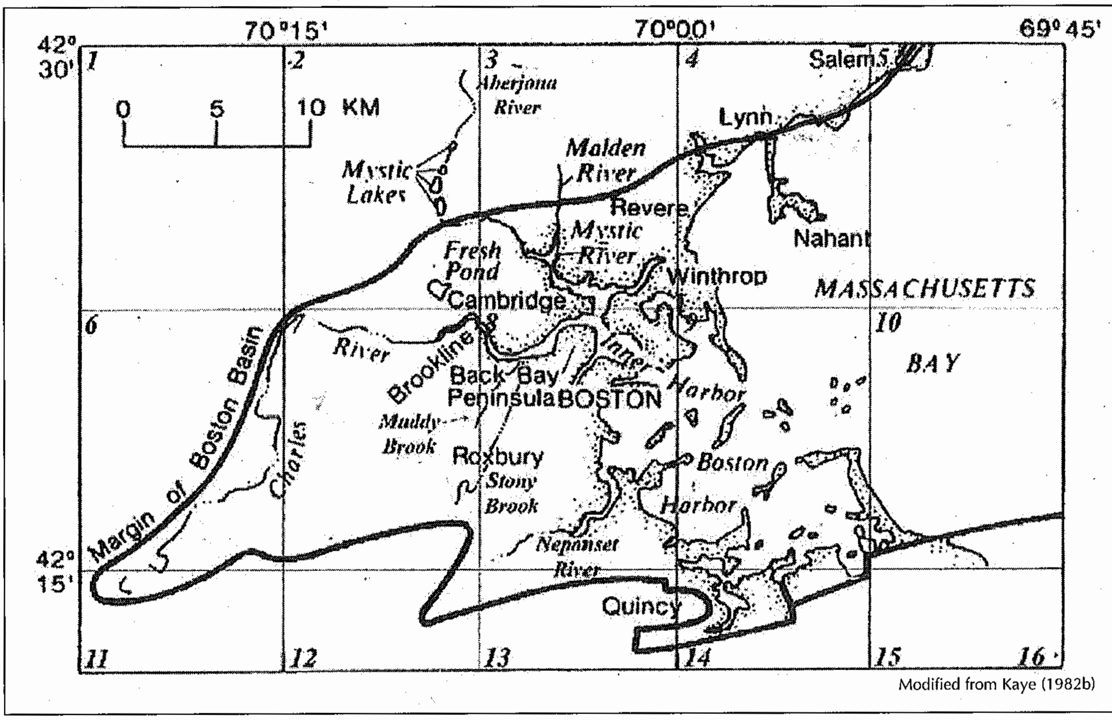



**FIGURE 3-6. Map showing the border of Boston Basin with included towns and rivers, plus an index of 1:24,000 scale quadrangle maps. The numbers indicate the quadrangle maps listed in Table 3-1.**

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.

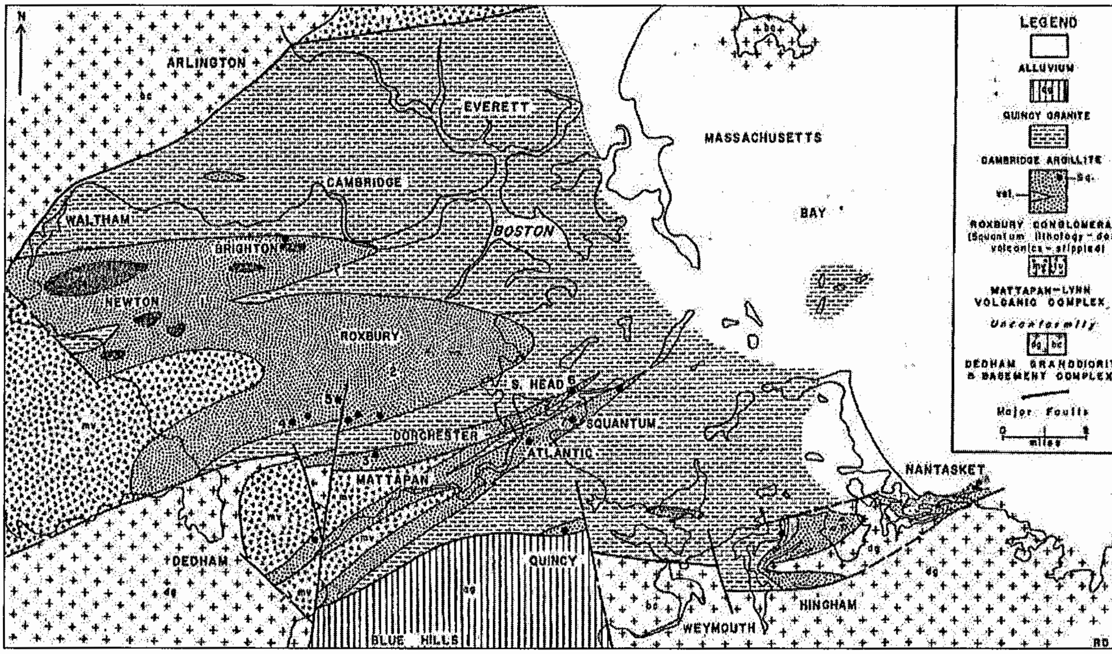



**FIGURE 3-7. Simplified geologic map of the Boston Basin by Dott (1961), after LaForge (1932), showing the generalized distribution of lithologies and locations of stratigraphic studies.**

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-

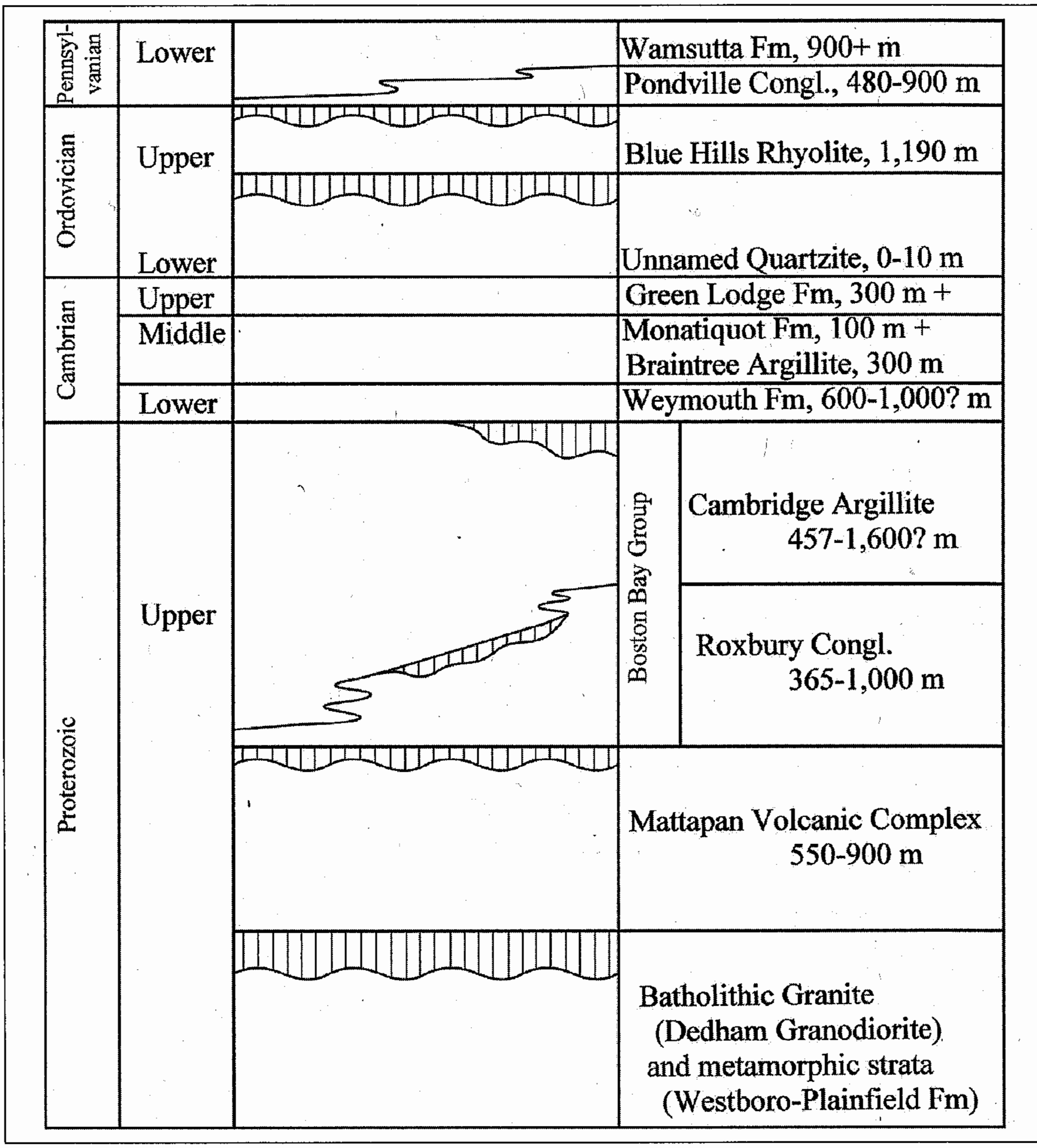



**FIGURE 3-8. Stratigraphic column for the Boston Basin.**

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

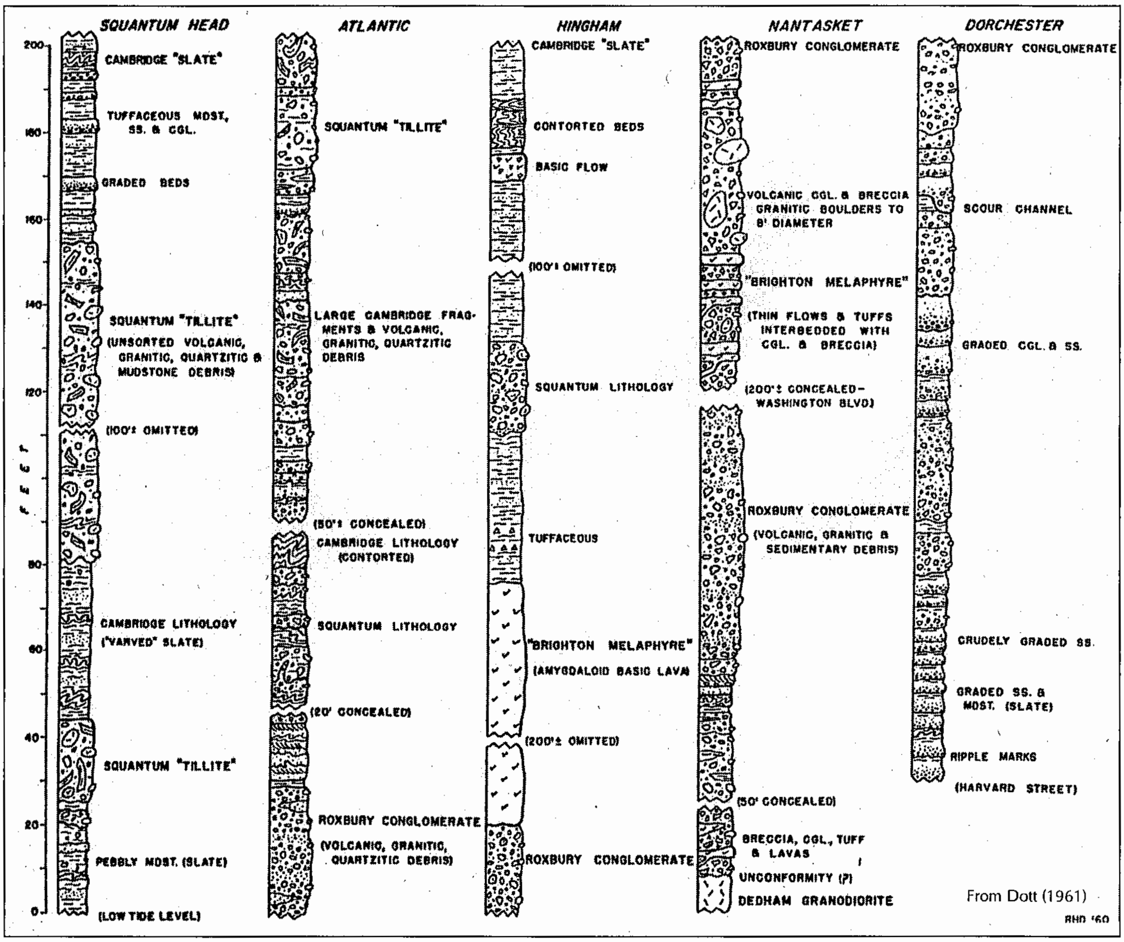



**FIGURE 3-9. Stratigraphic sections along the southern side of the Boston Basin demonstrating large local variations.**

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

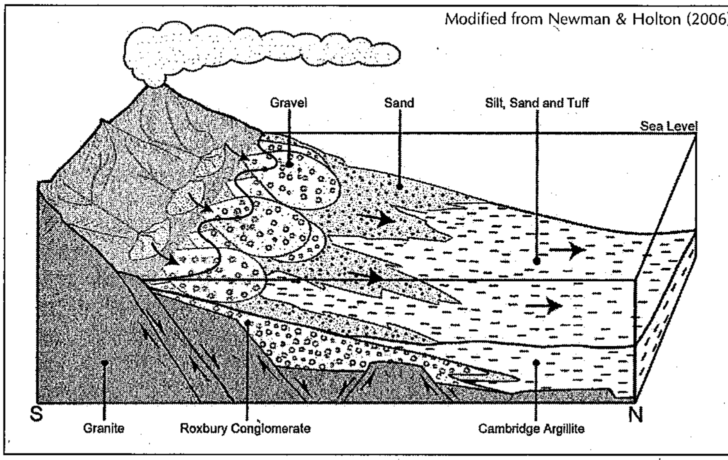



**FIGURE 3-10. Diagram illustrating the depositional environment of the Boston Basin.**

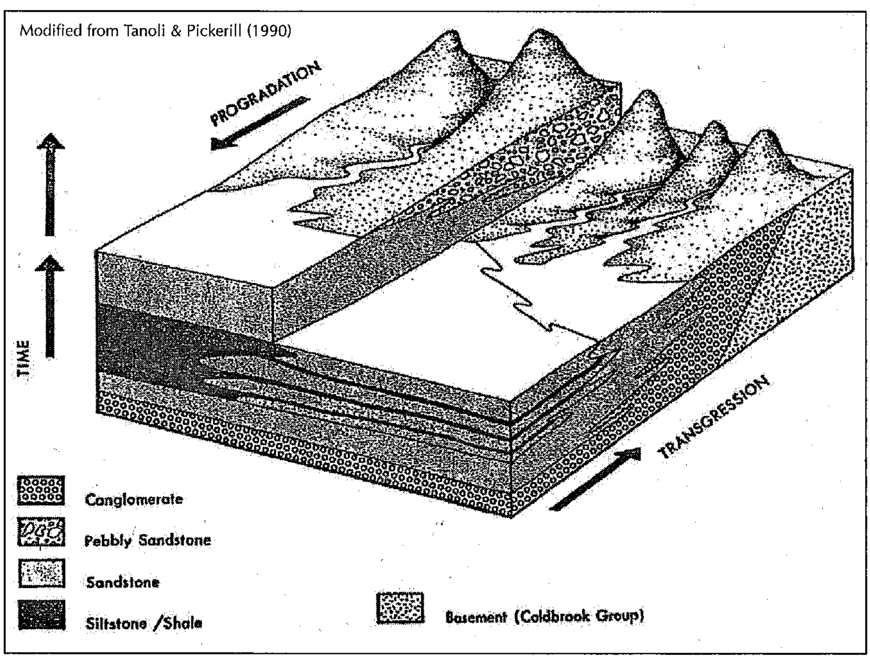



**FIGURE 3-11. Diagram showing the interpretation of facies changes in the Ratcliff Brook Formation during the deposition of Early Cambrian marine transgressive strata near Saint John, New Brunswick.**

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

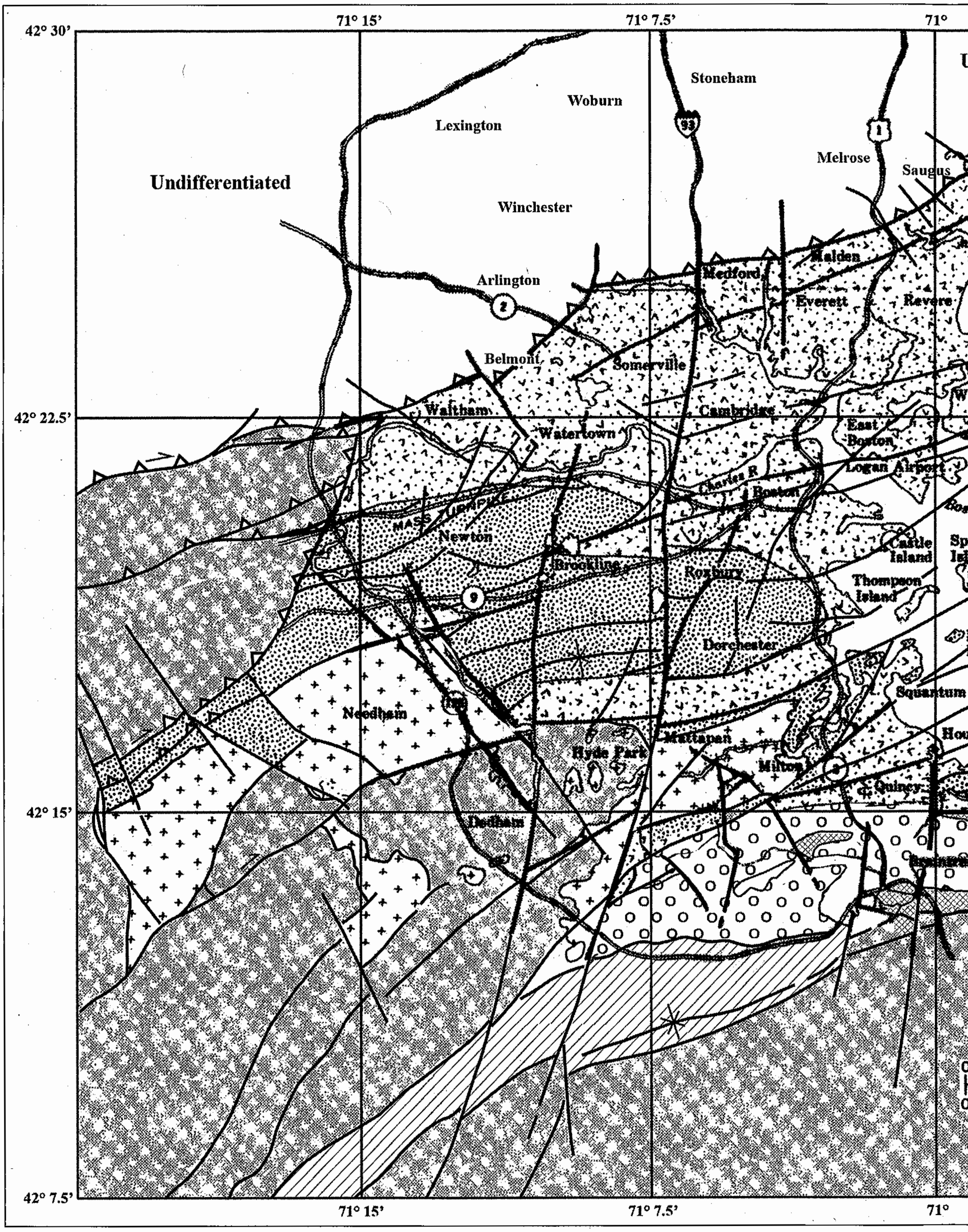
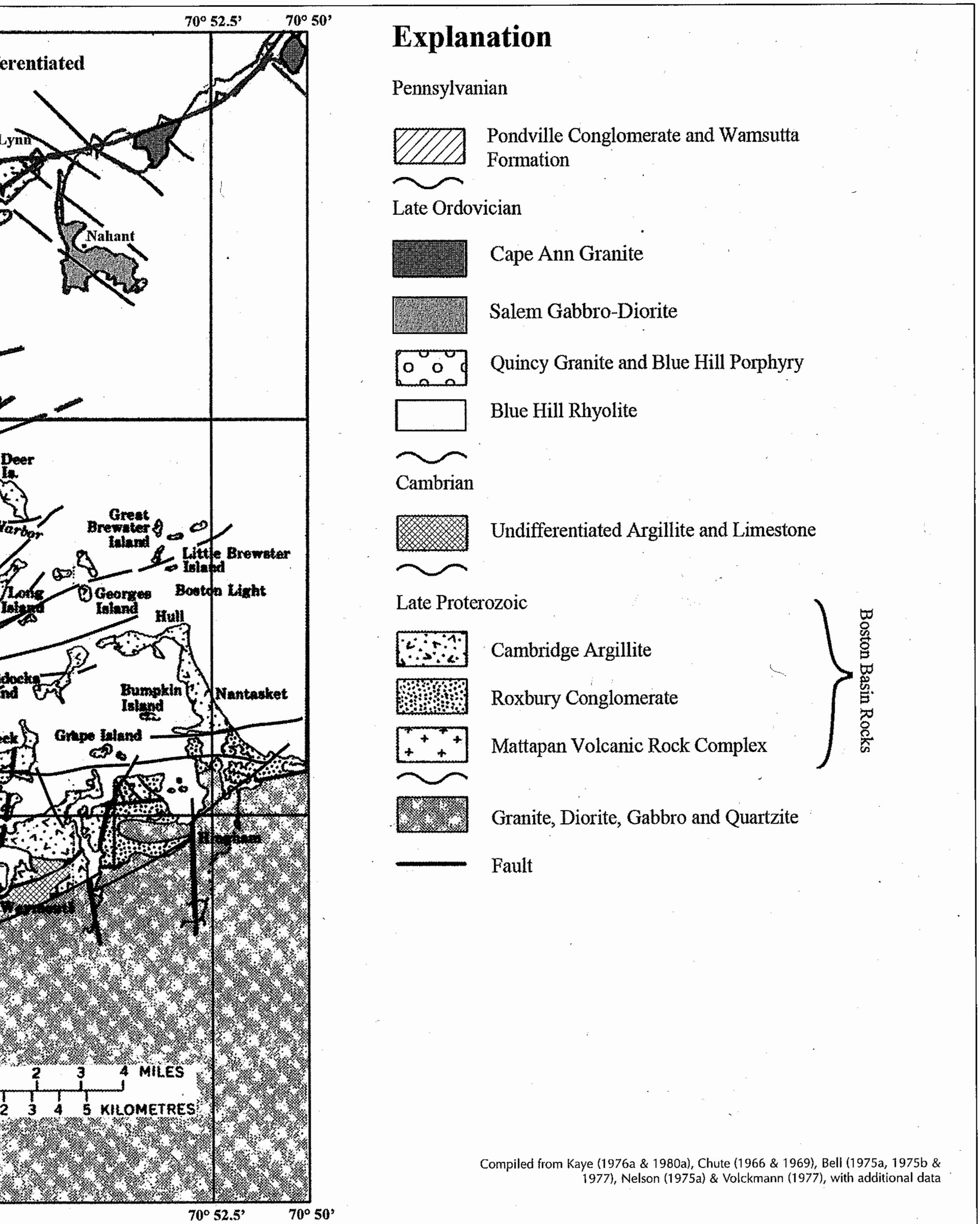



FIGURE 3-12. Bedrock geologic map of the Boston area.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erentiated
Lynn
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Deer Is.
Harbor
Great Brewster Island
Little Brewster Island
Long Island
Georges Island
Boston Light
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Bumpkin Island
Nantasket
Grape Island
Hingham
2 3 4 MILES
2 3 4 5 KILOMETRES
70° 52.5'
70° 50'
Explanation
Pennsylvanian
Pondville Conglomerate and Wamsutta Formation
Late Ordovician
Cape Ann Granite
Salem Gabbro-Diorite
Quincy Granite and Blue Hill Porphyry
Blue Hill Rhyolite
Cambrian
Undifferentiated Argillite and Limestone
Late Proterozoic
Cambridge Argillite
Roxbury Conglomerate
Mattapan Volcanic Rock Complex
Boston Basin Rocks
Granite, Diorite, Gabbro and Quartzite
Fault
Compiled from Kaye (1976a & 1980a), Chute (1966 & 1969), Bell (1975a, 1975b & 1977), Nelson (1975a) & Volckmann (1977), with additional data

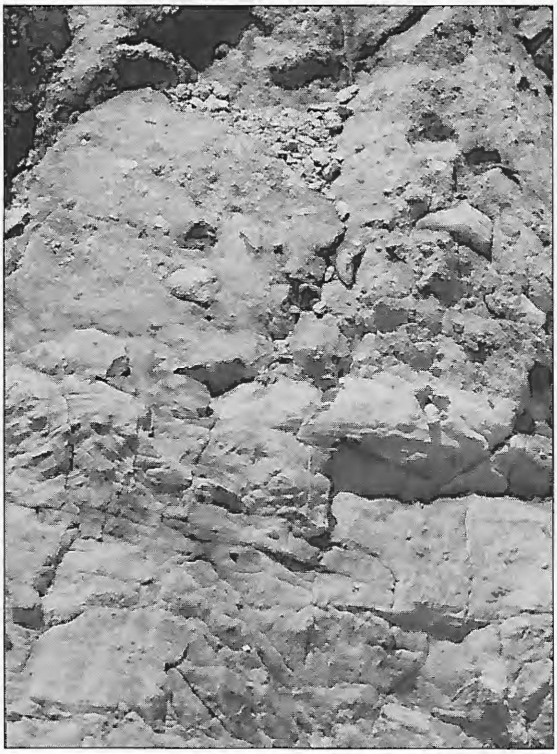

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**FIGURE 3-13. Pebbly mudstone slump deposit, which has been called the "Squantum Tillite," in the Cambridge Argillite at Squaw Head, Squantum, Quincy.**

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.**

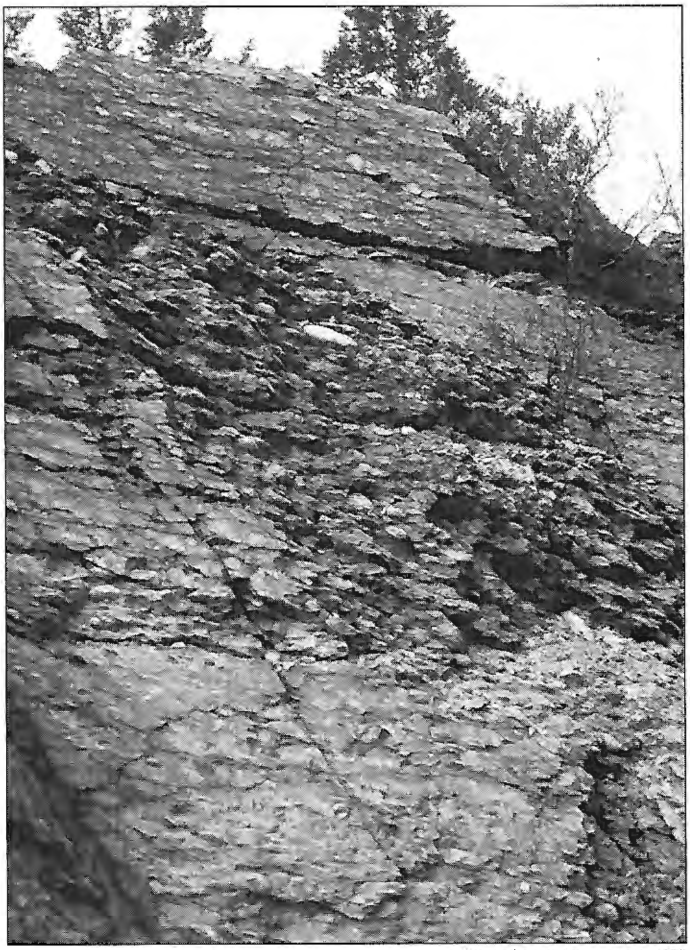
lies within eastern Needham (Kaye, 1980a). It is part of the volcanic complex and may have served as the main vent.

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

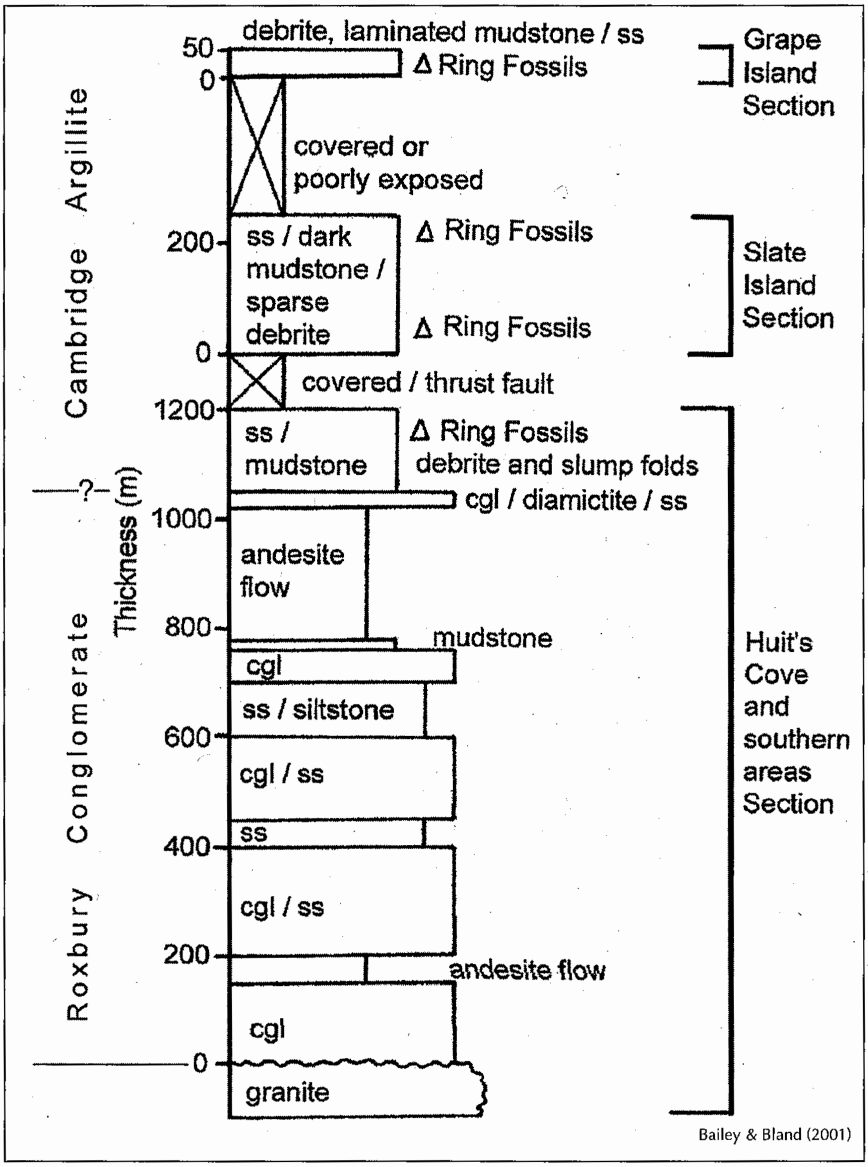



**FIGURE 3-16. Generalized composite faulted stratigraphic section across the Roxbury-Cambridge boundary in Hingham.**

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 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.

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.

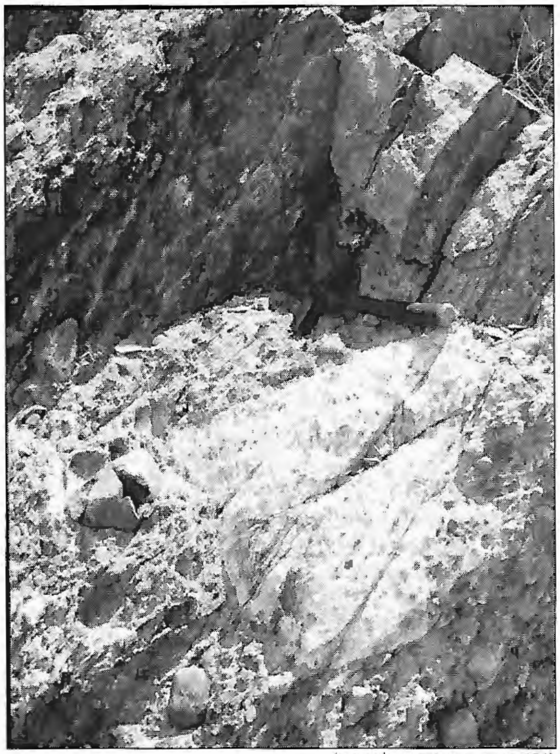
Bedding in the argillite ranges from laminated through thin-bedded to locally massive 1.5 meter (5 foot) beds. Beds usually are 0.5 to 5 centimeters (0.3 to 2 inches) and may be bundled together in units. Features that can be seen in the argillite include: graded-bedding, pinch-and-swell bedding, small-scale 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.

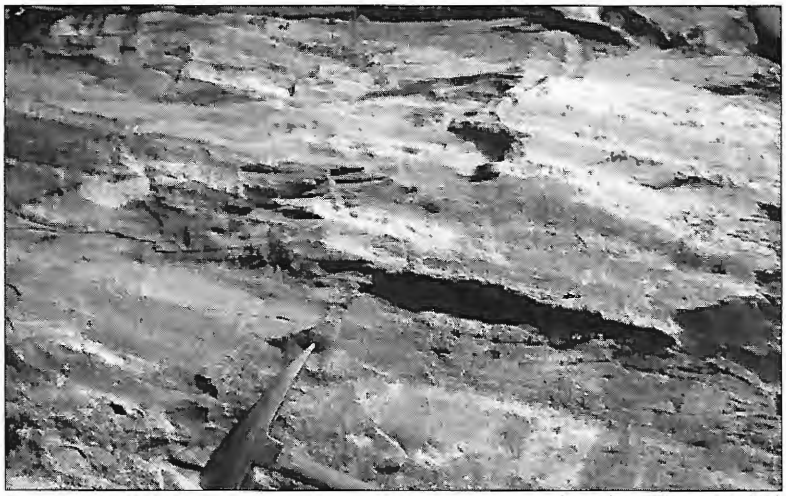
The Cambridge Argillite is found overlying various parts of the Roxbury Conglomerate

(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).

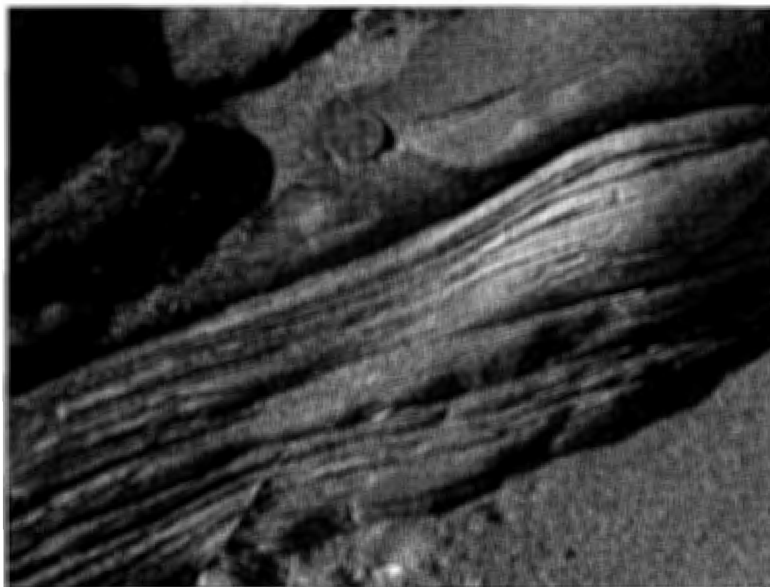
*Green Lodge Formation.* Very limited exposures of the Green Lodge Formation are present on the southwest side of the Blue Hills along Route 128 in Dedham (Rhodes & Graves, 1931; Chute, 1966). It consists of light-gray quartzite interbedded with dark-gray phyllite, most of which has light-gray siltstone 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.



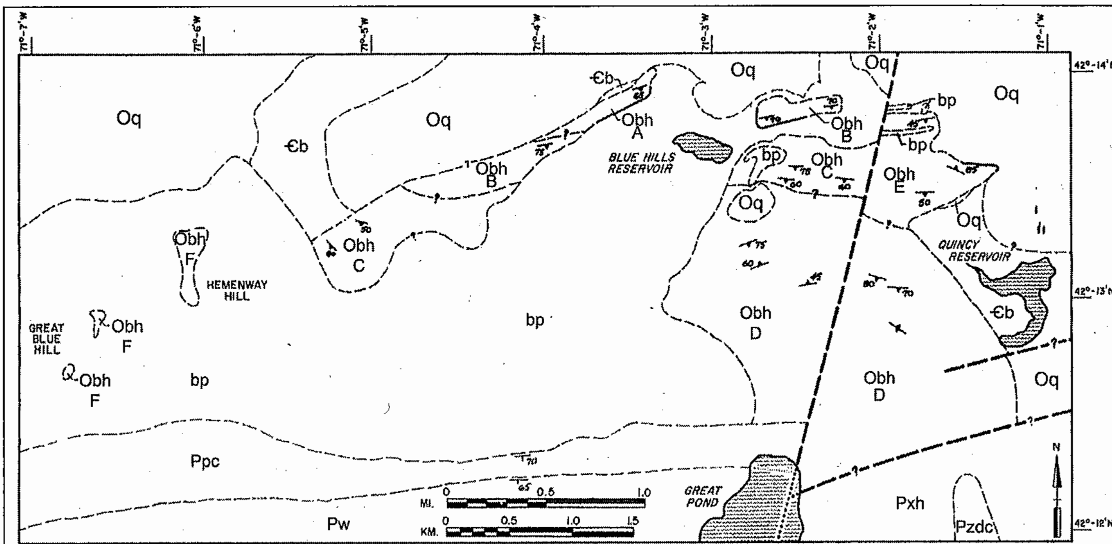
(see color version on page 455)

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

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 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




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

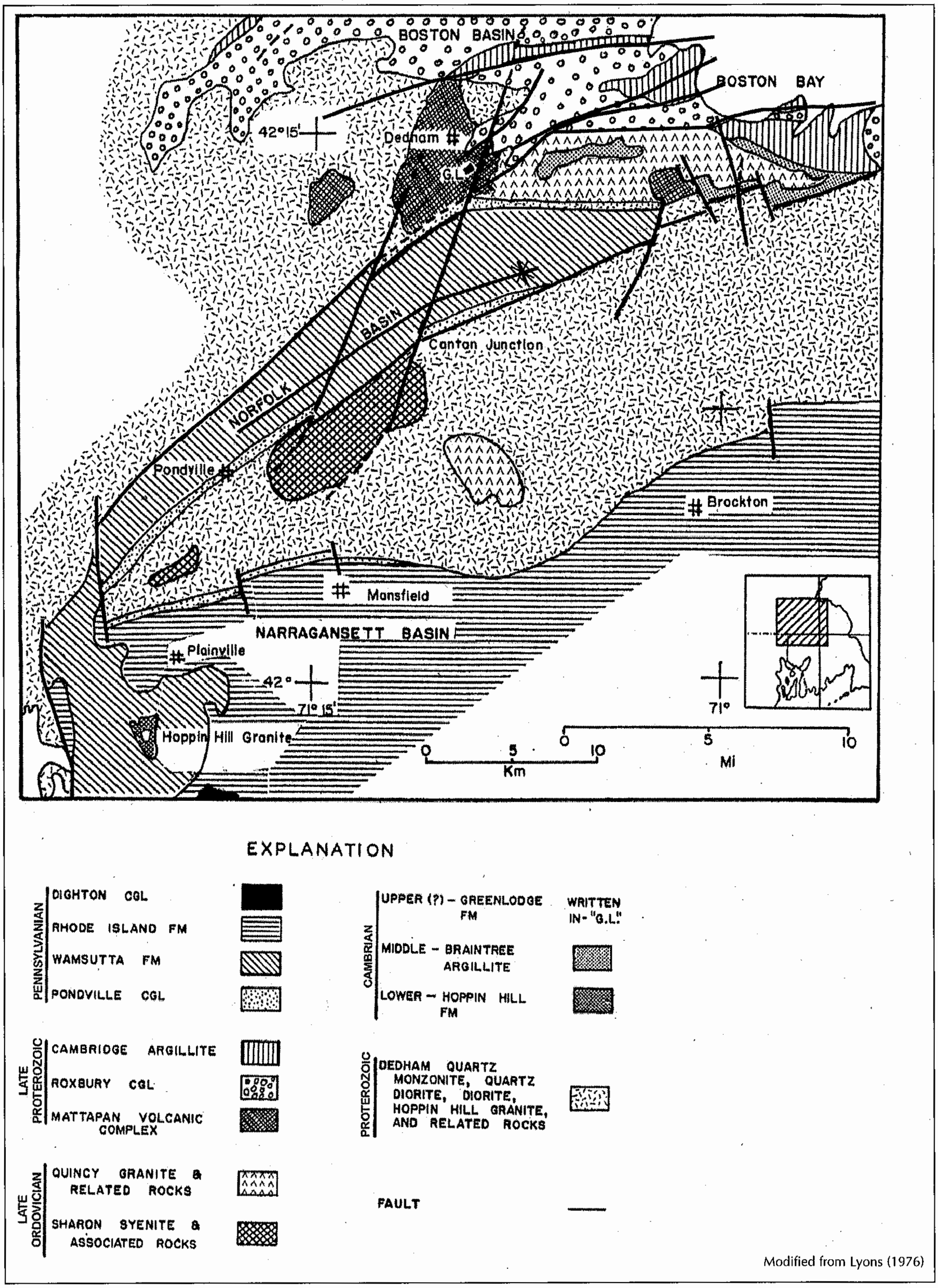



**FIGURE 3-29. Map of the Norfolk Basin showing stratigraphy and structural relation with the southern border of the Boston Basin.**

(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.**

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.

(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.**

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

(see color version on page 457)

**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).

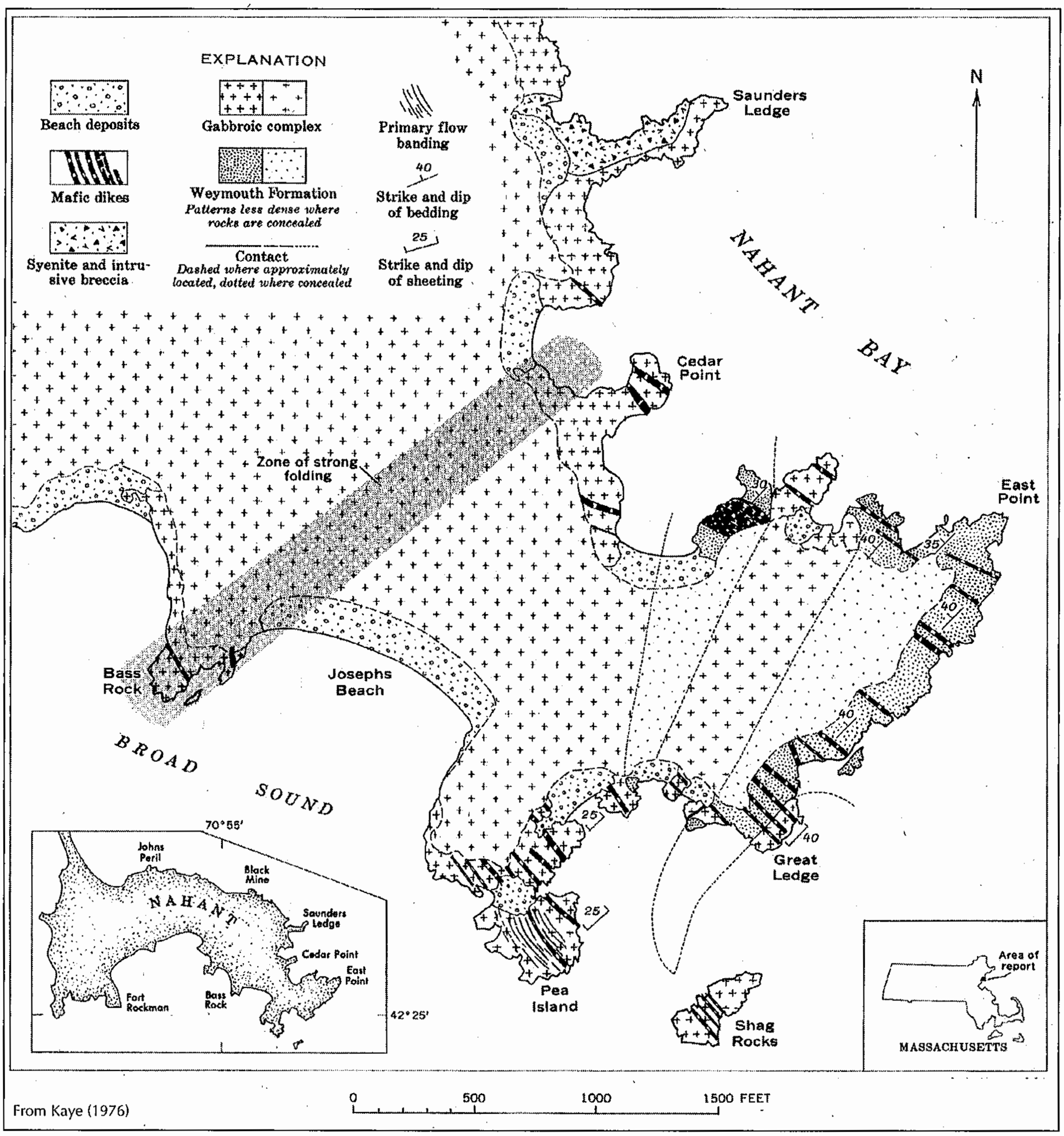



**FIGURE 3-34. Geologic map of southeastern Nahant.**

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-

(see color version on page 458)

**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 diorite, 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).

*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).

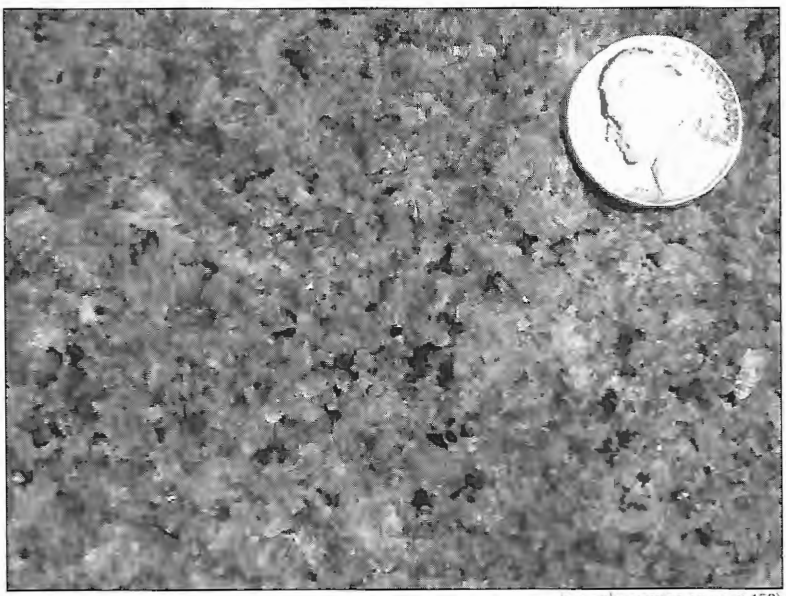


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FIGURE 3-37. Quincy Granite closeup at the Granite Rail Quarry in Quincy.

*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).

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

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).

*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

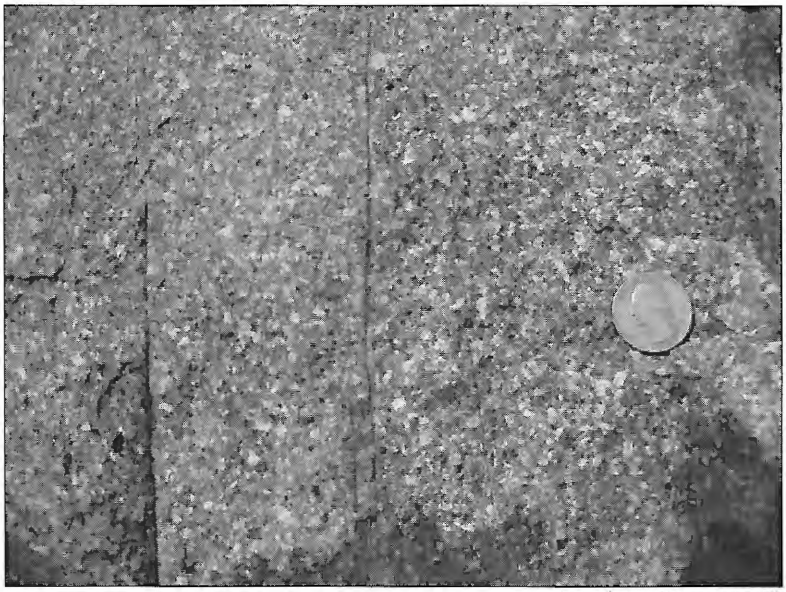

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**FIGURE 3-39. Blue Hills Granite Porphyry at Blue Hills.**

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

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**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.

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-

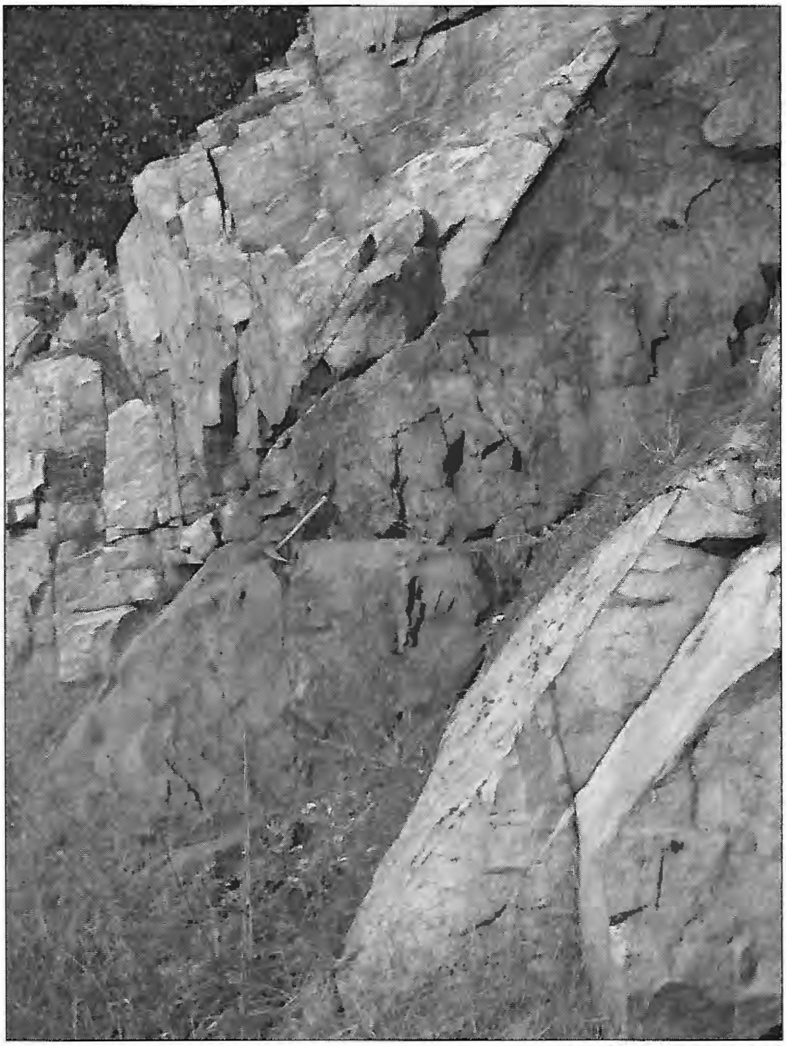

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**FIGURE 3-41. Greenstone dike cutting Late Proterozoic Dedham Granodiorite on Route 128, near Exit 16, west of route 109 in Dedham.**

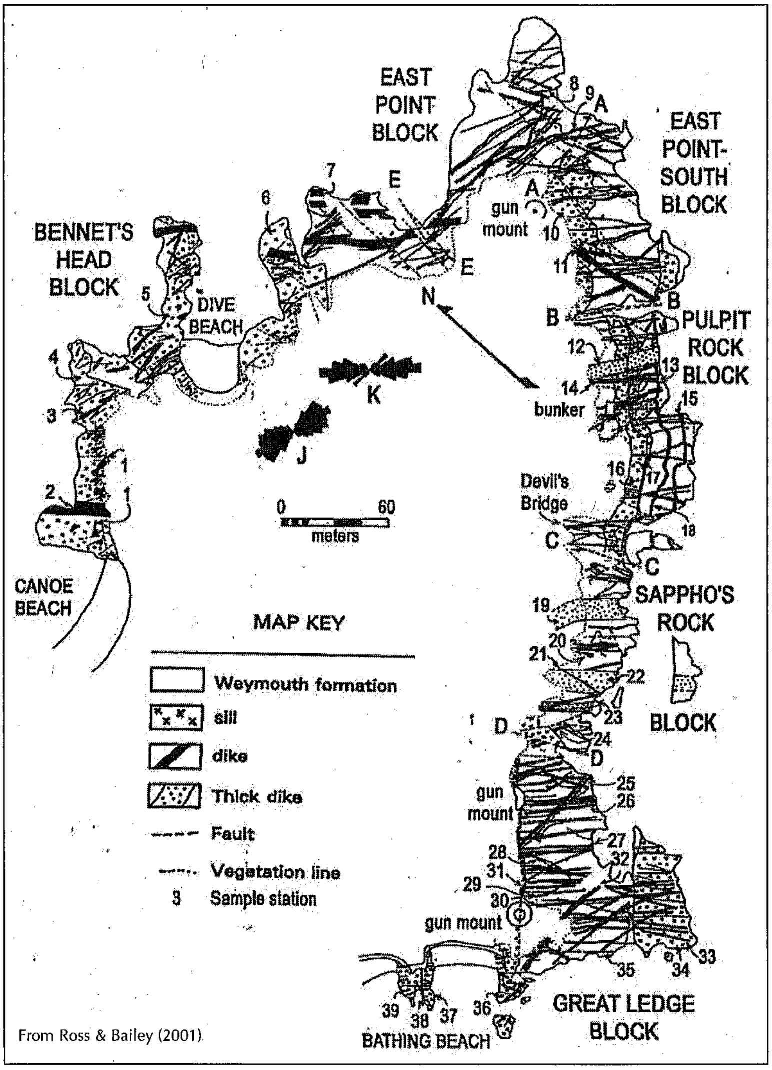


**FIGURE 3-42. Map showing the diabase dike complex at East Point in Nahant.**

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).

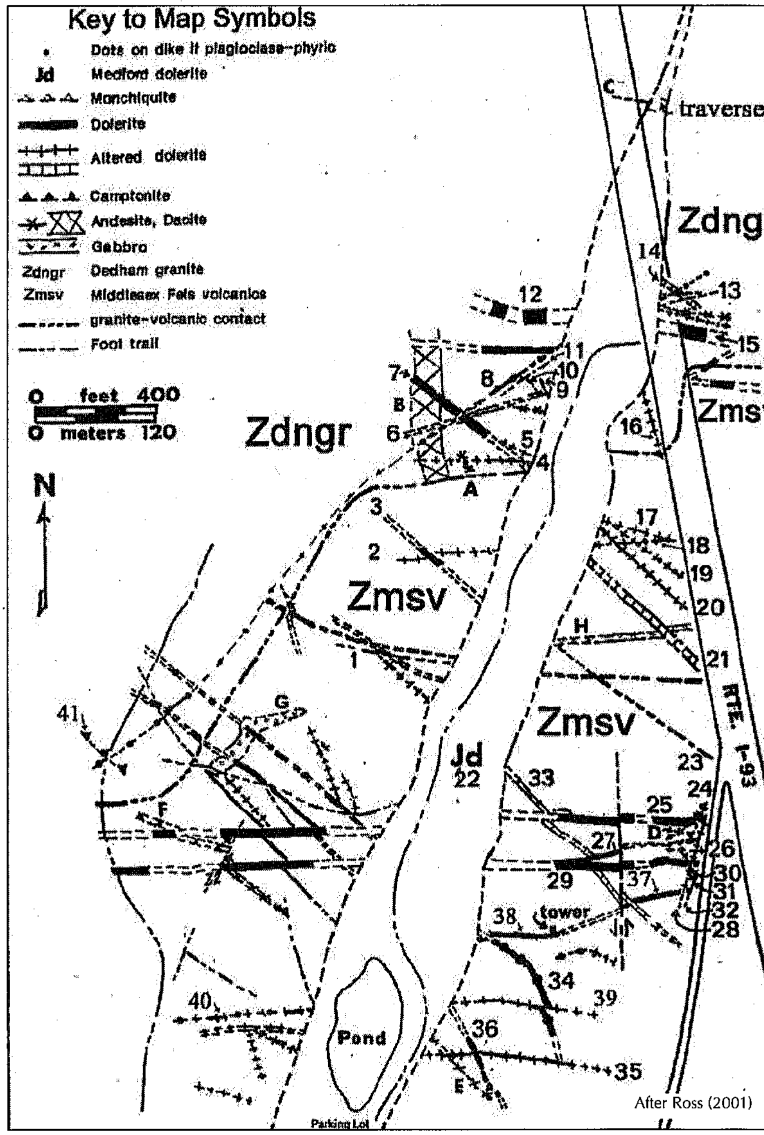


**FIGURE 3-43. Map of the Medford Dike at the northern border of the Boston Basin in Medford.**

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

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

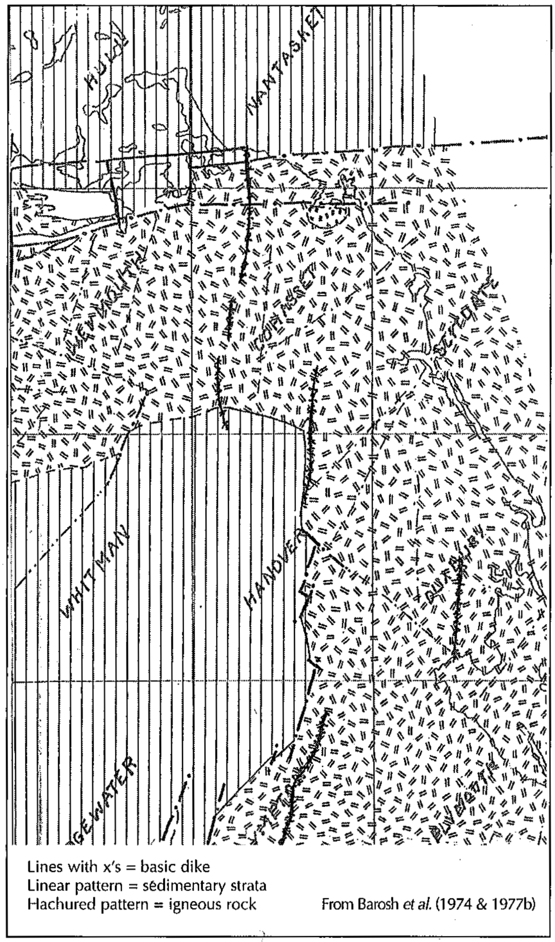



**FIGURE 3-45. Large basic dikes indicated by linear aeromagnetic anomalies south of the Boston Basin.**

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.**

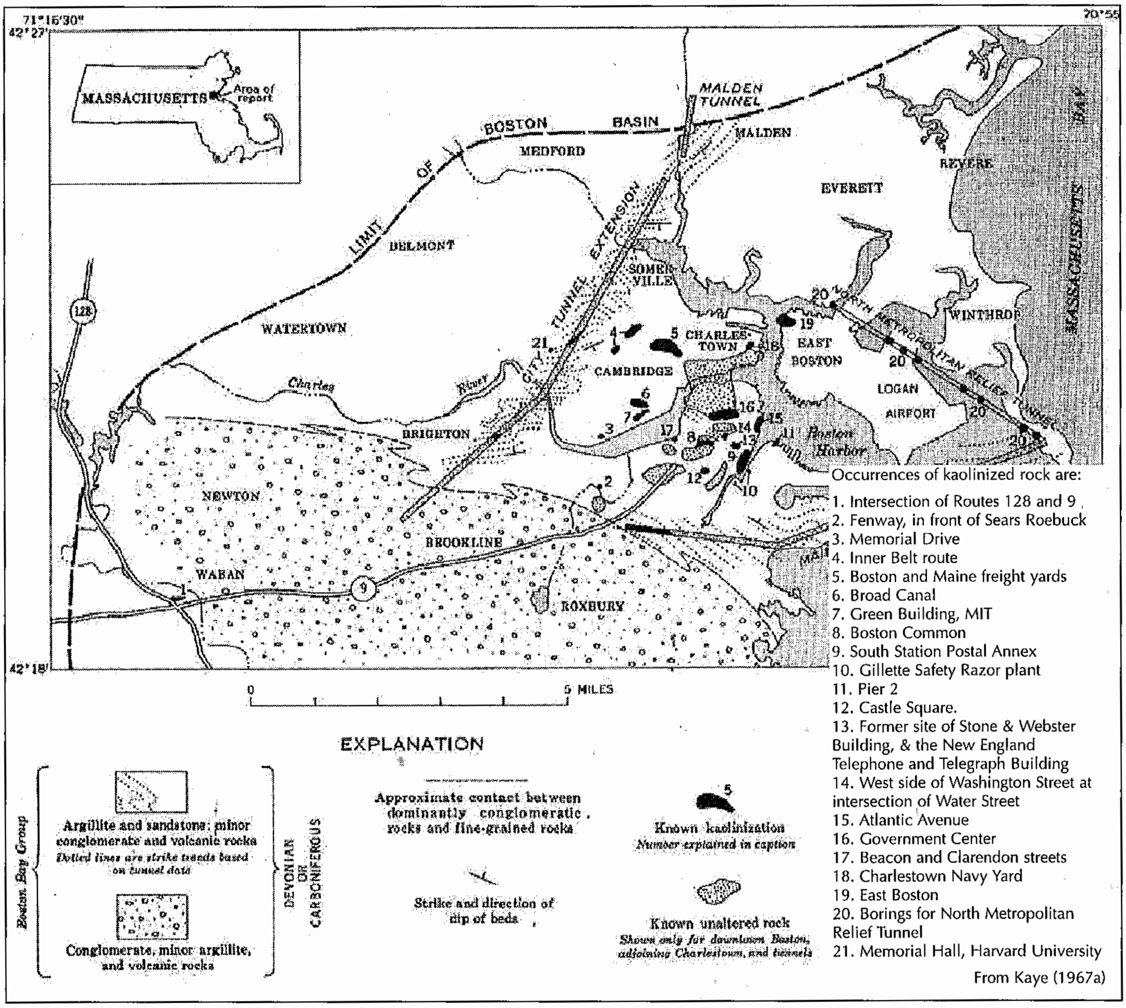



**FIGURE 3-48. Map of the Boston area showing the areas of known kaolinized rock, the bedrock tunnels and the generalized geology of the Boston Bay Group.**

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).

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

(see color version on page 459)

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

(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:

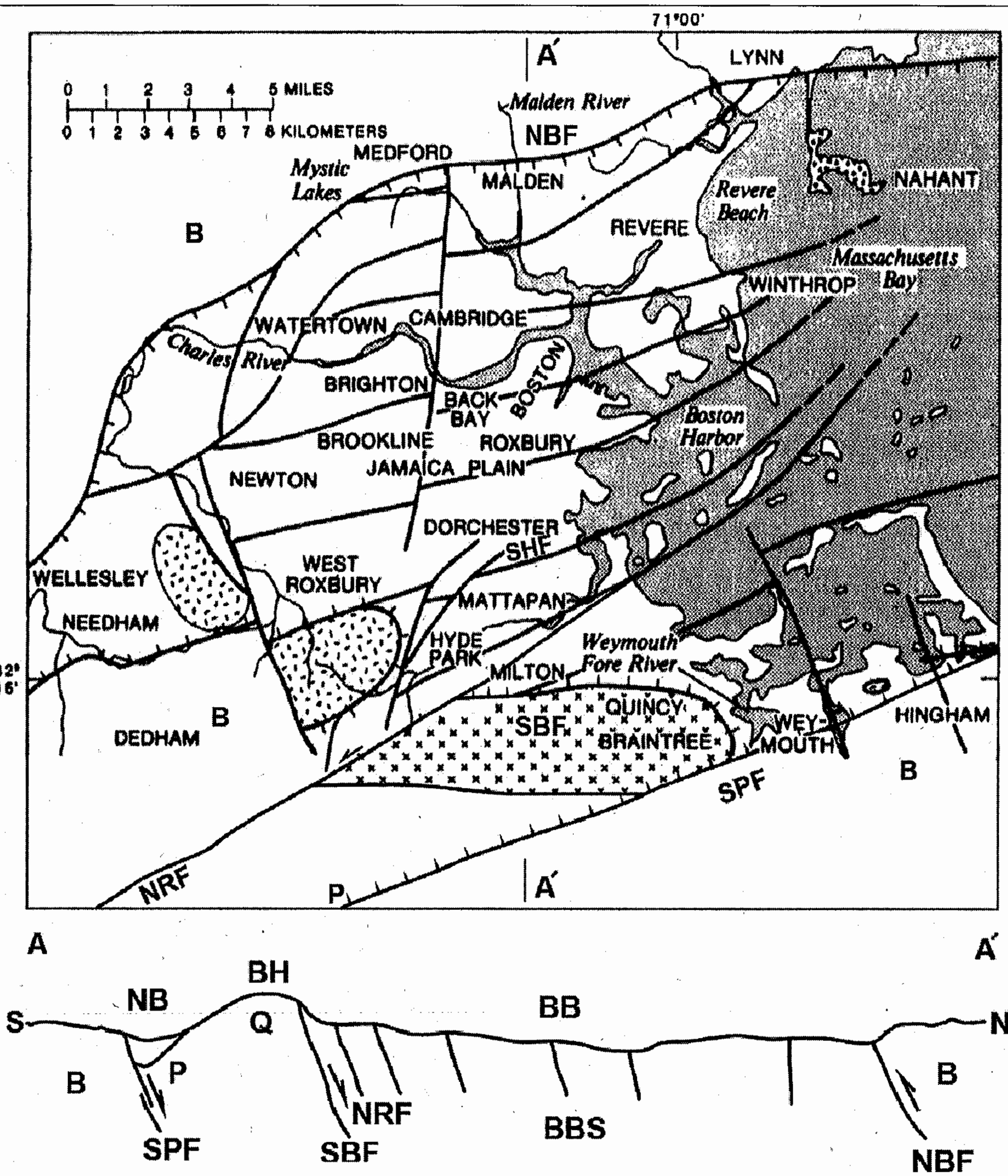
- east-trending Late Proterozoic normal faults (in which the block above the fault has moved downward relative to the block below), which are chiefly along the southern side of the basin and initiated basin growth;
- northeast- to east-trending Late Ordovician thrust faults, which are more prominent 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).**

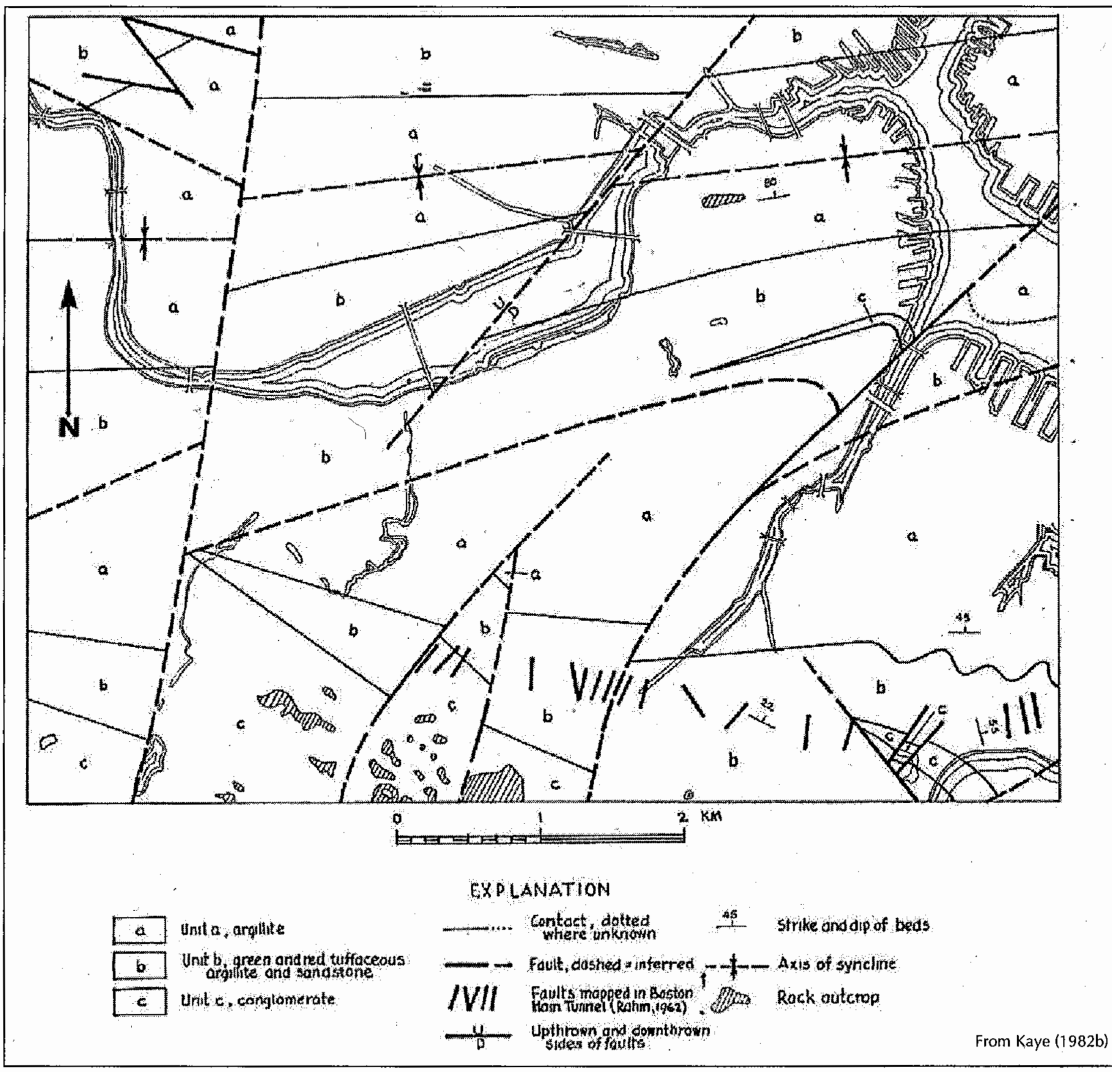



**FIGURE 3-51. Bedrock geologic map of the central Boston portion of the Boston South quadrangle.**

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.

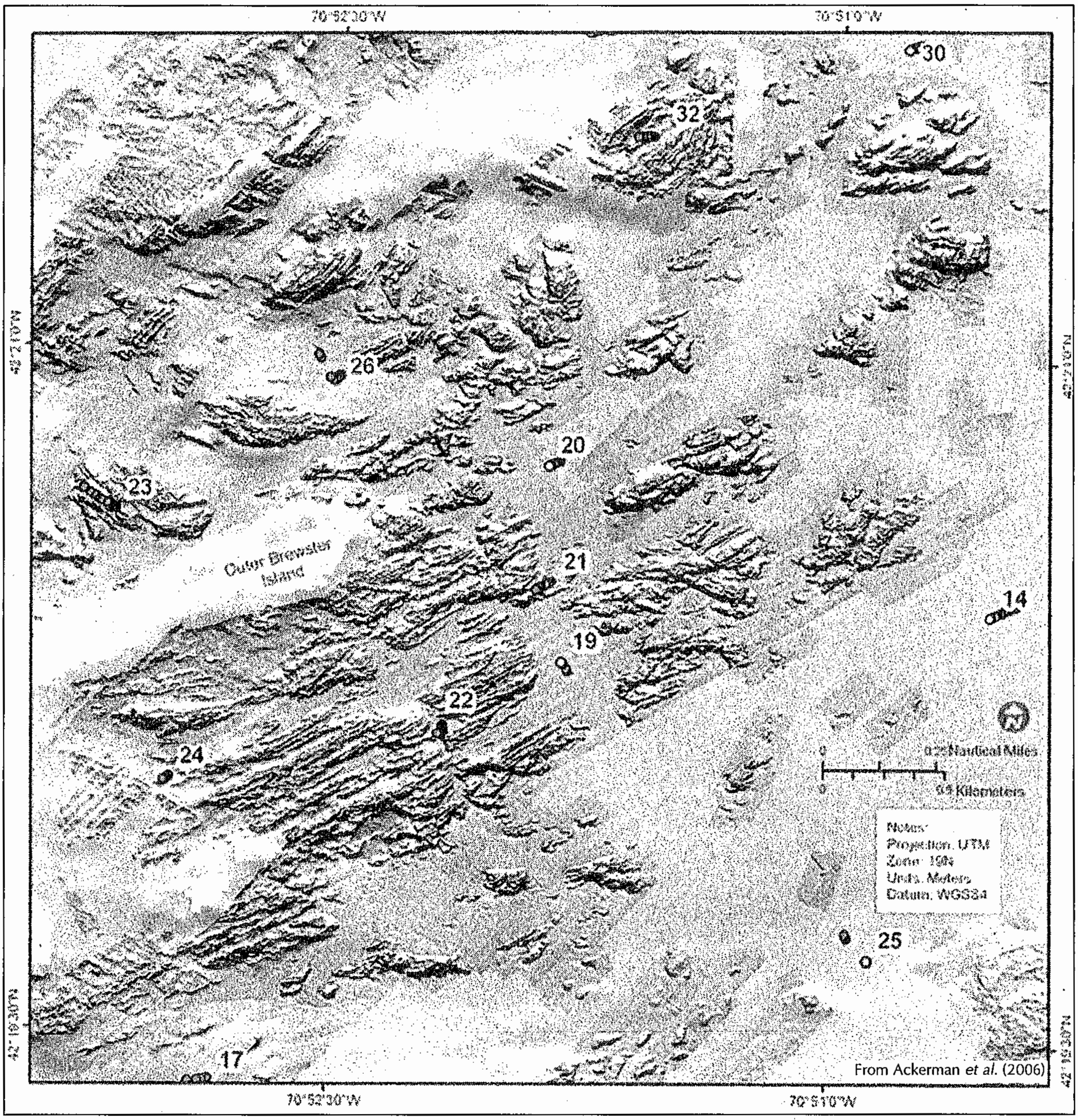



**FIGURE 3-52. Submerged ledges east of the Brewster Islands.**

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

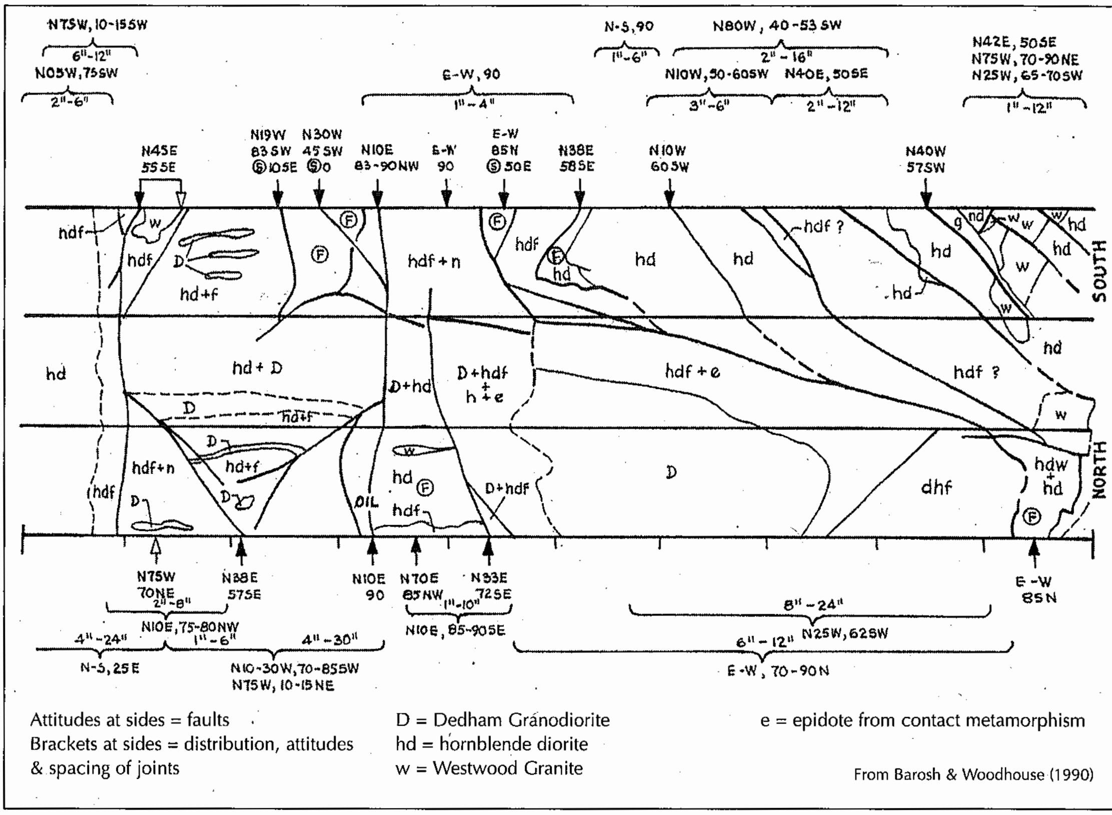



**FIGURE 3-53. Geologic map of the roof and both sides of a 61 meter (200 foot) segment of the Wellesley Extension Intercept Tunnel in Dedham showing all faults and joints.**

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

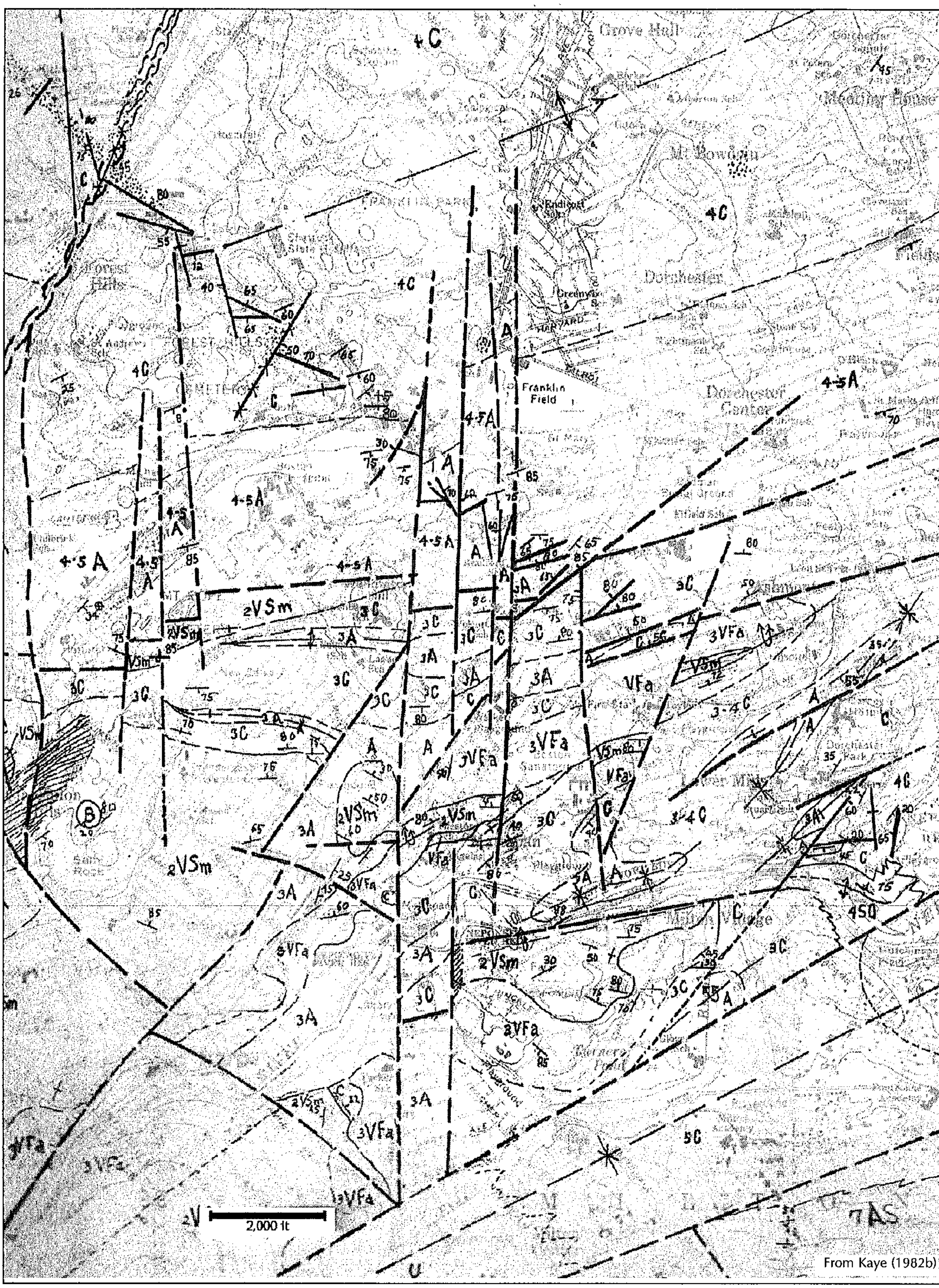


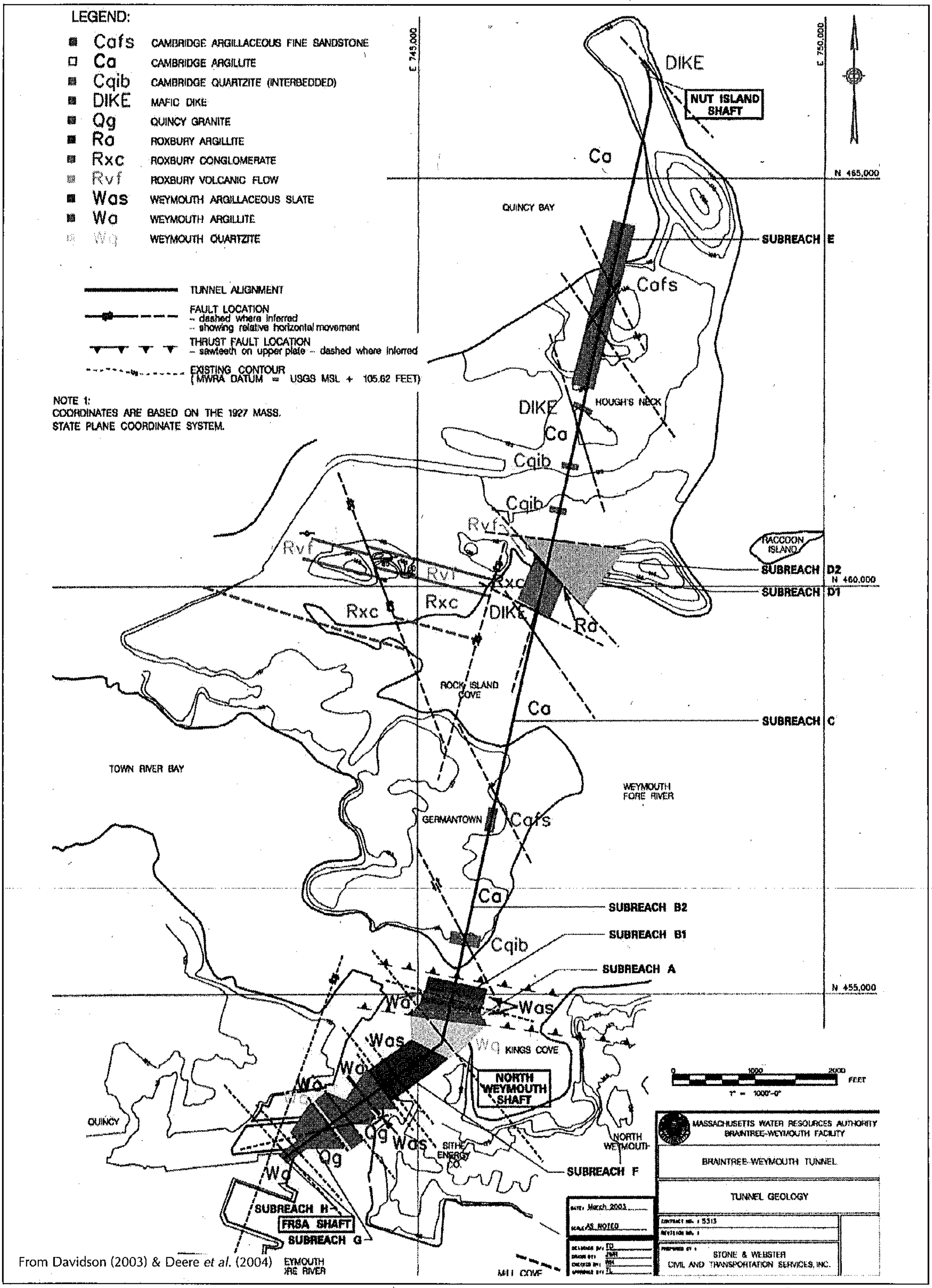

**FIGURE 3-54. Bedrock geologic map of the Dorchester-Milton portion of the Boston South quadrangle.**

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




(see color version on page 460)

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

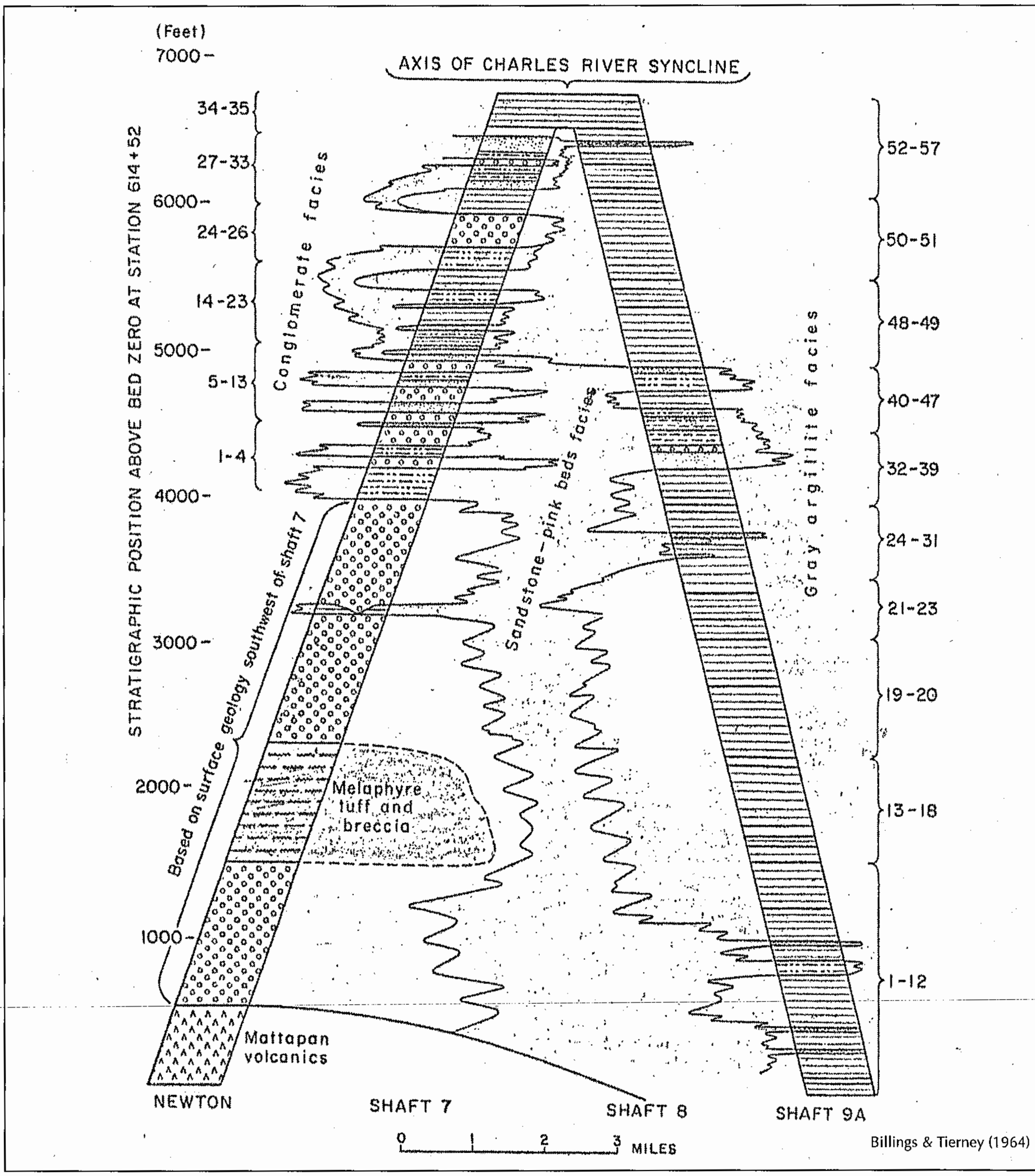



**FIGURE 3-56. Strong lithologic contrast across the axis of the "Charles River syncline" in the City Tunnel Extension described as facies changes by Billings and Tierney (1964), but the abruptness could only indicate the presence of a fault. Numbered brackets on the sides indicate the stratigraphic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

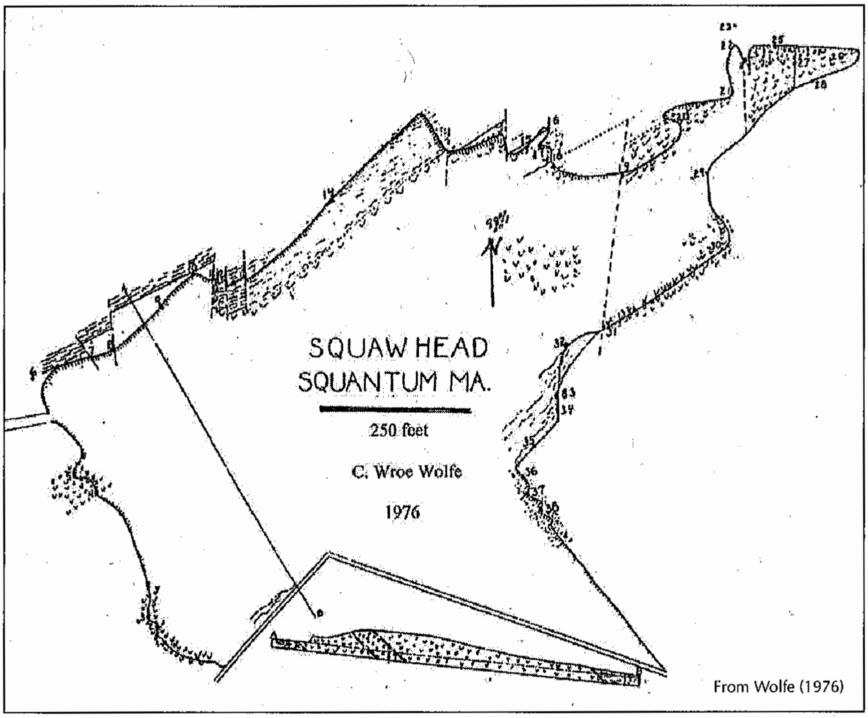



**FIGURE 3-57. Geologic map of Squaw Head, Squantum, Quincy, showing closely spaced north-trending faults. The area is underlain by pebbly mudstone to conglomeratic slump deposit lenses in the Cambridge Argillite, with normal argillite along the northwest shore.**

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.

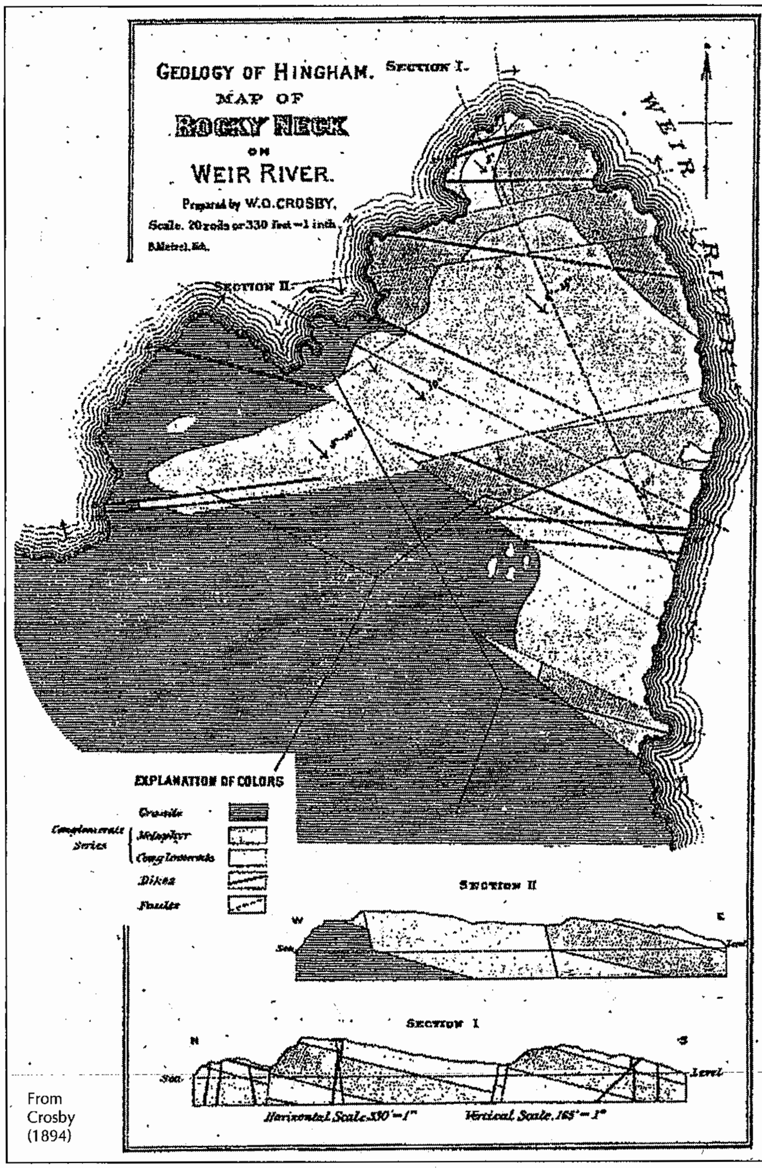



**FIGURE 3-58. Map and cross section of Rocky Neck in Hingham.**

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.

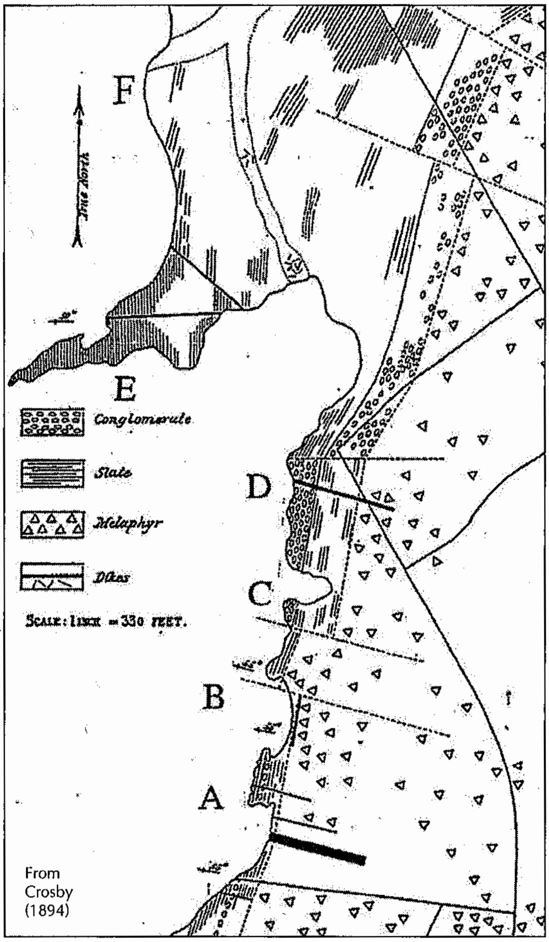



**FIGURE 3-59. Geologic map of Huit's Cove.**

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

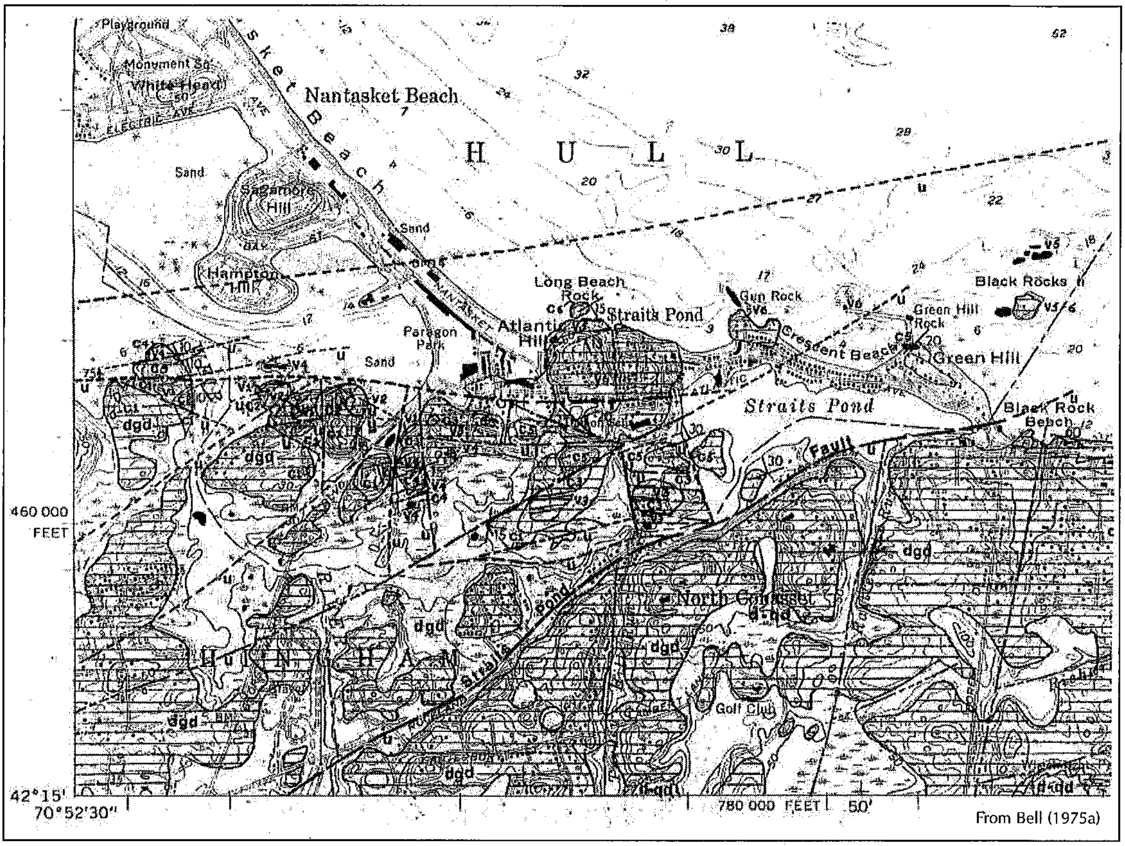



**FIGURE 3-60. Geologic map of the southwest corner of the Hull quadrangle.**

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

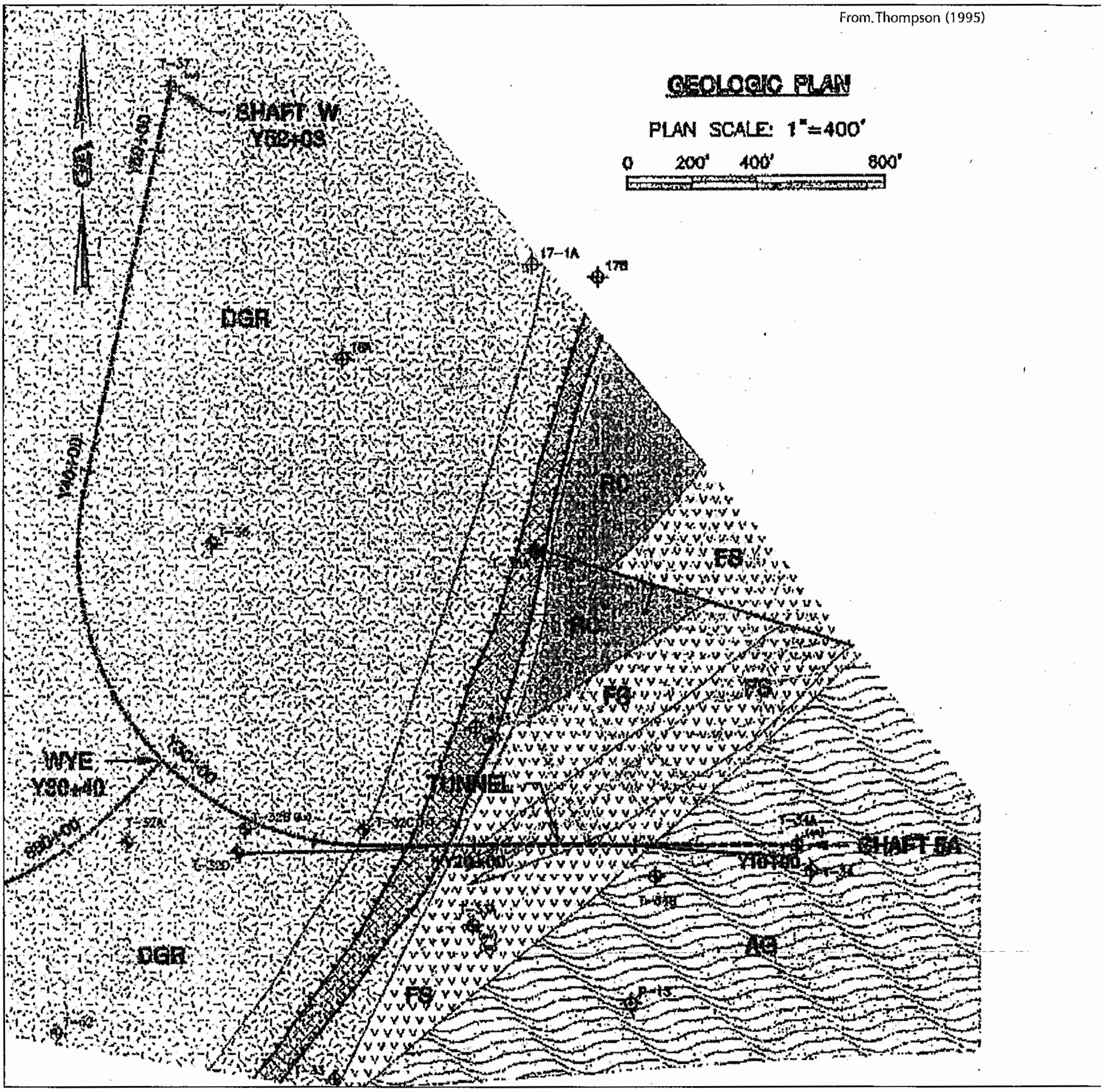
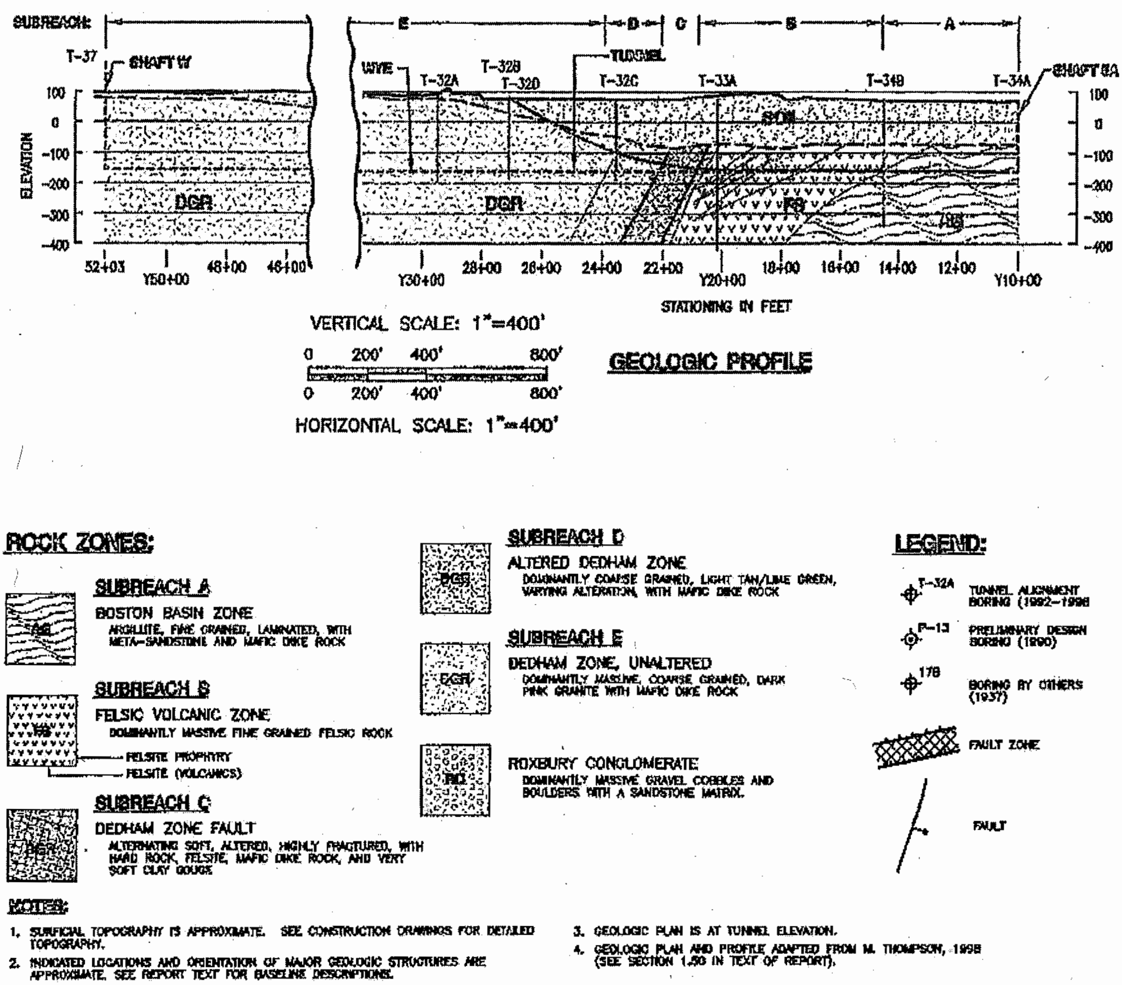


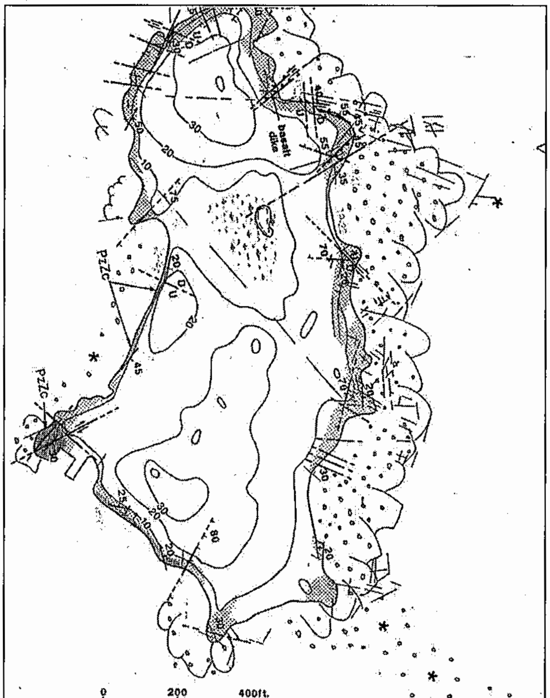

**FIGURE 3-61. Geologic map and section of the east end of the MetroWest Water Supply Tunnel in Weston and Newton showing the boundary fault of the Boston Basin.**

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




coarse stippling = igneous intrusive
Fine stippling = Cambridge Argillite
Fine long-dashed lines = photo lineaments
Heavy lines = faults

From Turner *et al.* (1988)

**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

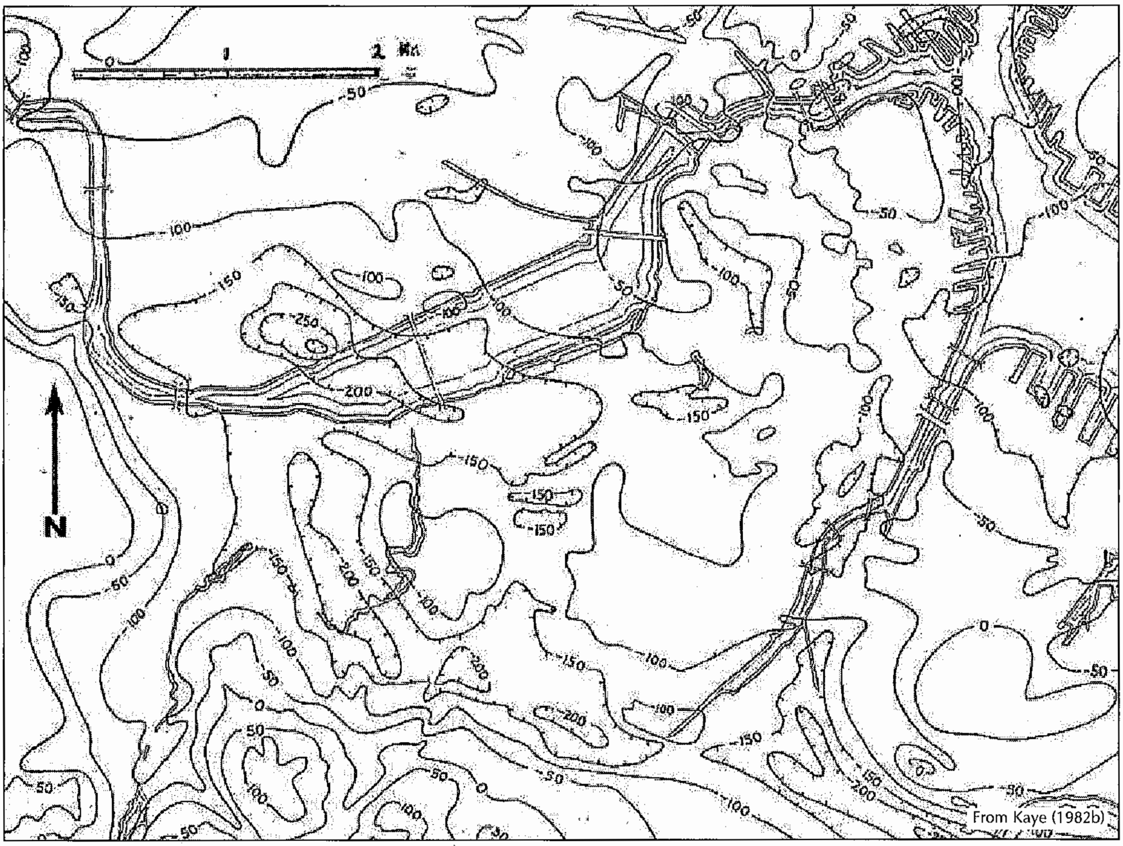



**FIGURE 3-63. Simplified bedrock surface beneath Boston. The contour interval is 15 meters (50 feet) measured from MSL.**

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;

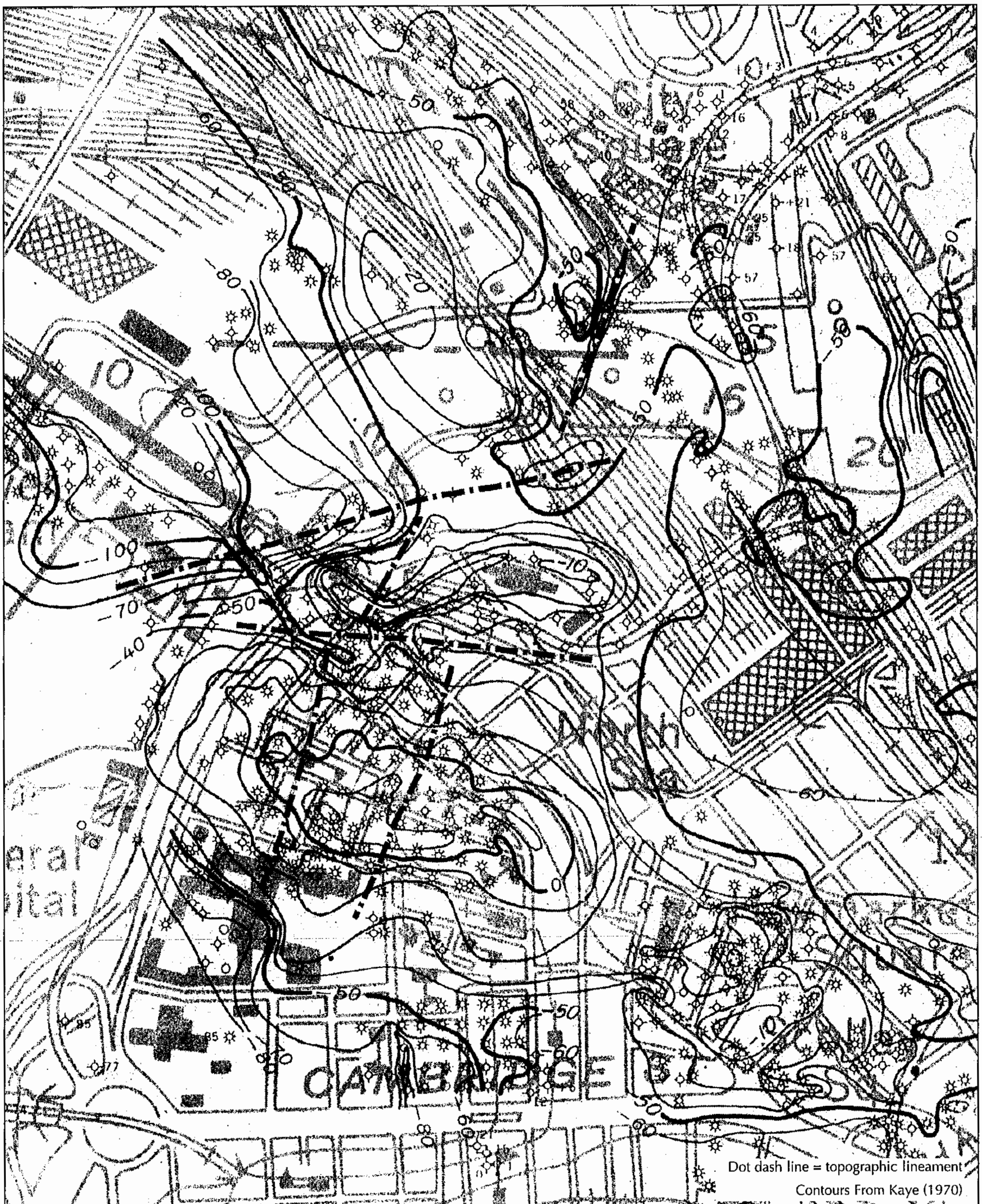



**FIGURE 3-64. Bedrock surface beneath Boston between Beacon Hill and North Station with topographic lineaments representing probable fault zones. The contour interval is about 3 meters (10 feet) MSL.**

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

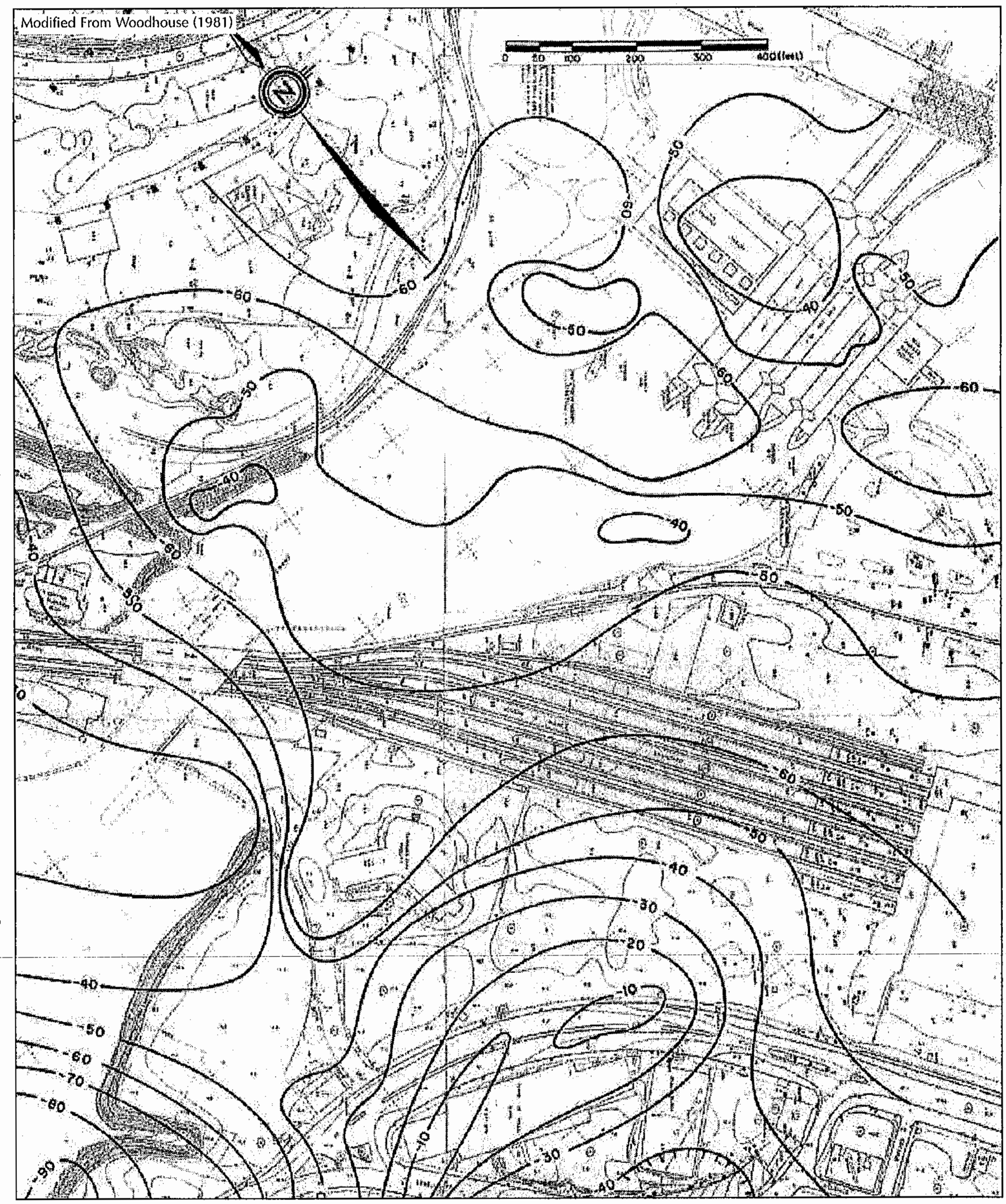



**FIGURE 3-65. Bedrock surface in the North Station area, Boston — a detail of northeast corner of Figure 3-64. The contour interval is about 3 meters (10 feet) MSL.**

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

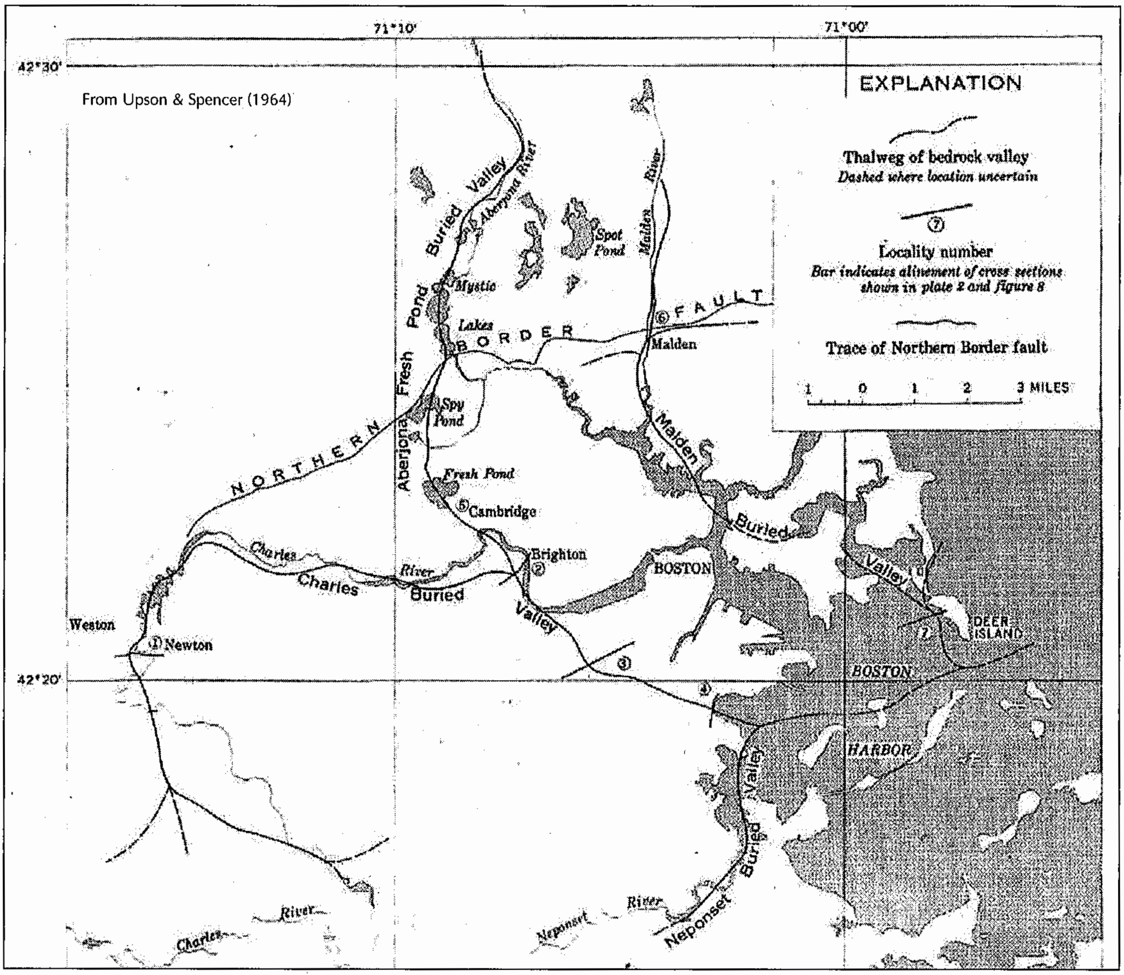



**FIGURE 3-66. Map of the environs of Boston Basin showing the four major buried river channels carved into the bedrock.**

(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

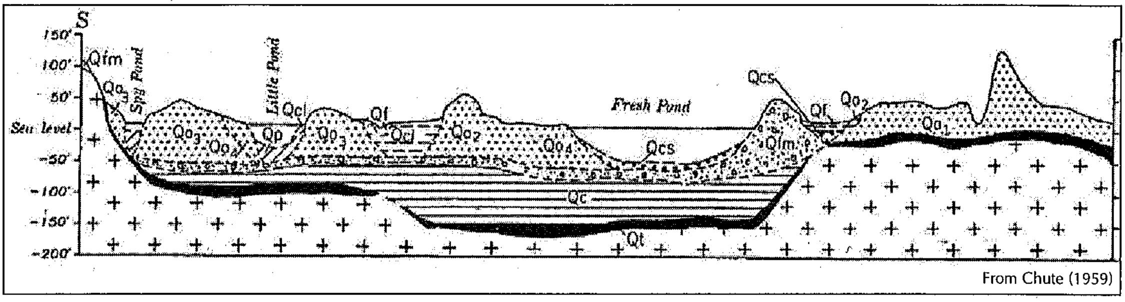



**FIGURE 3-67. Section through the ancestral Aberjona river channel in bedrock beneath the Pleistocene deposits north of Fresh Pond showing an incised inner channel.**

(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

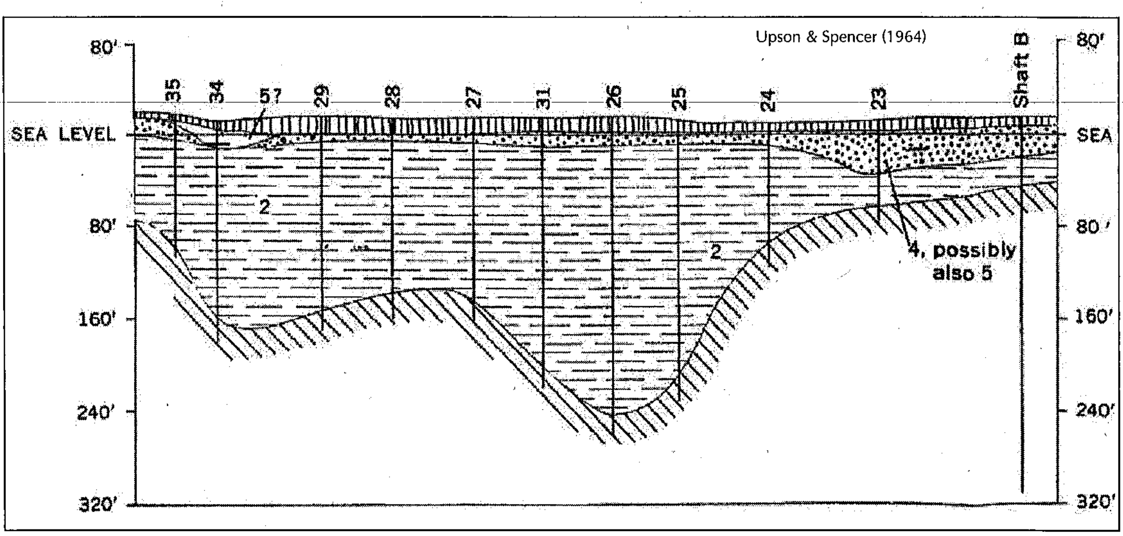



**FIGURE 3-68. Section along the shore of Dorchester Bay showing the bedrock surface across the Charles buried valley at Columbus Park; view west-northwest. Data from Main Drainage Tunnel boreholes.**

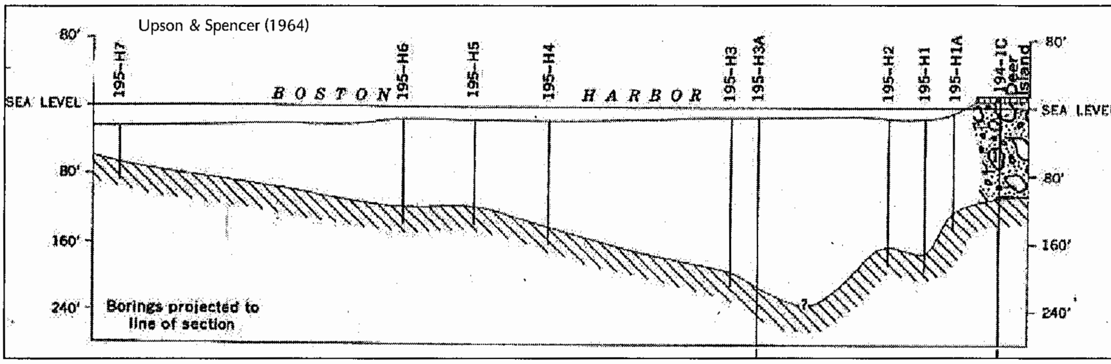



**FIGURE 3-69. Section southwest of northern Deer Island showing the bedrock surface across the Malden buried valley; view north-northwest. Data from Main Drainage Tunnel boreholes.**

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

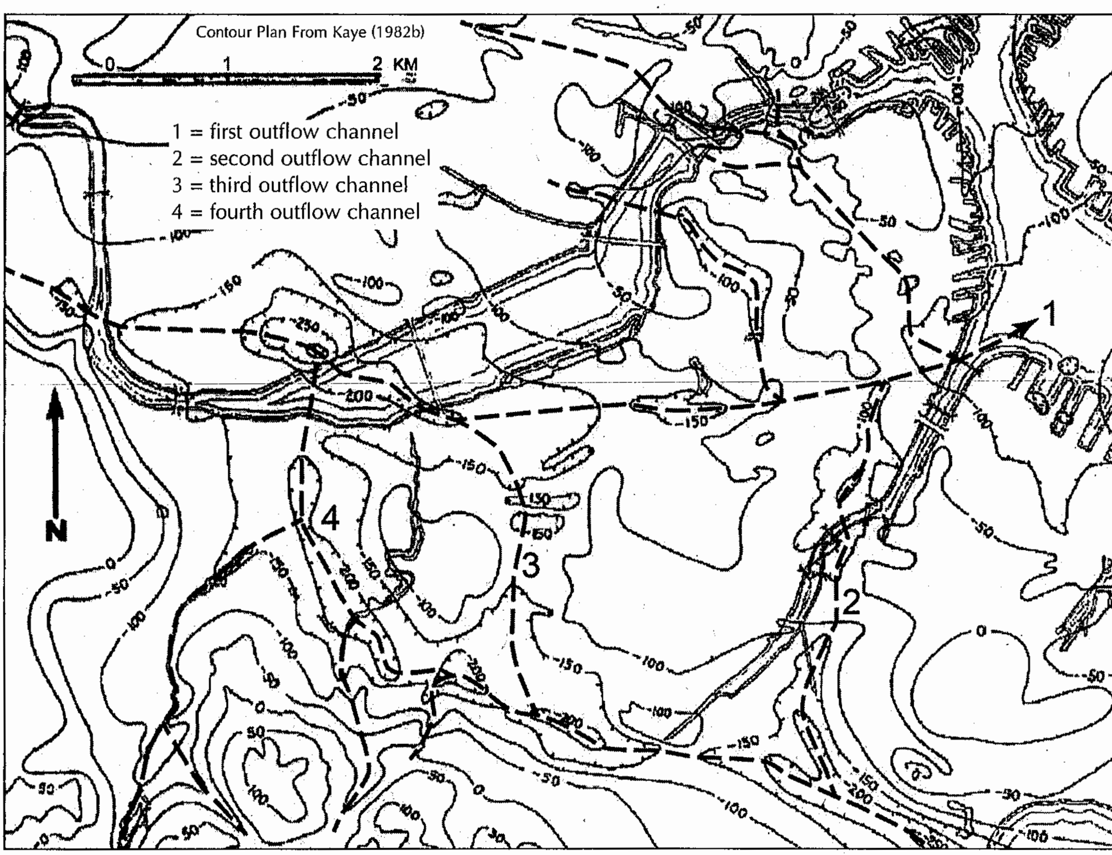



**FIGURE 3-70. Bedrock surface beneath Boston showing paleo-river system and sequence of pirating of the ancestral Charles River.**

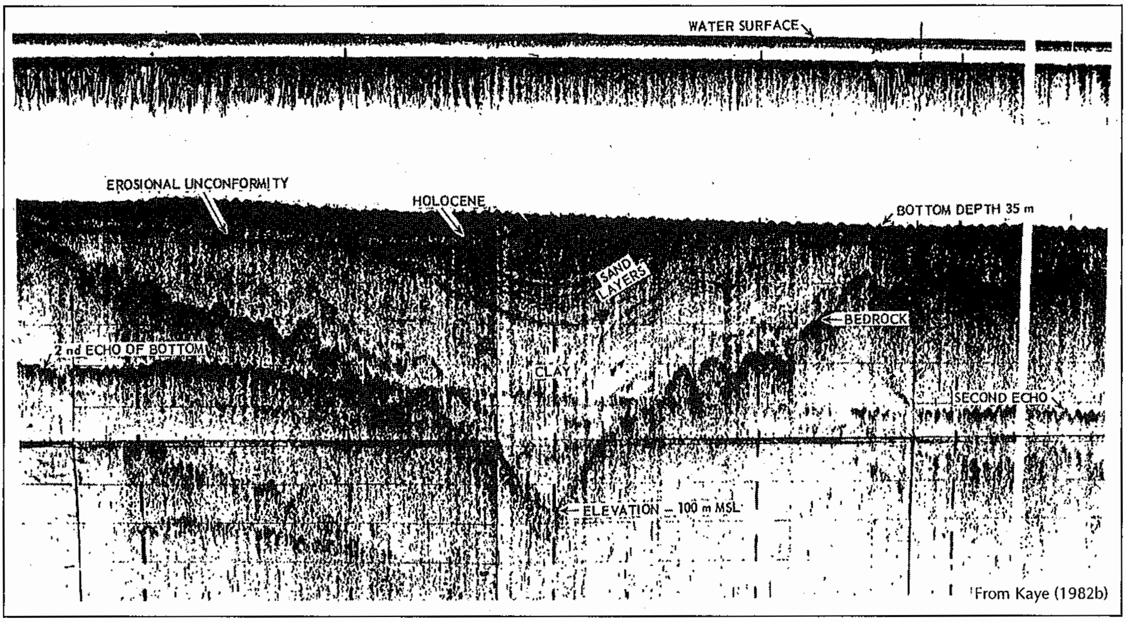



**FIGURE 3-71. Sub-bottom seismic profile in western Massachusetts Bay, off Boston, showing V-shaped trough in bedrock filled with marine clay and, in upper part, interbedded sand (upper outwash). Note conformable bedding, erosional unconformity and overlying post-glacial sand. The bottom of trough is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

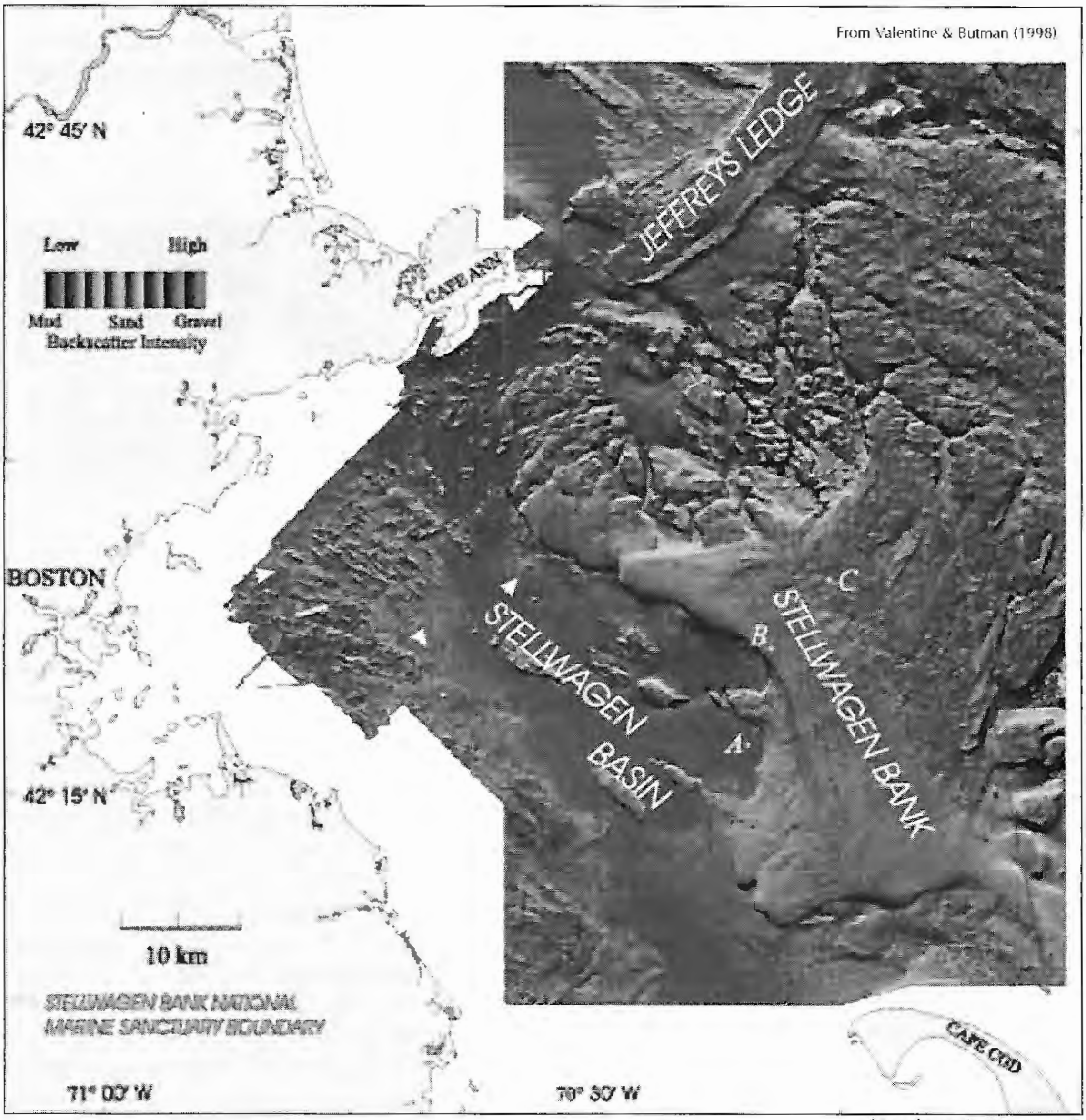
west and thence north, along a fault, into southern Back Bay near the Prudential Center at an elevation of about –45 meters (–150 feet) MSL to capture more of the eastern part of the ancestral Charles. Finally the headwaters of the "Carson" river extended farther northwestward to divert the rest of the 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

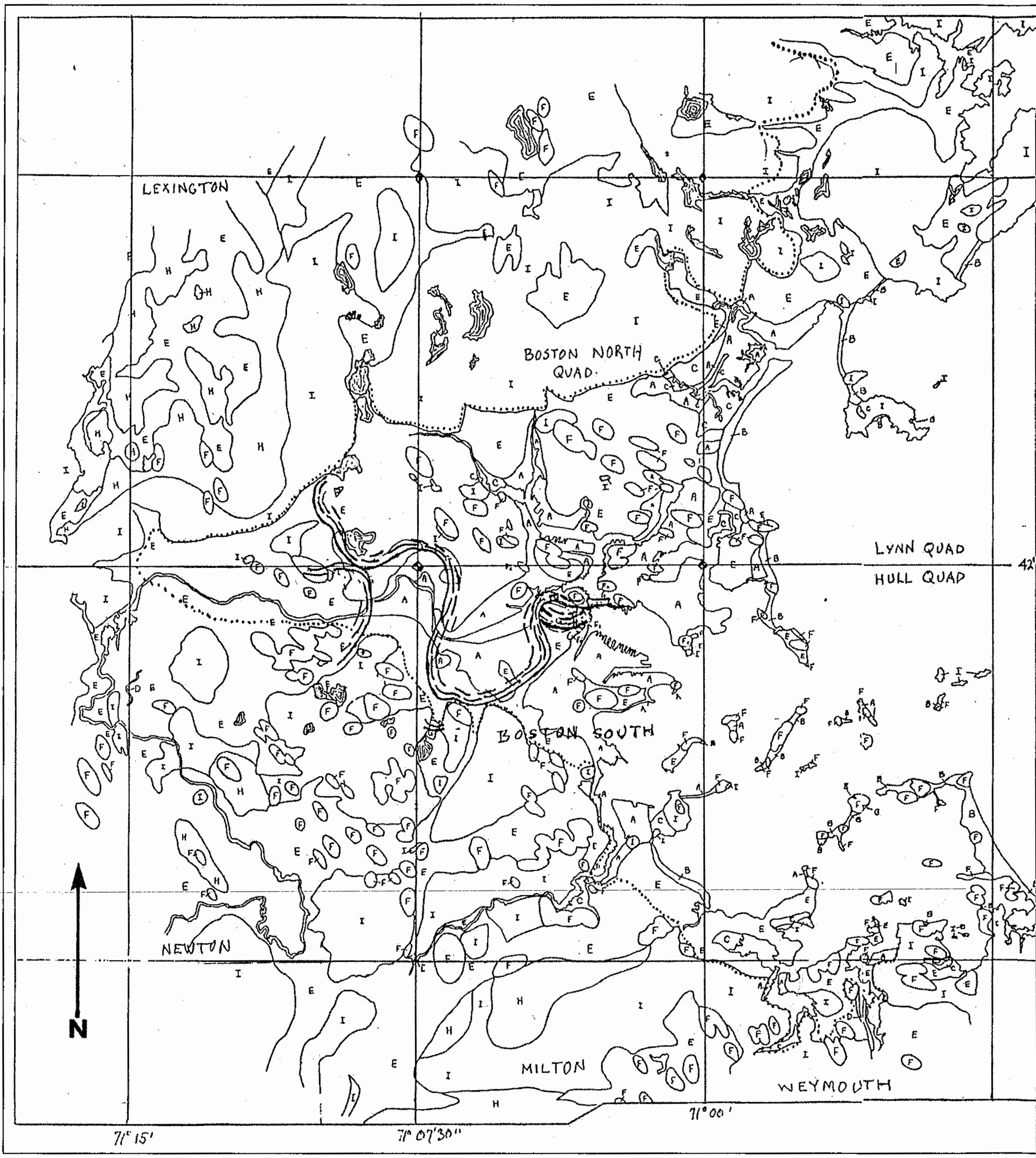
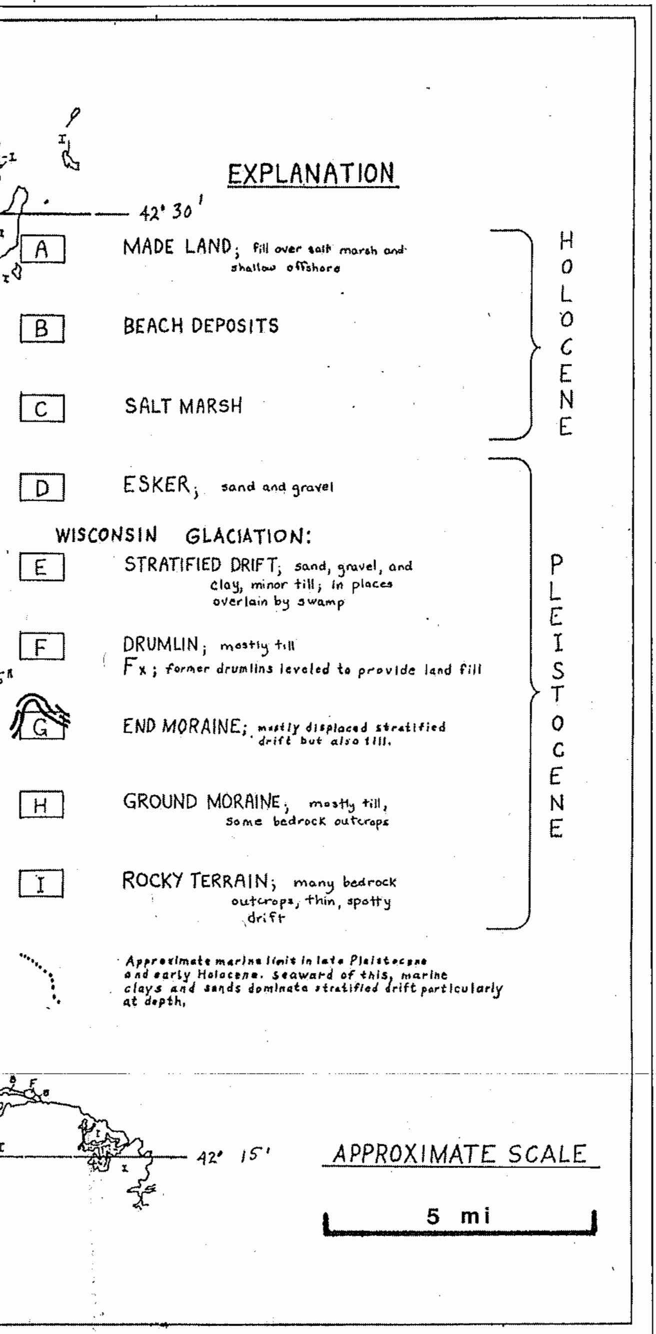



**FIGURE 3-73. Surficial geologic map of Boston and vicinity.**

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

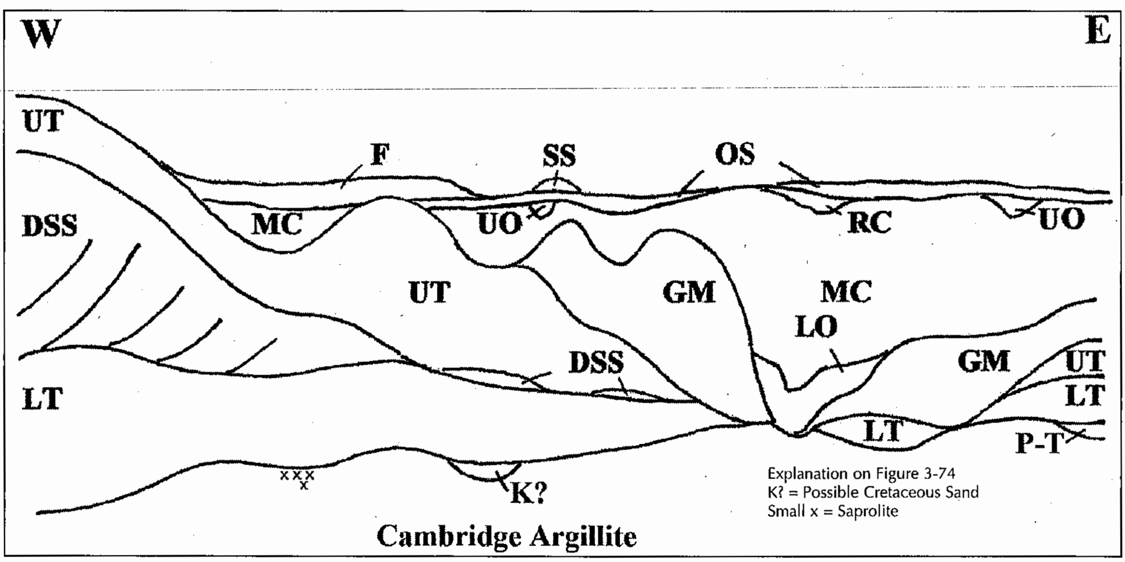



**FIGURE 3-75. Diagrammatic sketch showing relations of Quaternary deposits of Boston and vicinity.**

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

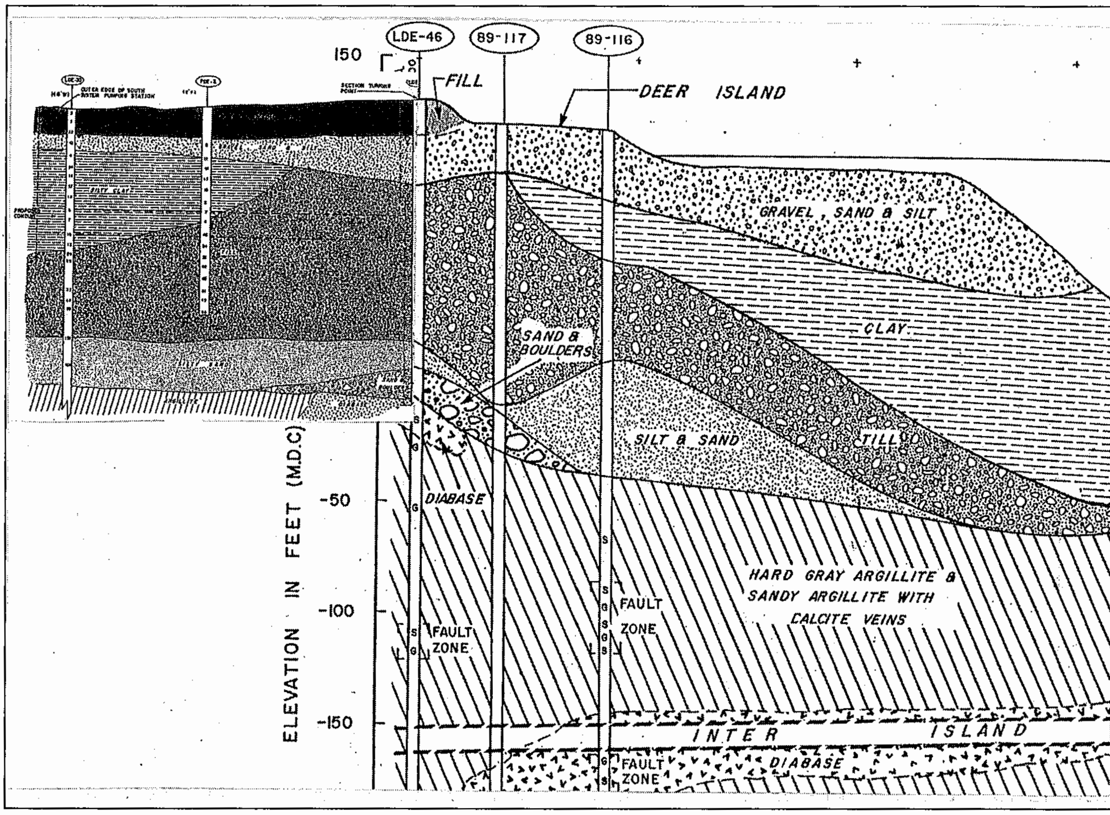



**FIGURE 3-76. Sand and gravel deposit beneath the lowest till deposit at the southern end of Deer Island and the Inter-Island Tunnel, view east.**

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 subsurface 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.**

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).

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

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-

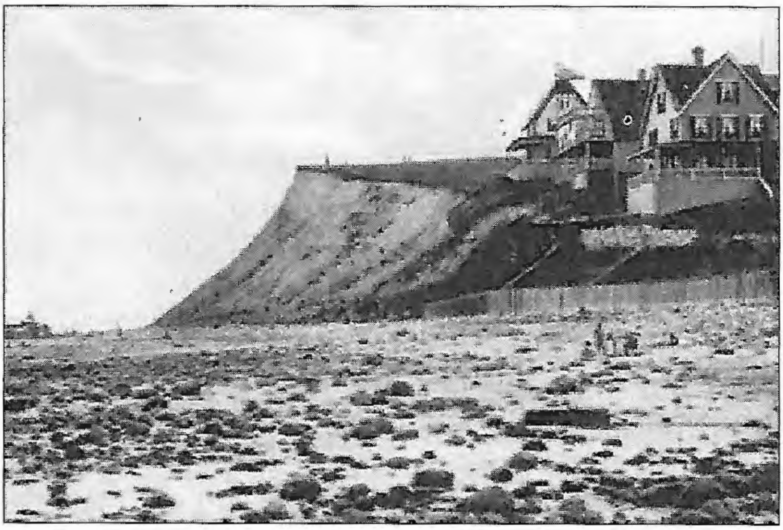
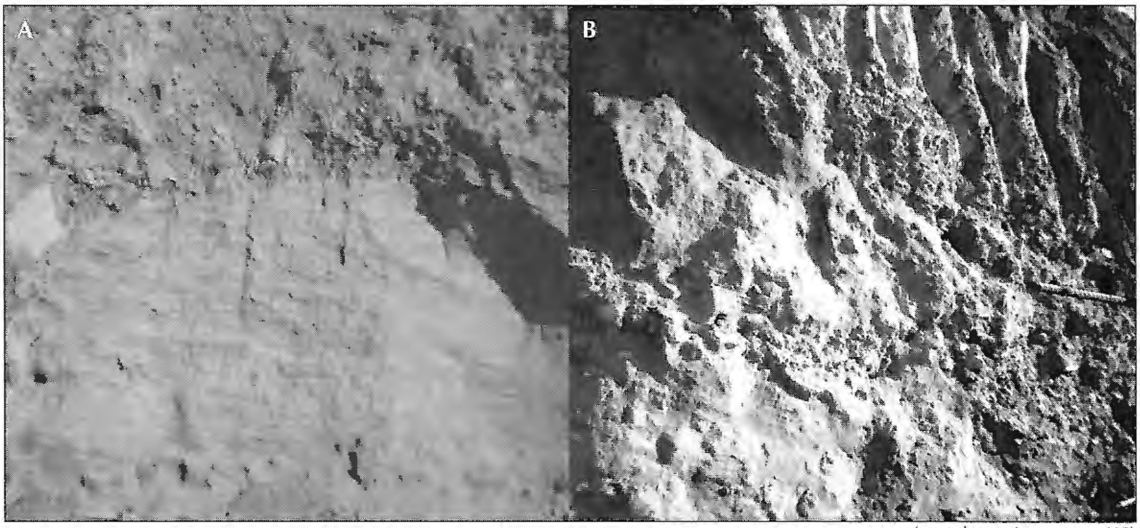


**FIGURE 3-79. At Great Head in Winthrop in 1908, showing an eroding drumlin consisting mainly of lower till, in which were found thirty-four species of Sangamon fossils. Residual boulders from eroded till litter Rocky Beach in the foreground.**

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




(see color version on page 462)

**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-

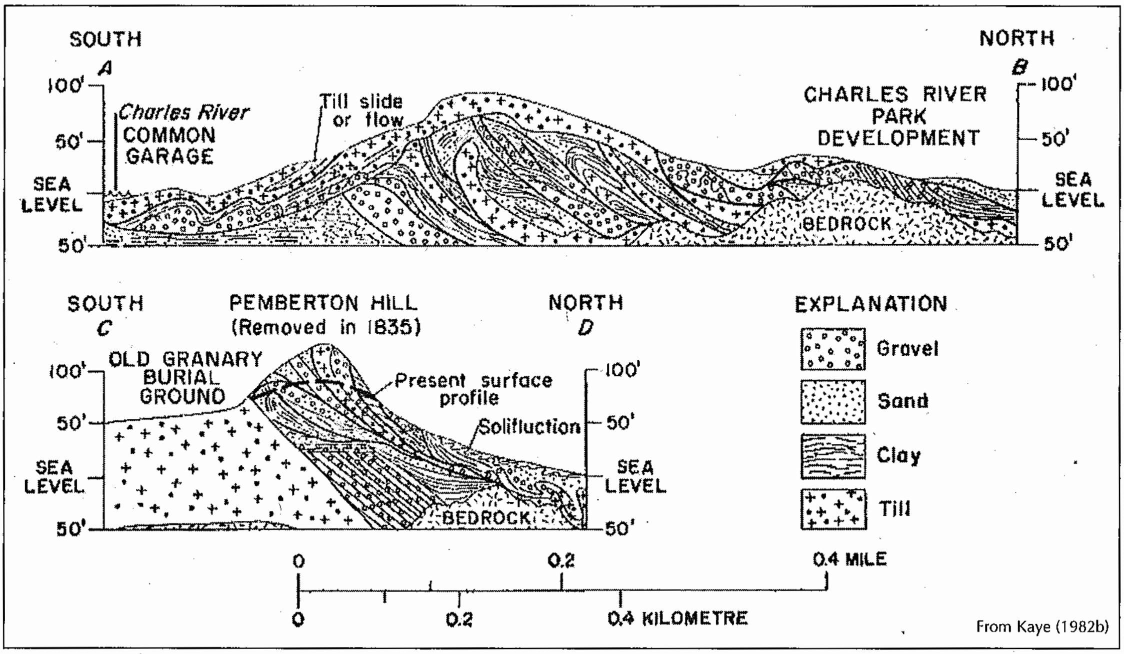



**FIGURE 3-81. Sections across Beacon Hill, top, and Pemberton Hill, bottom, showing the disturbed beds revealed in deep excavations for foundations beneath the upper till.**

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

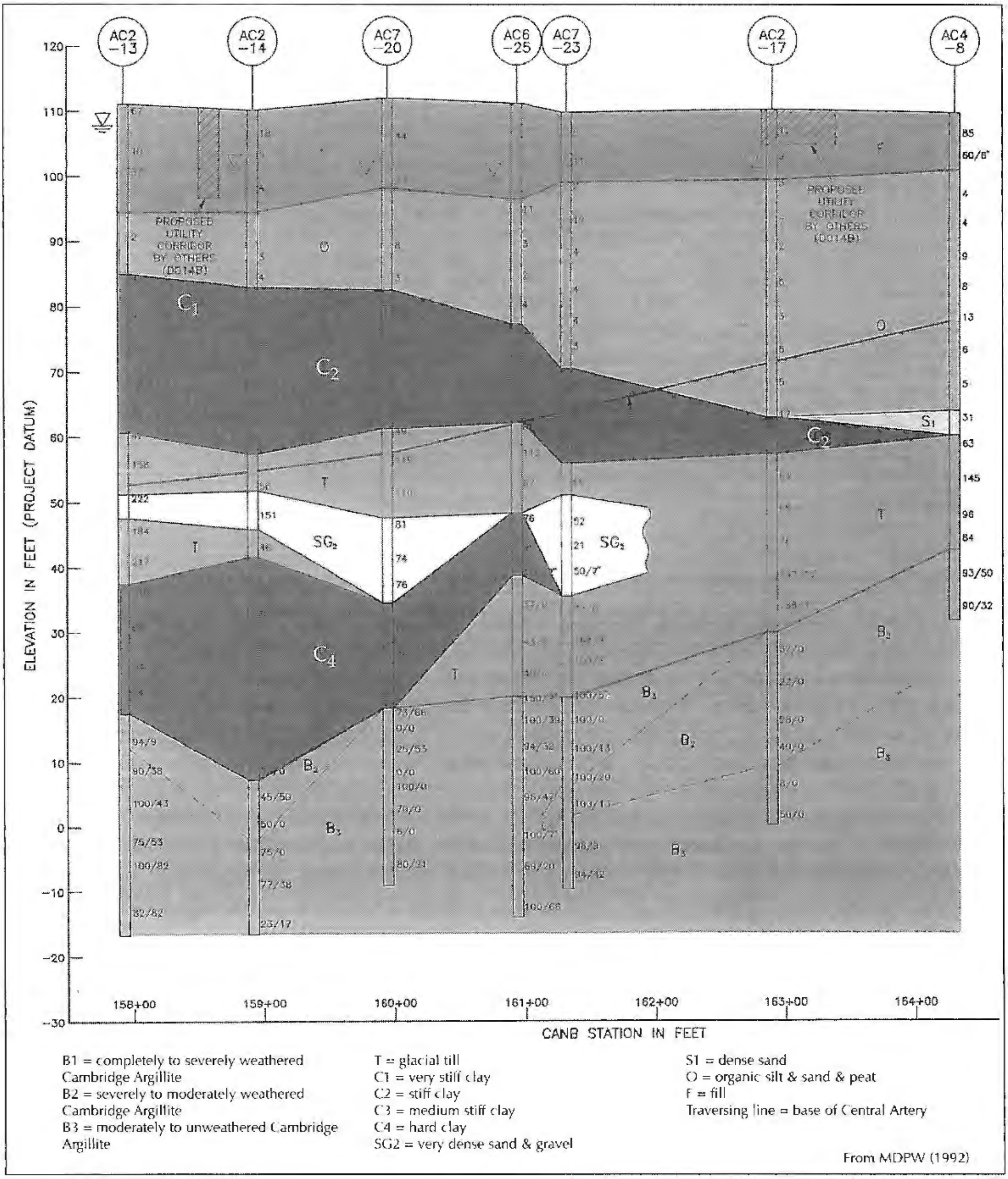



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**FIGURE 3-82. Geologic cross-section (from the southwest) along the Central Artery Tunnel between Valenti Way and Causeway Street (east slurry wall, stations 158+00 to 164+00) showing an apparent clay and sand filling of a channel cut through the 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-

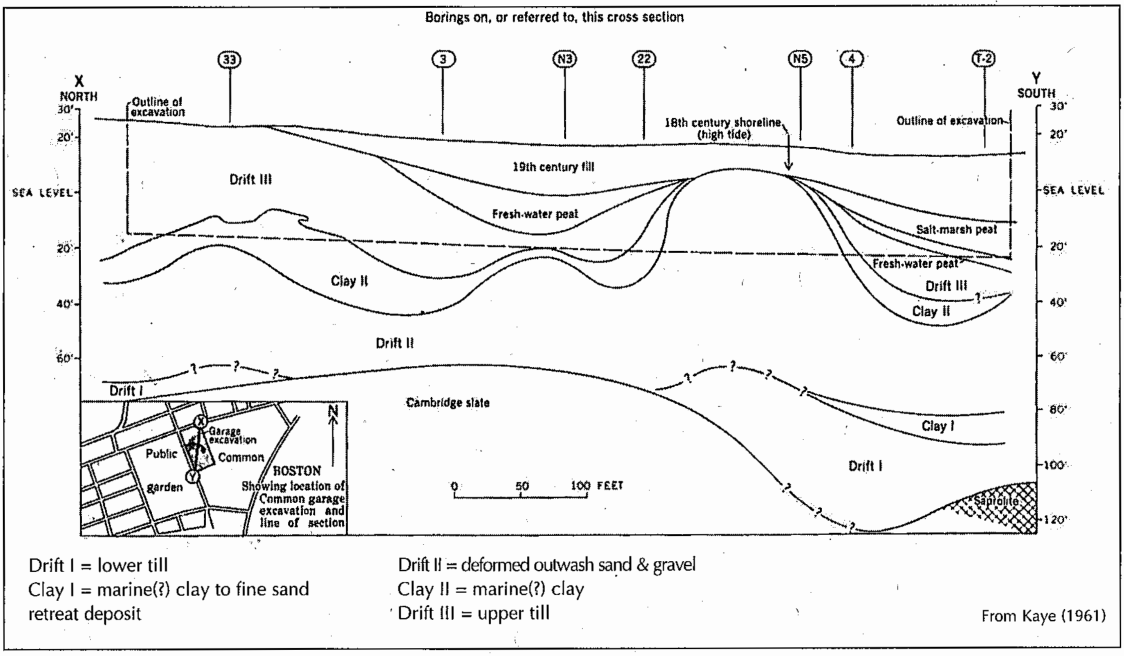


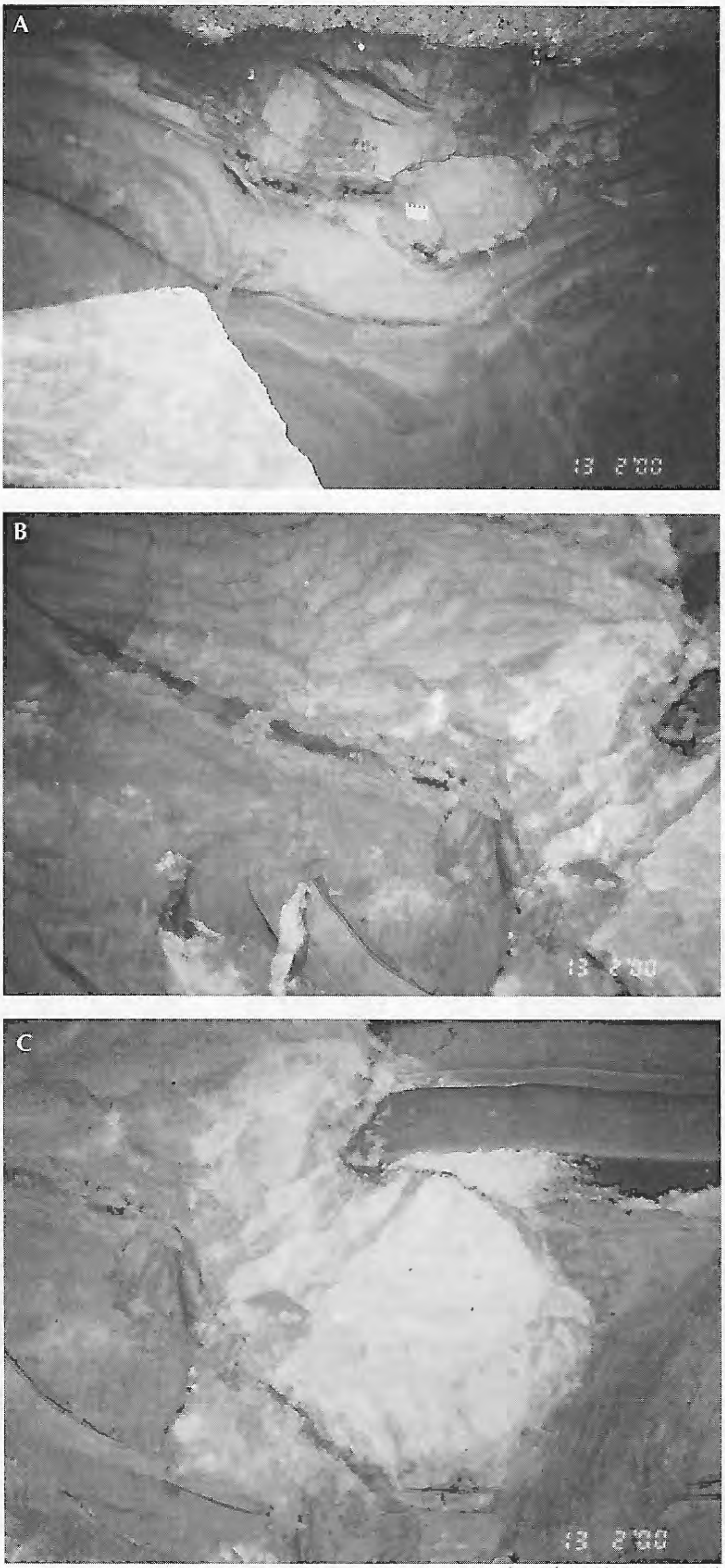

**FIGURE 3-83. Geologic section through folded and faulted sand and clay deposits at the underground Boston Common Garage site at the southern edge of Beacon Hill in northwestern Boston Common. The upper till is capped by organic deposit and fill. The minor marine clay, which overlies the upper till 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

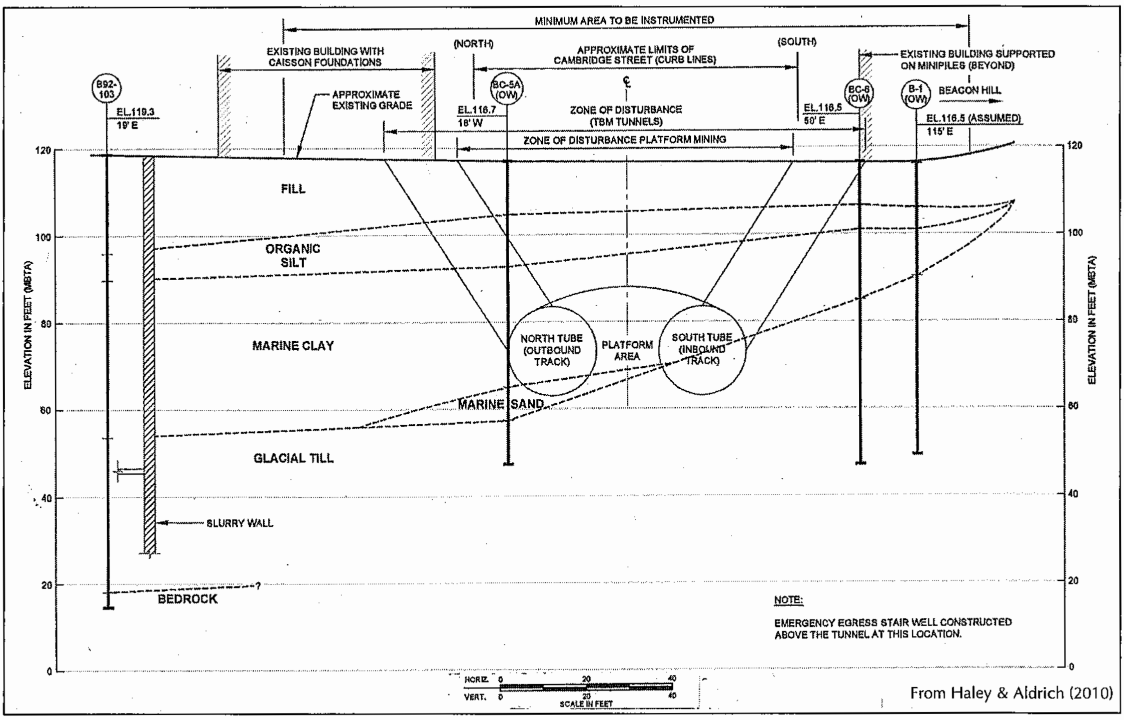



**FIGURE 3-85. North-south section (view east) showing the northward thinning base of the Beacon Hill drumlin and overlap of later deposits beneath Cambridge Street at the west side of Lindall Place (Station 11+00) across the line of the proposed Red Line/Blue Line connector at the Cambridge Station.**

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 north-

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

west 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

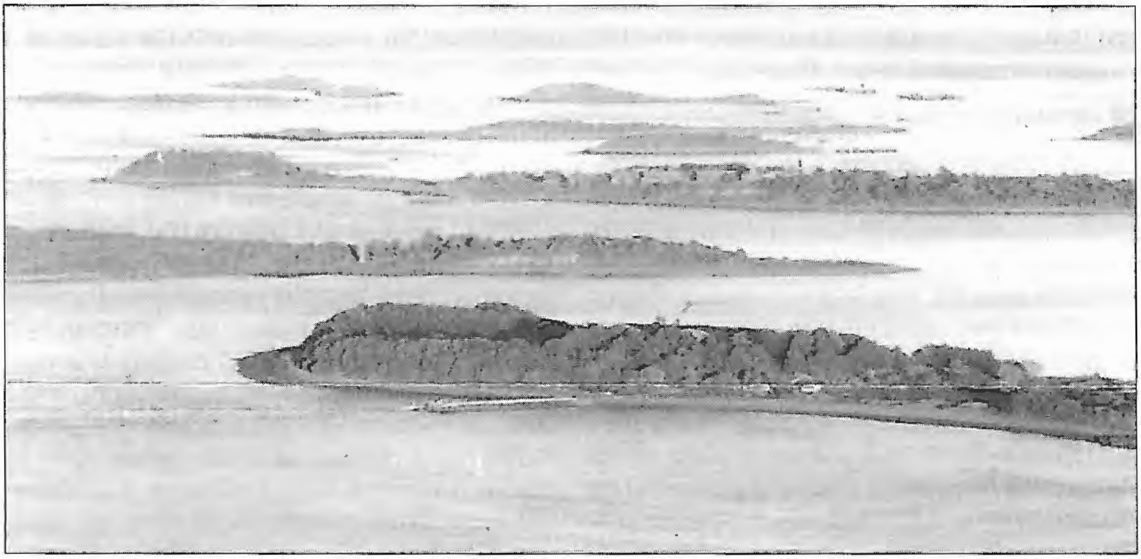


**FIGURE 3-87. View northeast at Thompson Island and beyond at drumlins forming the larger Boston Harbor islands. (Courtesy of the Boston Harbor Islands National Park.)**

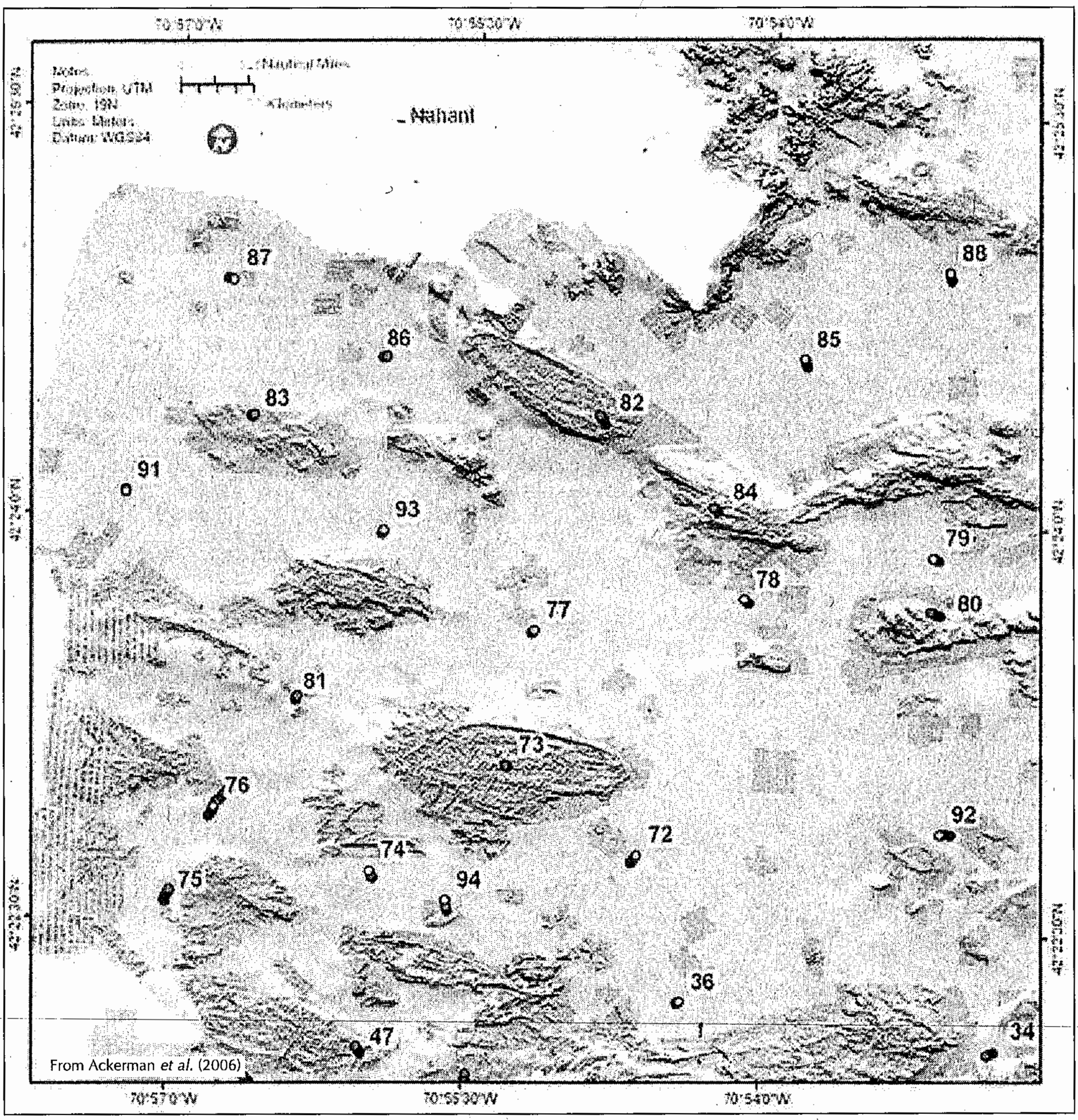



**FIGURE 3-88. Shaded relief bathymetric map of approaches to Boston Harbor showing raised ovoid features representing drumlins.**

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

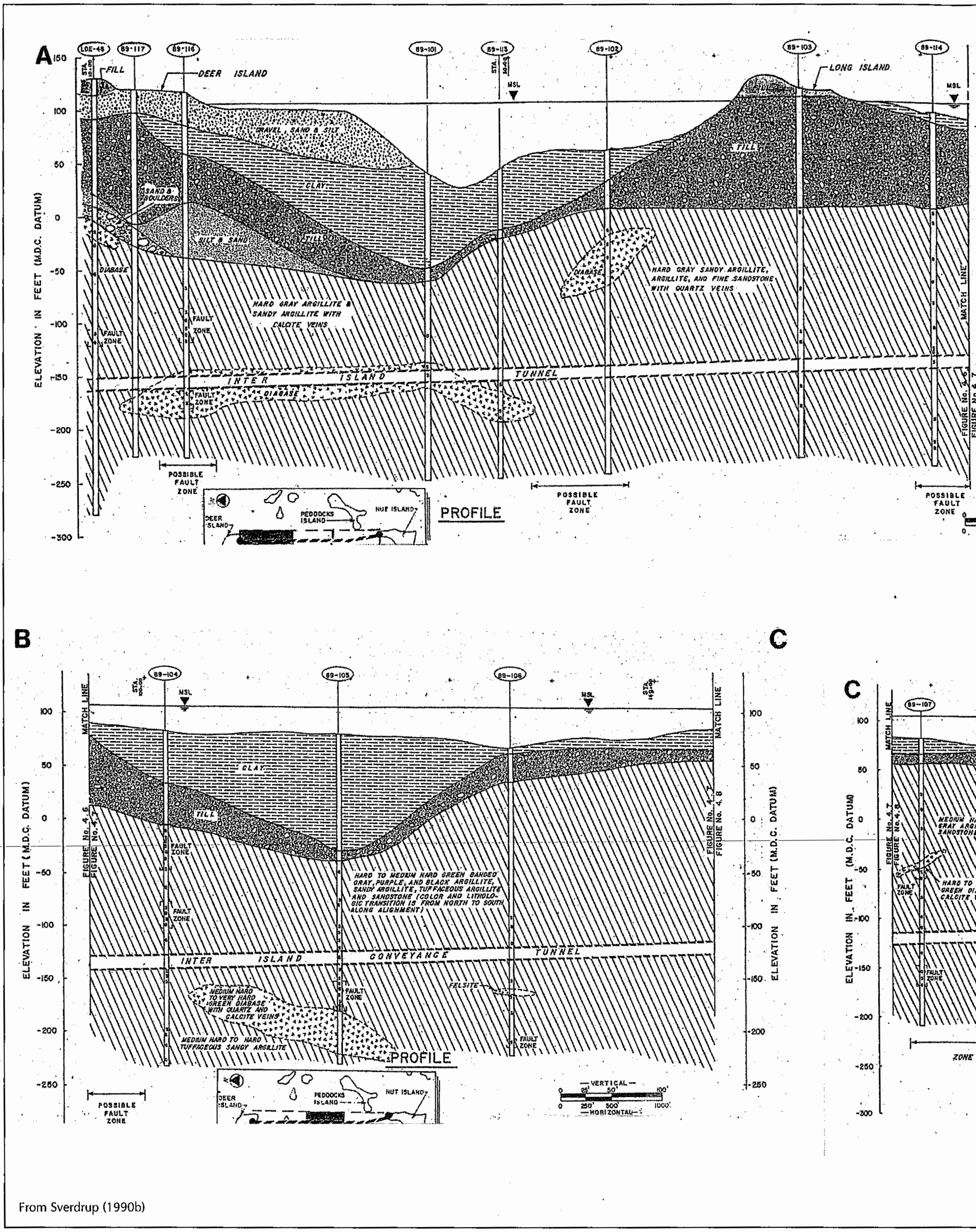



**FIGURE 3-89. North-south geologic section along the Inter-Island Tunnel (view east).**

**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

89–111 — TEST BORING NUMBER AND LOCATION

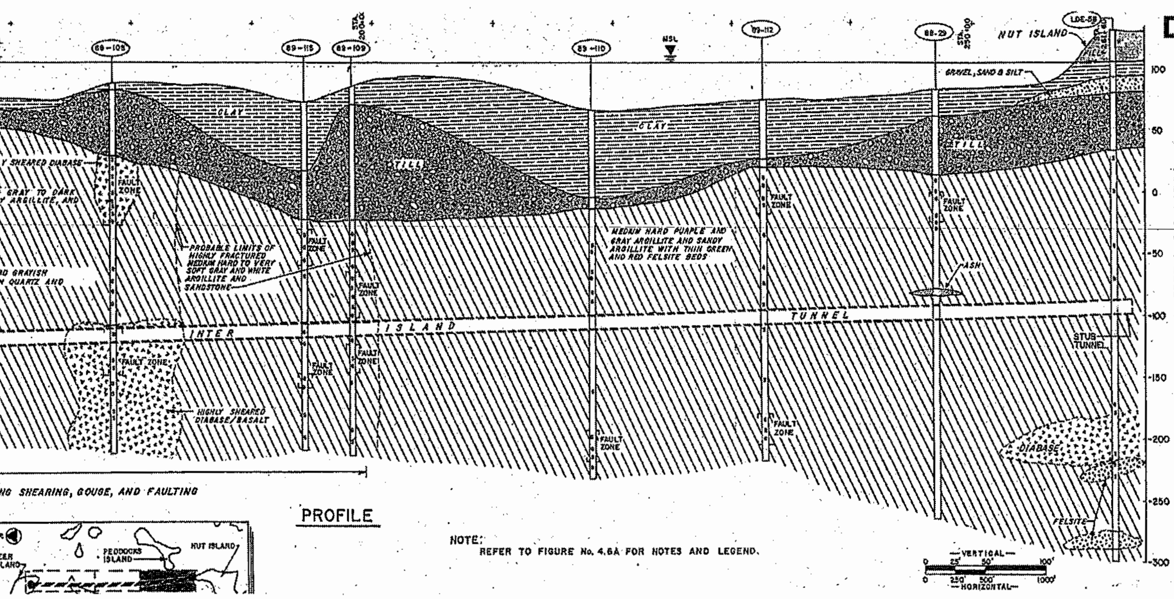
S — LOCATION OF SLICKENSIDED DISCONTINUITIES

G — LOCATION OF GOUGE–FILLED DISCONTINUITIES

PROBABLE FAULT ZONE

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.

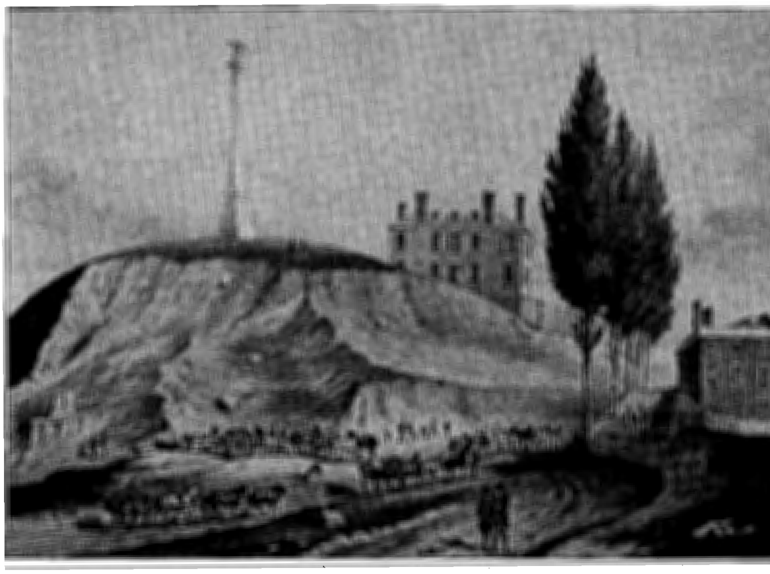


**FIGURE 3-90. A view of Beacon Hill from Mt. Vernon Street near head of Hancock Street circa 1811.**

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.

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

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 &

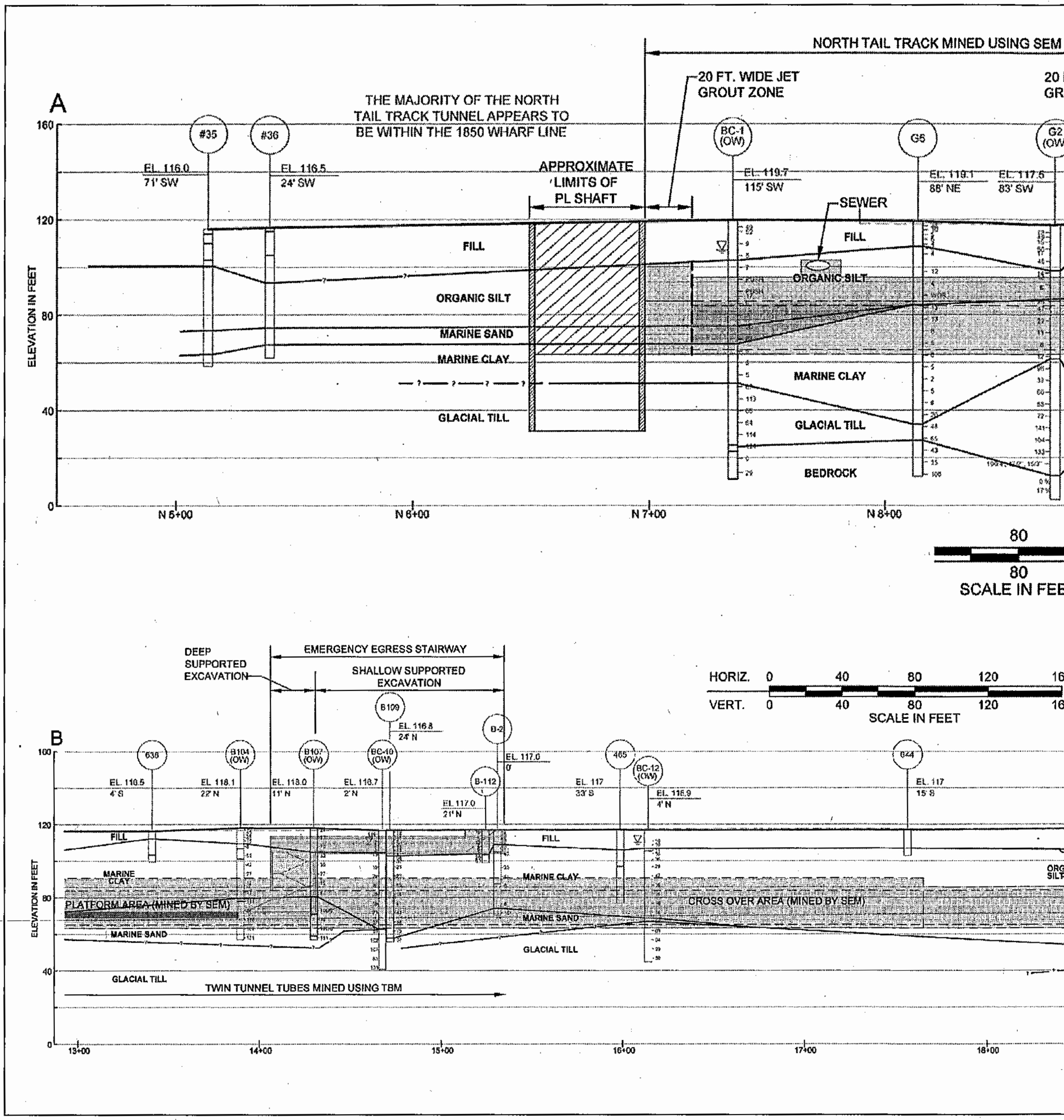
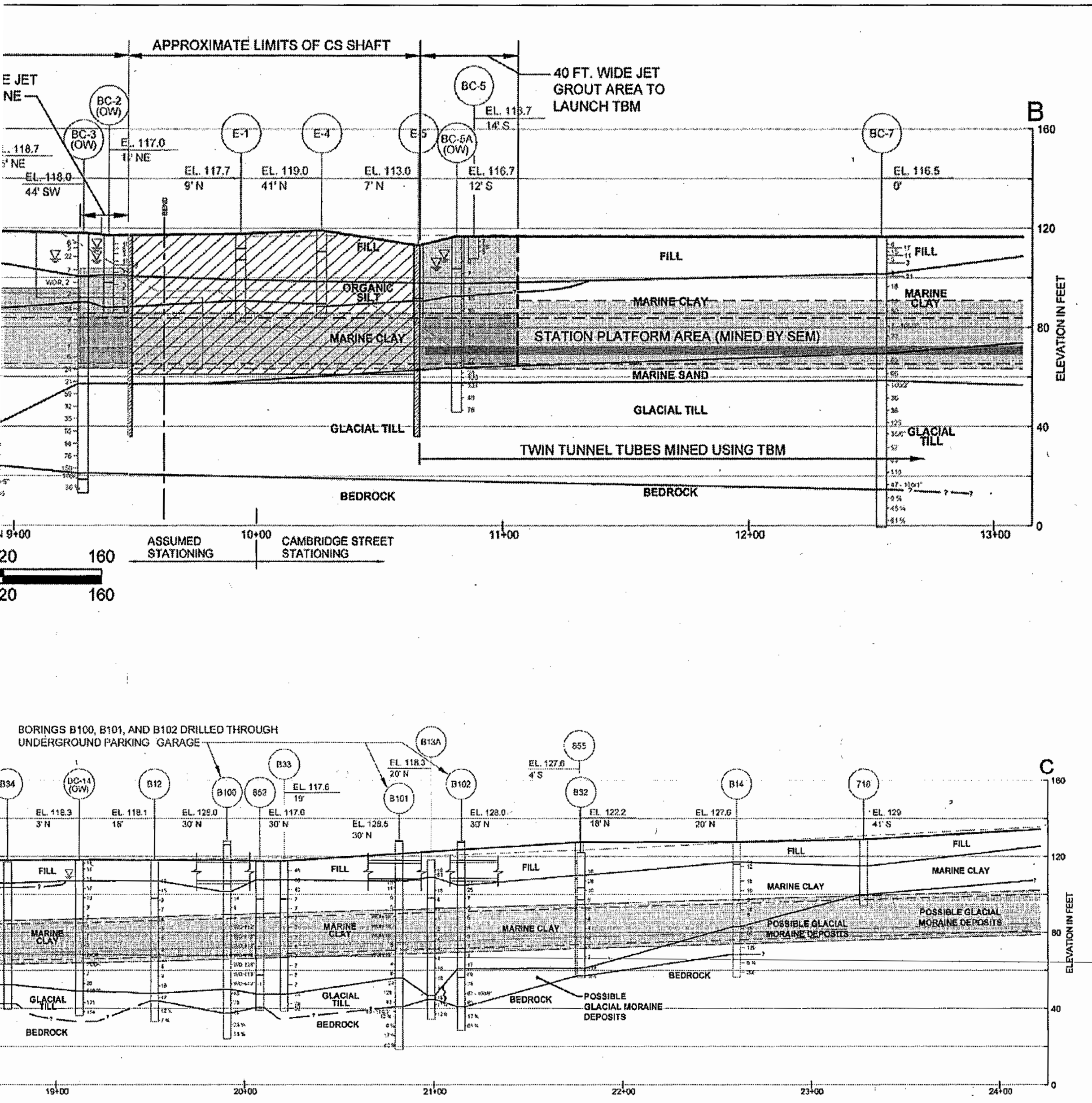



**FIGURE 3-91. East-west section (view from north) beneath Cambridge Street, north of Beacon Hill, along the north tube for the proposed Red Line/Blue Line Connector. (Figure continued on pages 204-205.)**

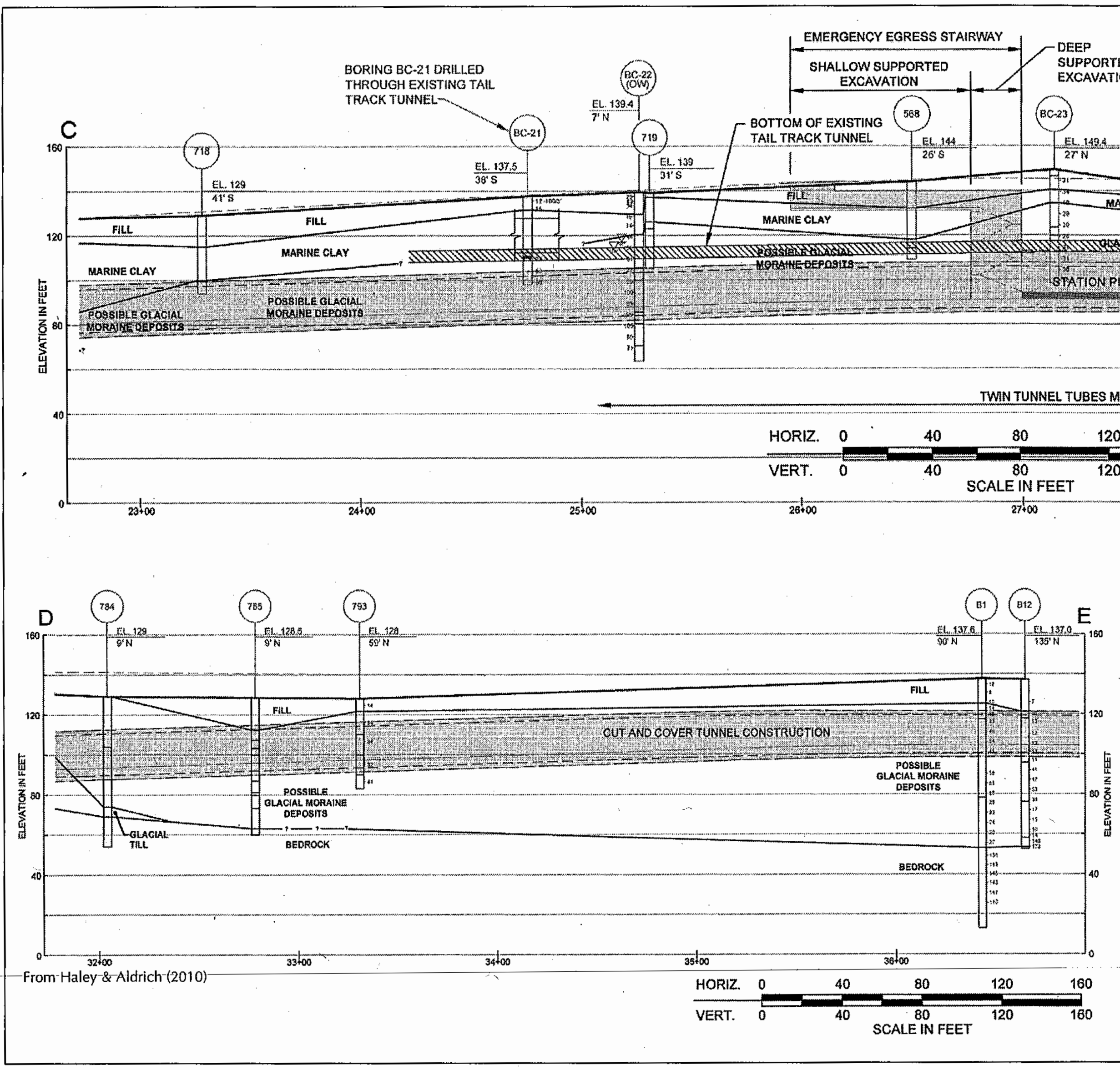
Aldrich, 2010), and extremely coarse cobbly clean gravel 9 to 12 meters (30 to 40 feet) thick fills a channel at Dewey Square by South Station (Miller, 2012). Across the Charles River in Cambridge, the outwash is thicker and increases westward to form a wedge-shaped deposit. The buried valley in Malden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

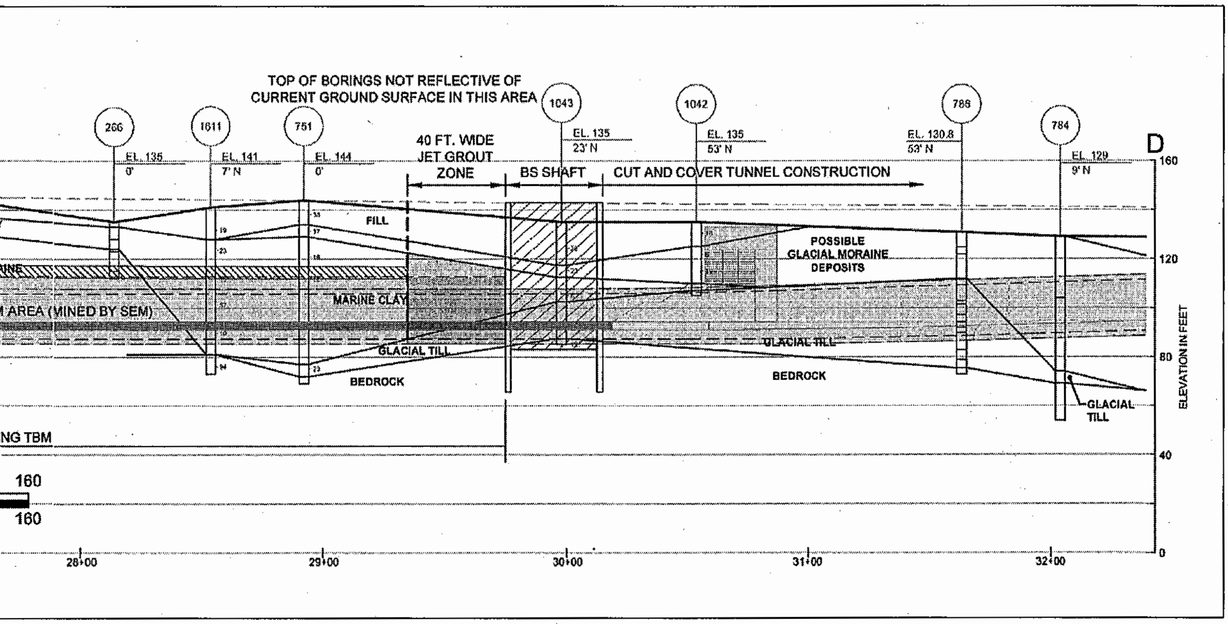
into the bedrock, passing just east of the MBTA Blue Line Airport Station. The relief on the west side of this buried channel reaches 42 meters (137 feet) in places (see Figure 3-93). Lenses also are found outside of the channels. A mound of the lower outwash sand grading southerly into gravel was found 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).



From Haley & Aldrich (2010)

**FIGURE 3-91. Continued.**

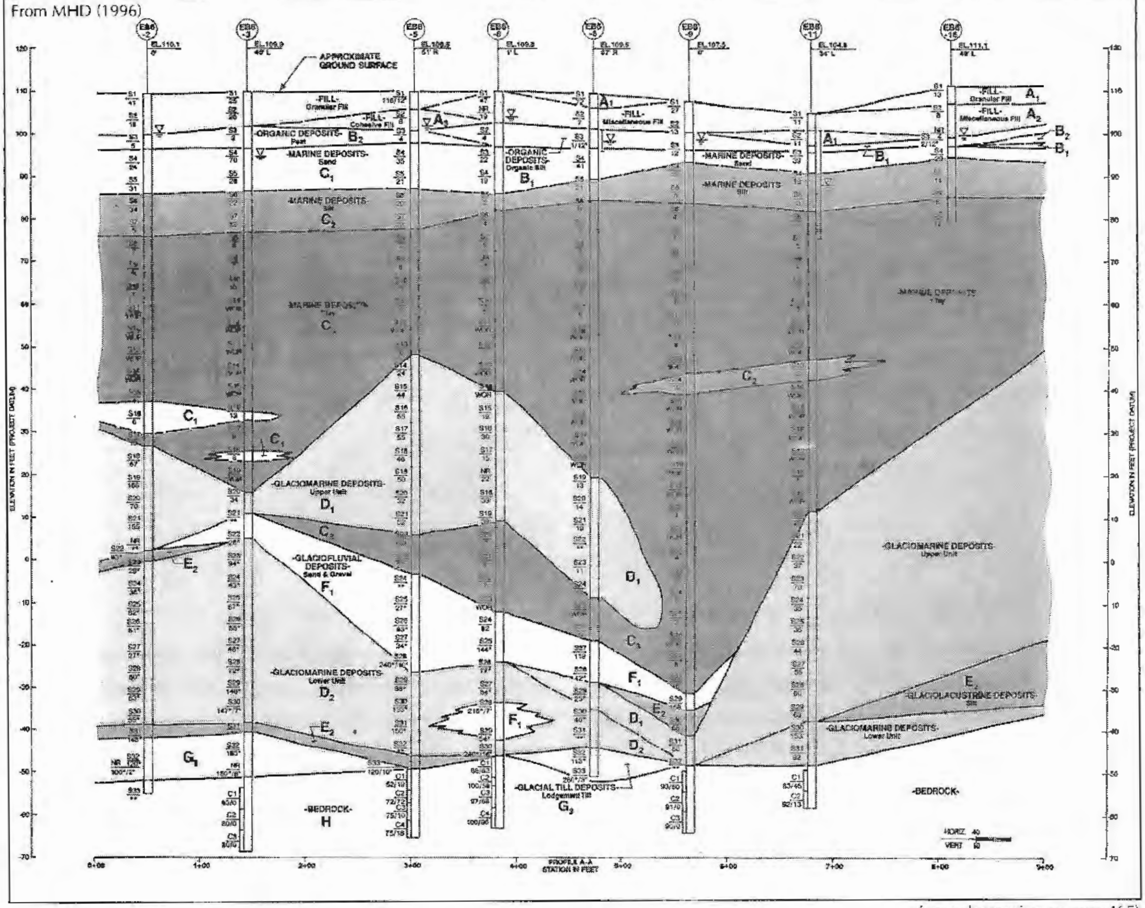
*Marine Clay.* Fine sediment from an increasingly more distant ice front, coupled with a rising sea level that inundated much of the low-lying areas, produced a thick blanket of marine clay that smoothed out most of the relief across the underlying units. The infilling of topographic lows and channels 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

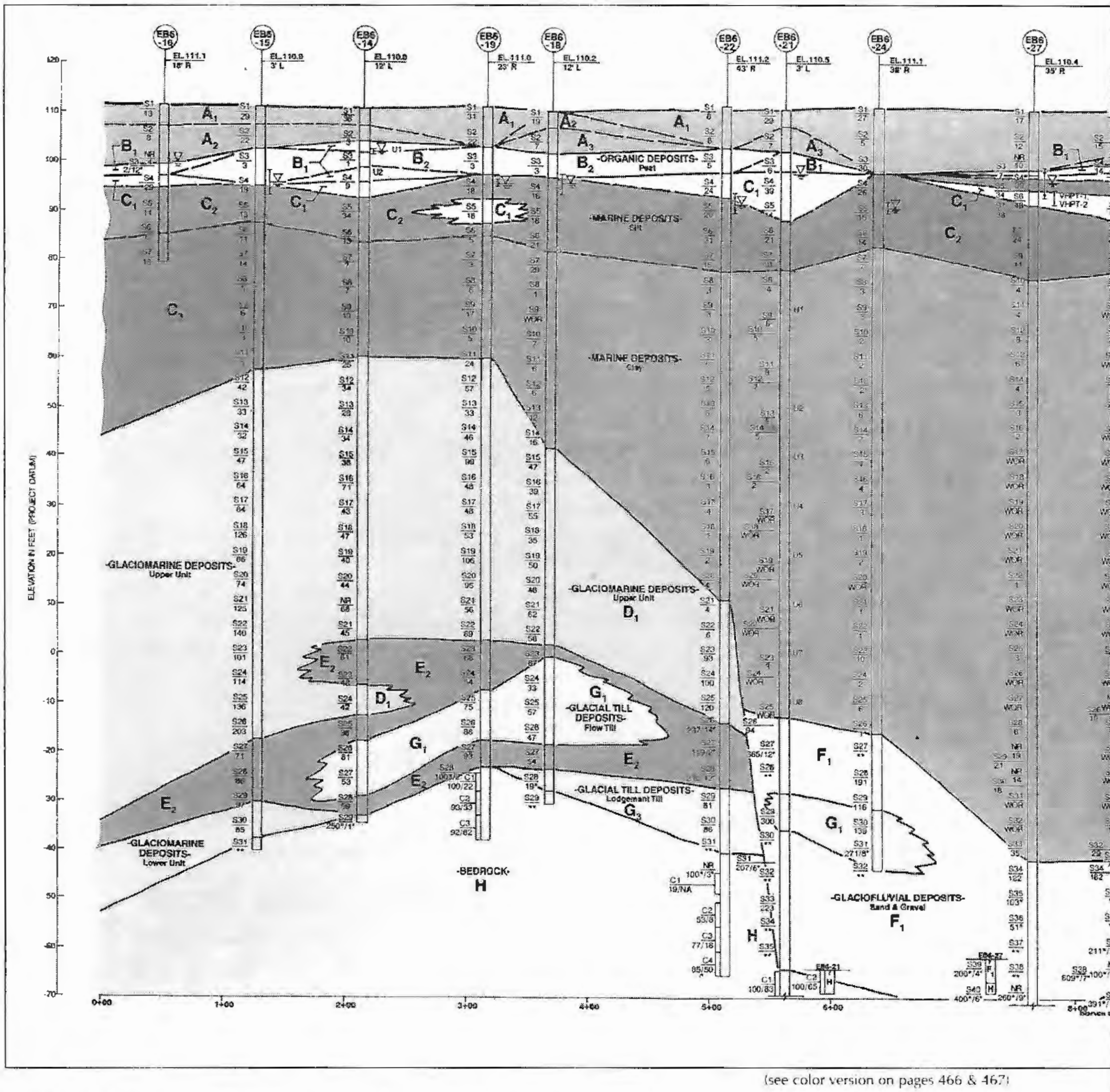



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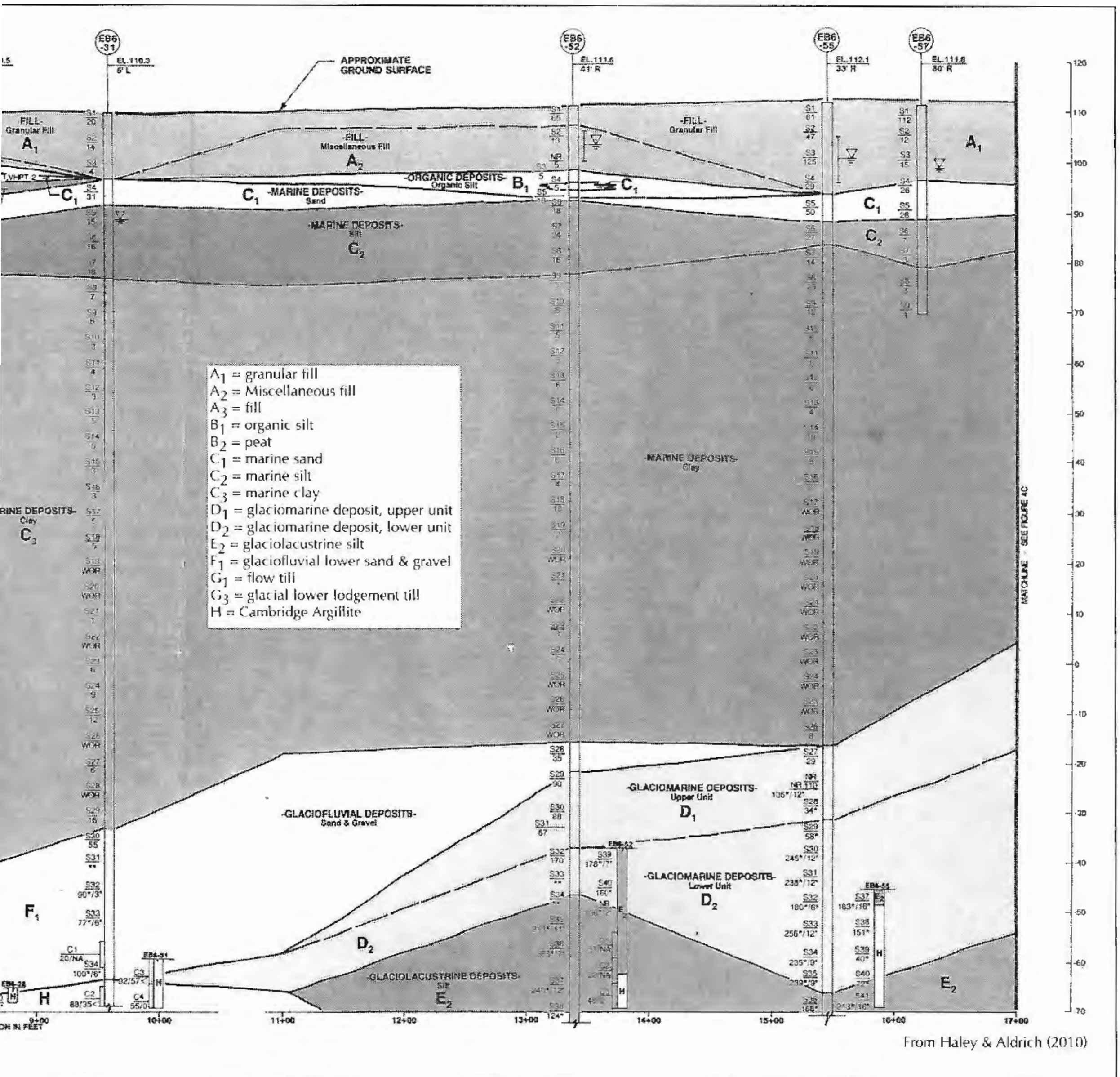
**FIGURE 3-93. Section from the Central Artery/Tunnel Project beneath Route 1 adjacent to MBTA Airport Station showing complex facies relations within the glaciomarine deposits resting on lower**

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

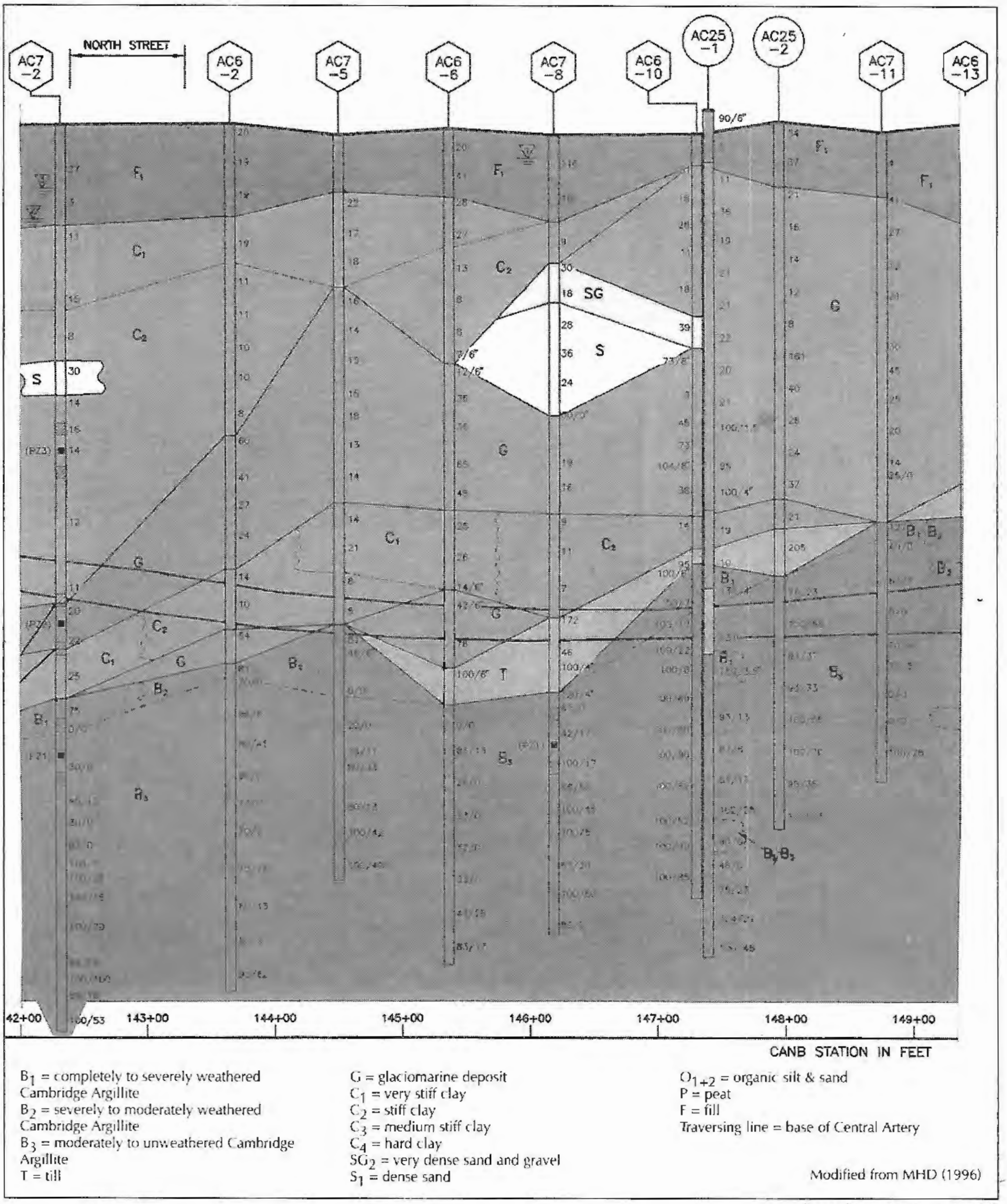



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**FIGURE 3-94. Section along the Central Artery between North Street and North Washington Street (west tunnel wall; stations 142+00 to 150+00) showing glaciomarine deposit interbedded with and overlain by marine clay above thin till, which are undifferentiated;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

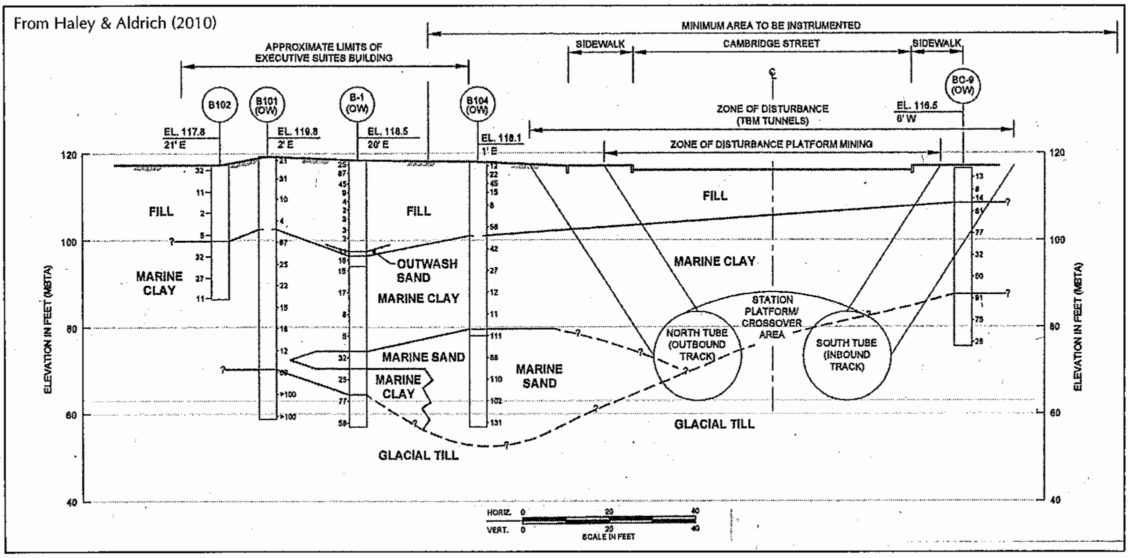



**FIGURE 3-95. North-south section (view east) showing lower outwash with clay lens filling a channel cut in till beneath Cambridge Street between Grove Street and Strong Place (Station 13+00) and the proposed twin tubes of the Red Line/Blue Line Connector.**

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 northeast. 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.)**

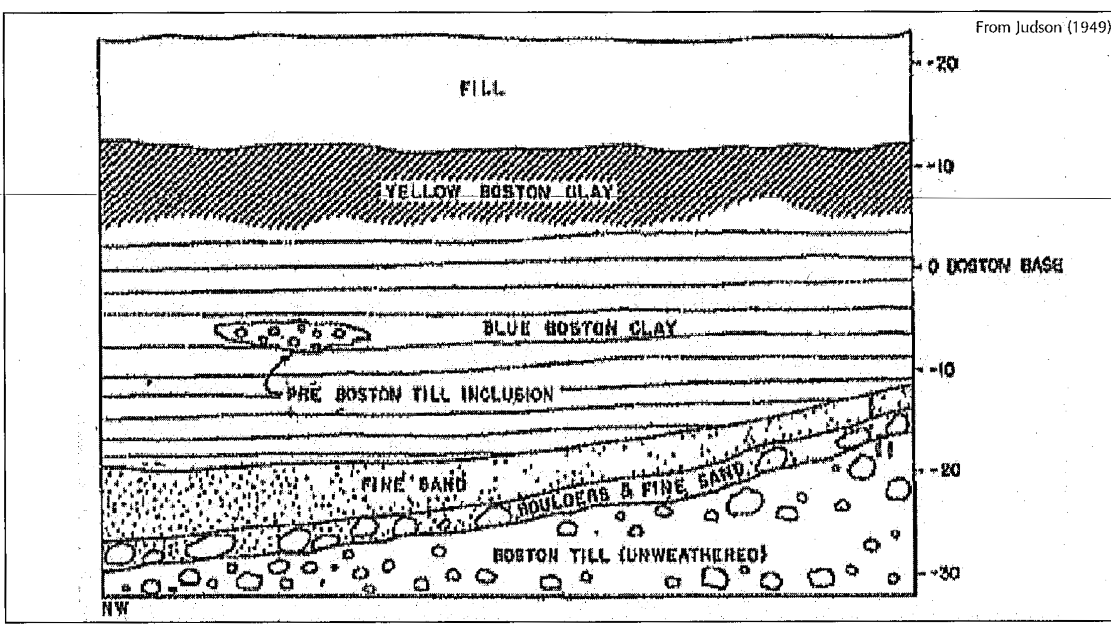



**FIGURE 3-98. Section showing the marine clay and its oxidized top above the upper till and the lower outwash at the New England Telephone and Telegraph Company Building at Franklin and Congress streets.**

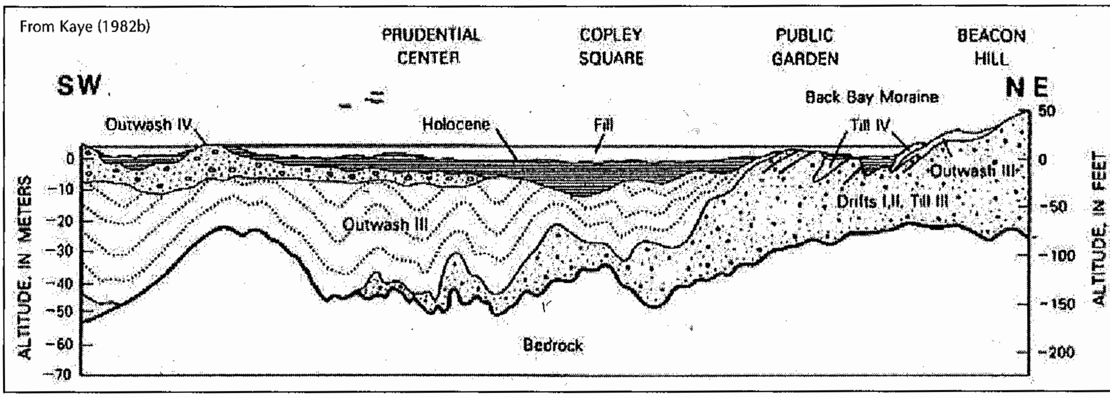



**FIGURE 3-99. Section extending southwest from Beacon Hill across part of the Back Bay showing draped marine clay (Outwash III) over bedrock and the upper till and beneath the upper outwash sand and gravel (Outwash IV). Vertical exaggeration 20×.**

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).

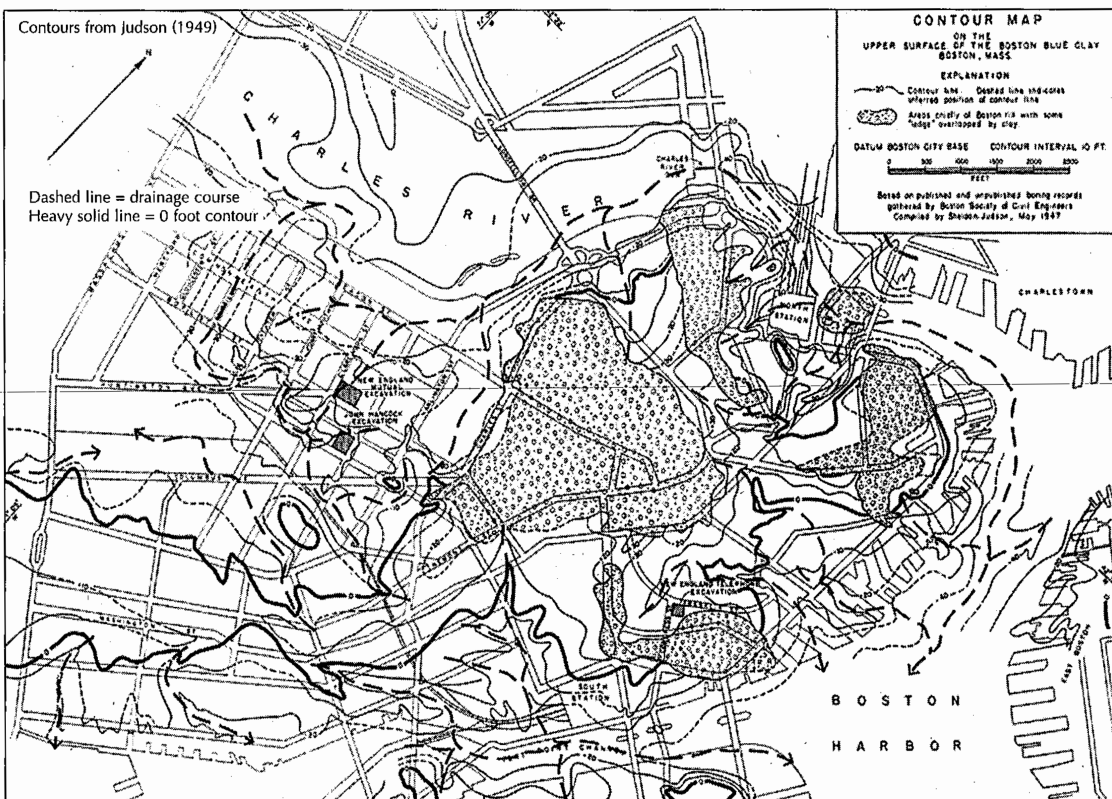



**FIGURE 3-100. Central Boston showing the contoured top of the marine clay (Boston Blue Clay), areas of predominantly underlying till and the interpreted drainage system that incised the clay.**

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

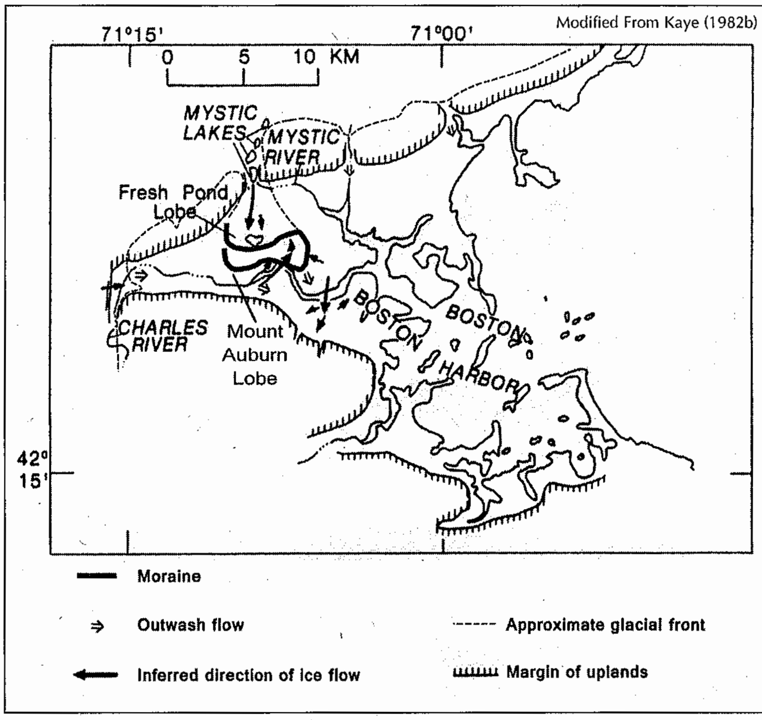



**FIGURE 3-101. Map showing the position of the glacial front of the Lexington Substage ice lobe when the Fresh Pond and the earlier Mount Auburn end moraines were formed, as well as showing sources of outwash.**

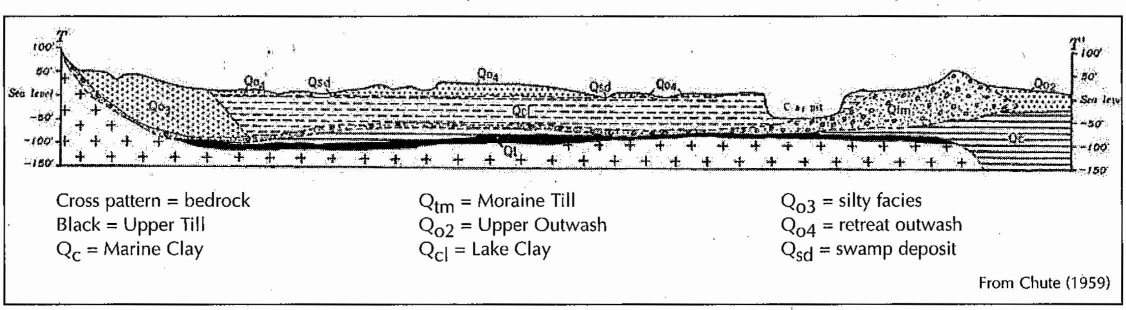



**FIGURE 3-102. North-south section passing just east of Fresh Pond showing relations of the Lexington Substage deposits.**

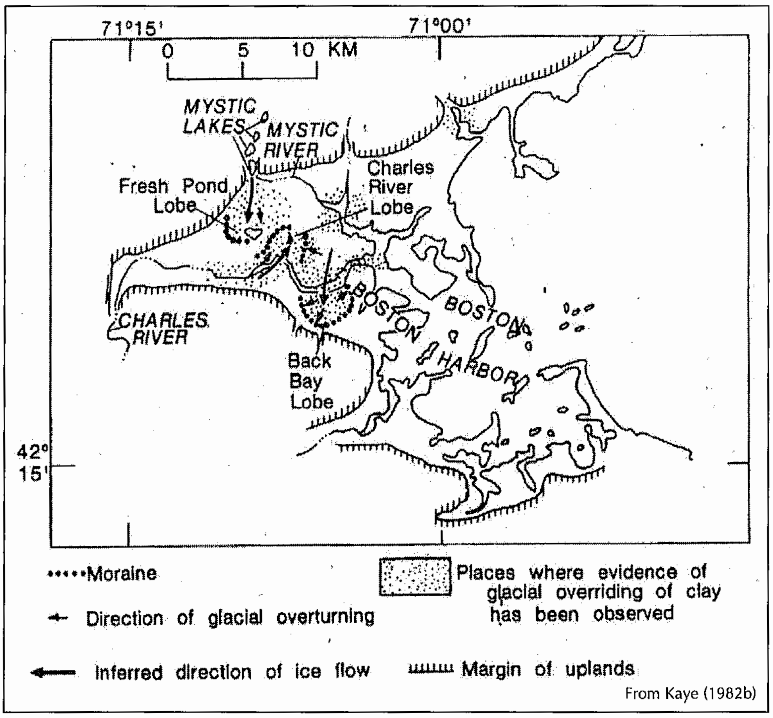



**FIGURE 3-103. Map showing Fresh Pond, Charles River and Back Bay moraines and areas that have yielded evidence of glacial overriding of clay.**

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

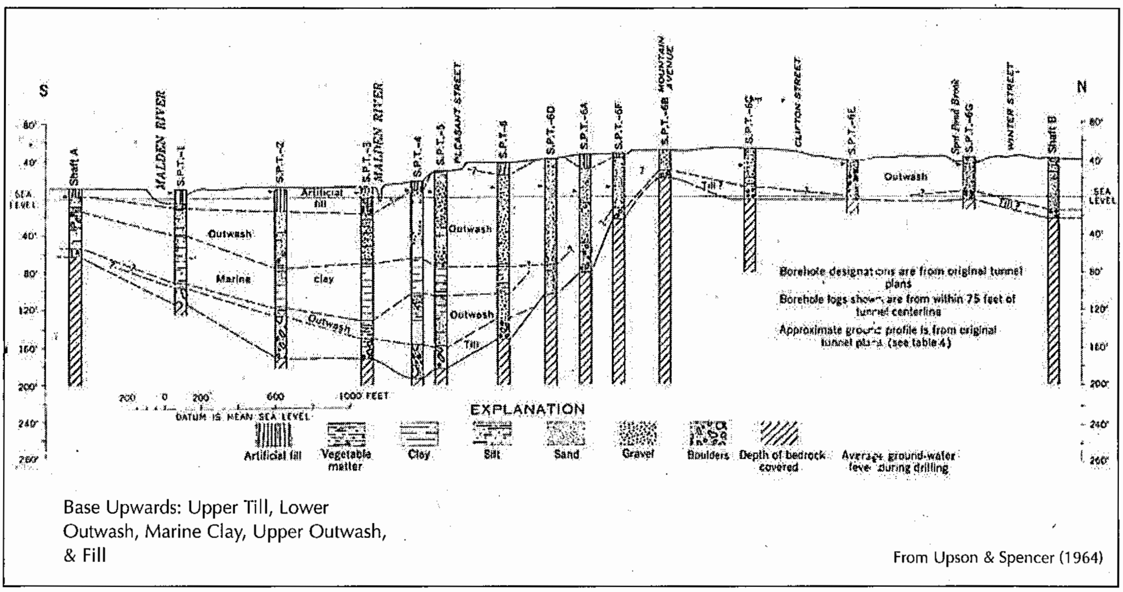



**FIGURE 3-104. Section along the Malden (Spot Pond Flood Control) Tunnel (view west), showing the buried Malden Valley.**

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

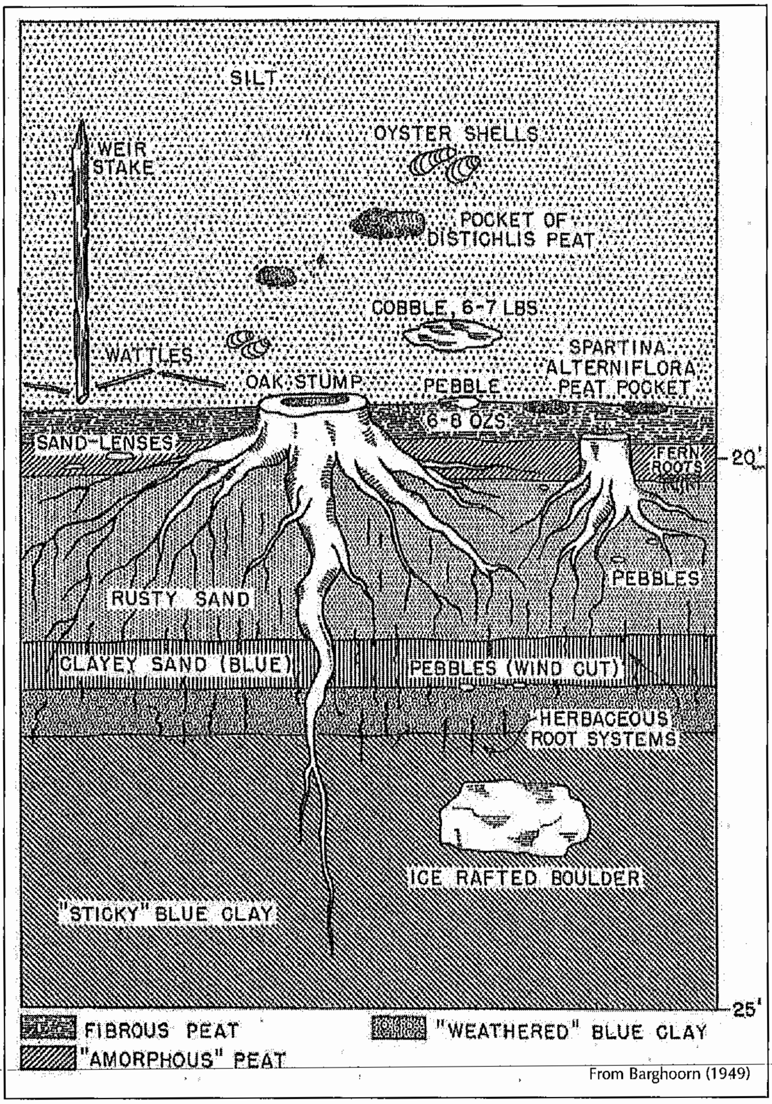



**FIGURE 3-105. Diagram of the John Hancock excavation in the Back Bay showing the top of marine clay, the rusty sand of the upper (Lexington) outwash and the organic deposit with in-place tree stumps and other features. (Note that the top of the right-hand stump should have been drawn above the fibrous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

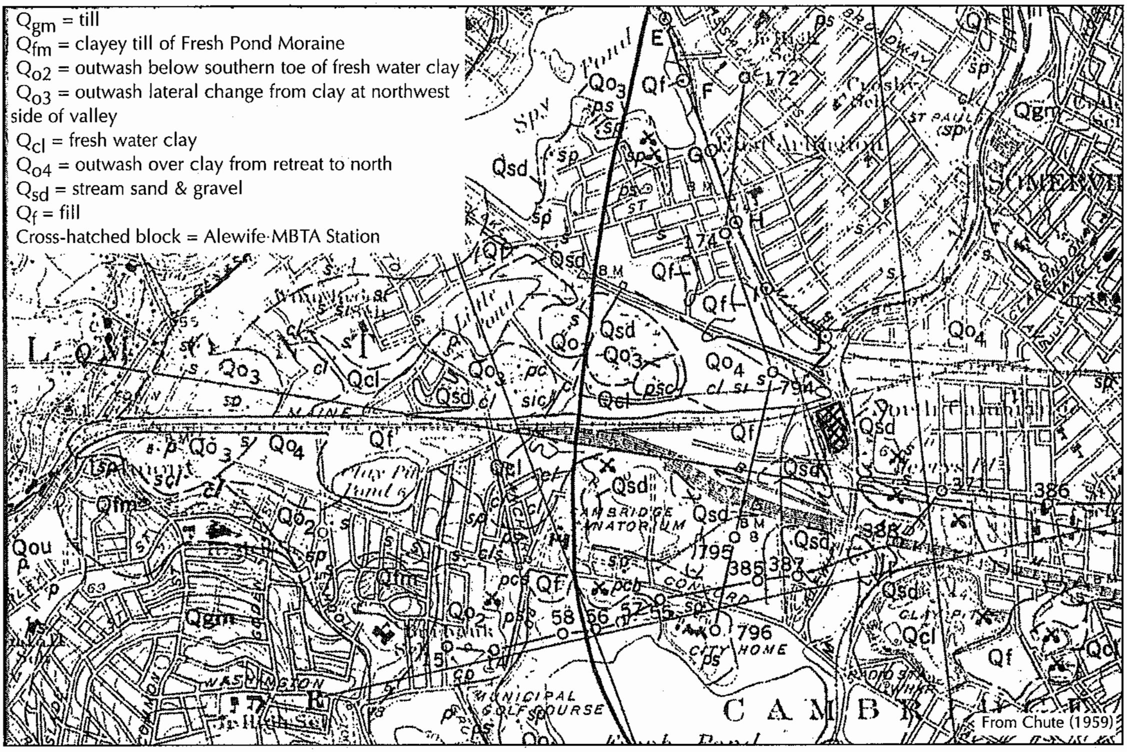



**FIGURE 3-106. Map of Fresh Pond area showing freshwater clay deposit of the Lexington Substage.**

*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.

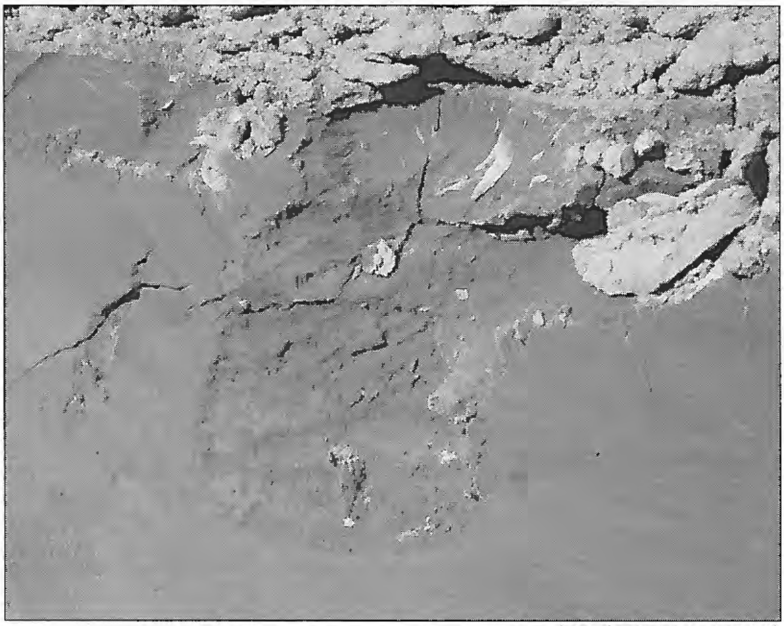
The clay and capping outwash formed as the ice stagnated and the sea began its retreat after 12,000 years ago. The sea level fell quickly with crustal rebound following the Lexington Substage ice retreat. The limited clay and outwash form the last glacial deposits in the Boston Basin. The lake clay would 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.



(see color version on page 470)

**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-

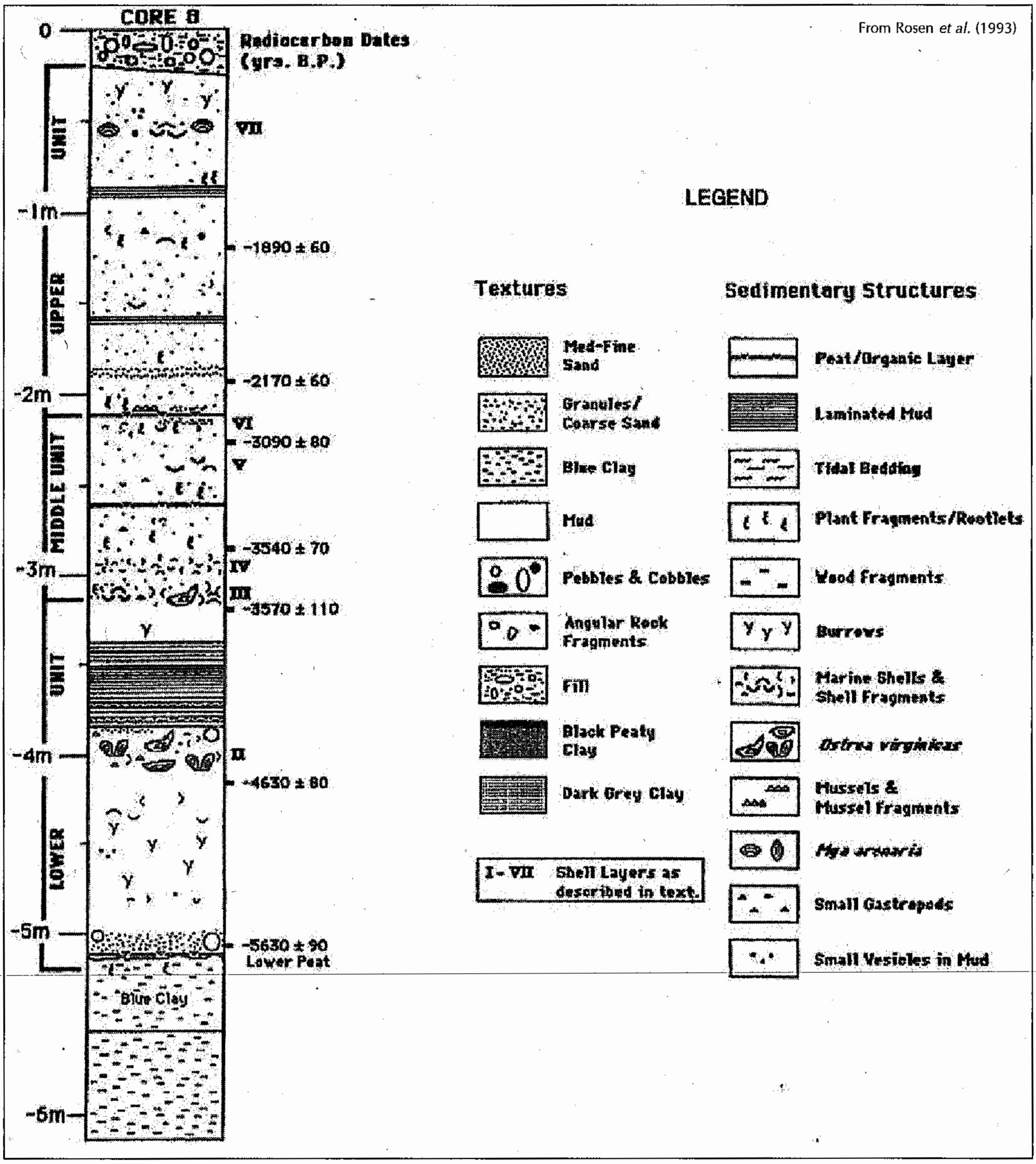



**FIGURE 3-108. Columnar section of the organic deposit at 500 Boylston Street, Back Bay.**

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

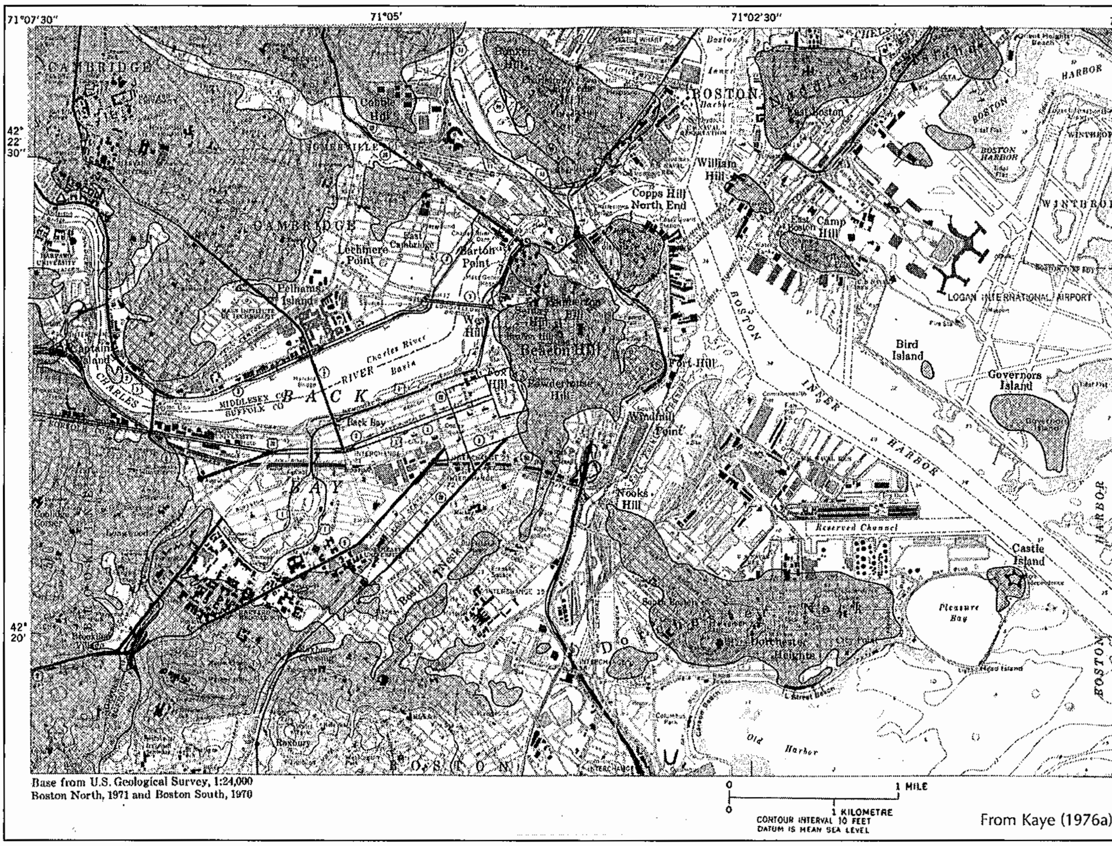



**FIGURE 3-109. Map of the Boston area showing the mean high tide shoreline as it probably existed in 1630, on the basis of sub-surface, surface and historical data superimposed on the modern extent of greater Boston.**

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

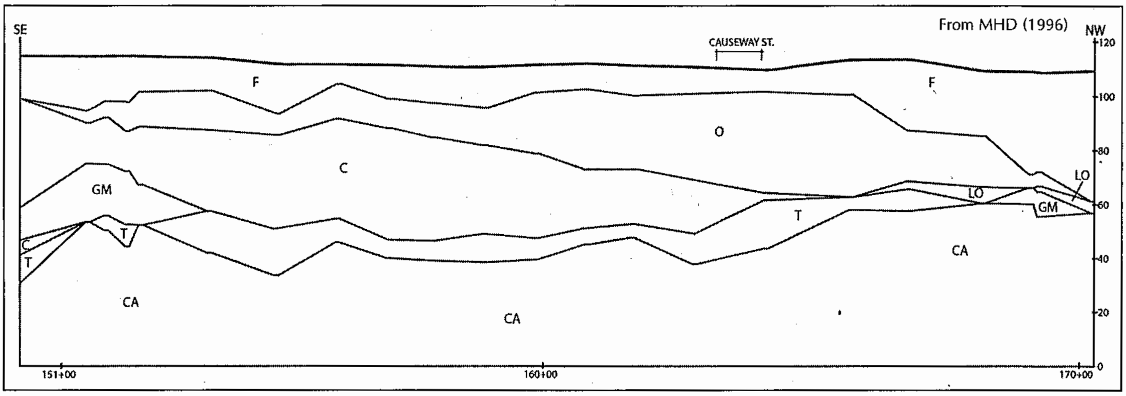
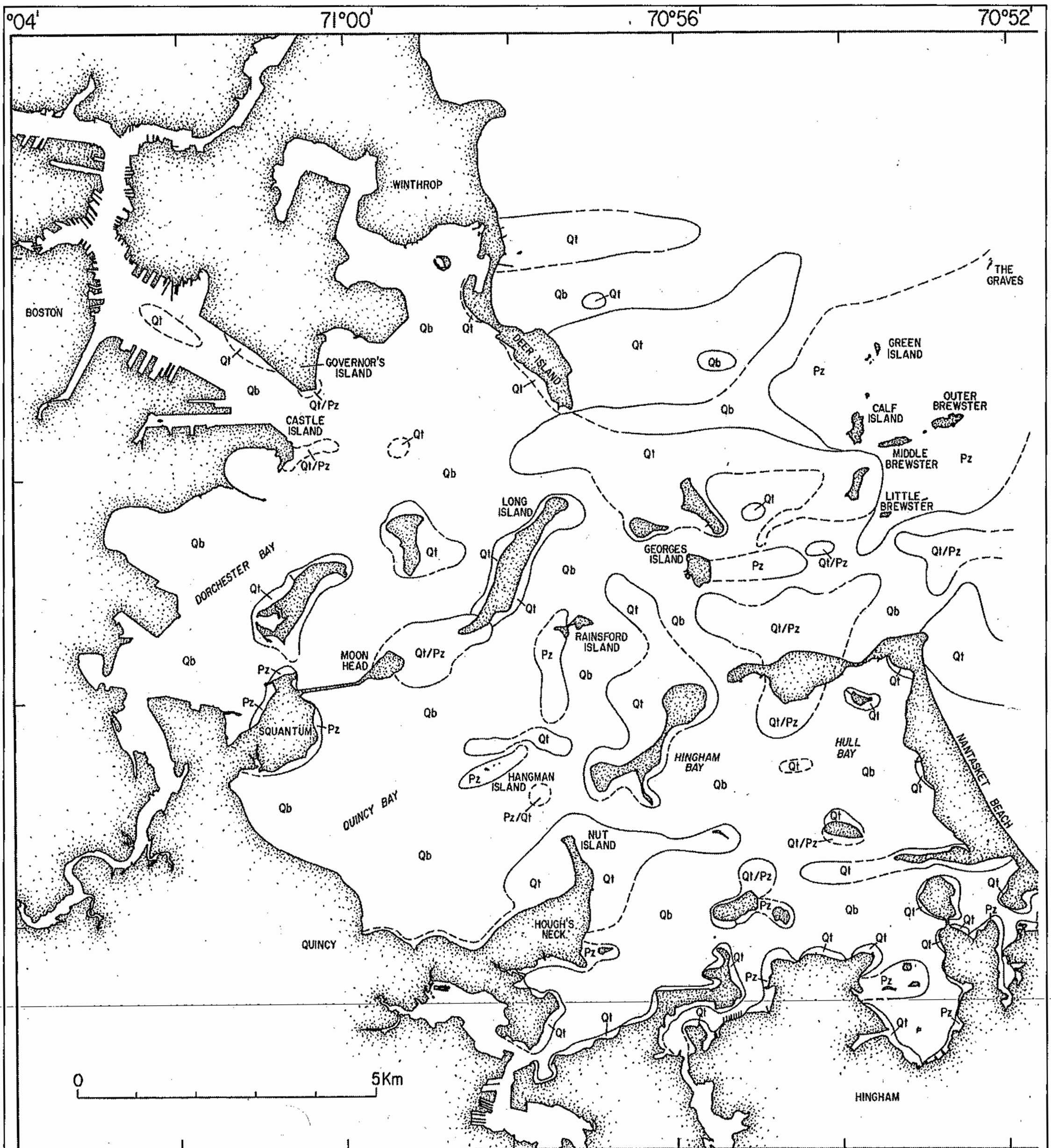



**FIGURE 3-110. Simplified section along the northern Central Artery Tunnel, New Sudbury Street to North Station, showing the distribution of the organic deposit on the side of the early Charles River channel in the marine clay (west tunnel wall between Stations 150+00 and 170+00).**

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,

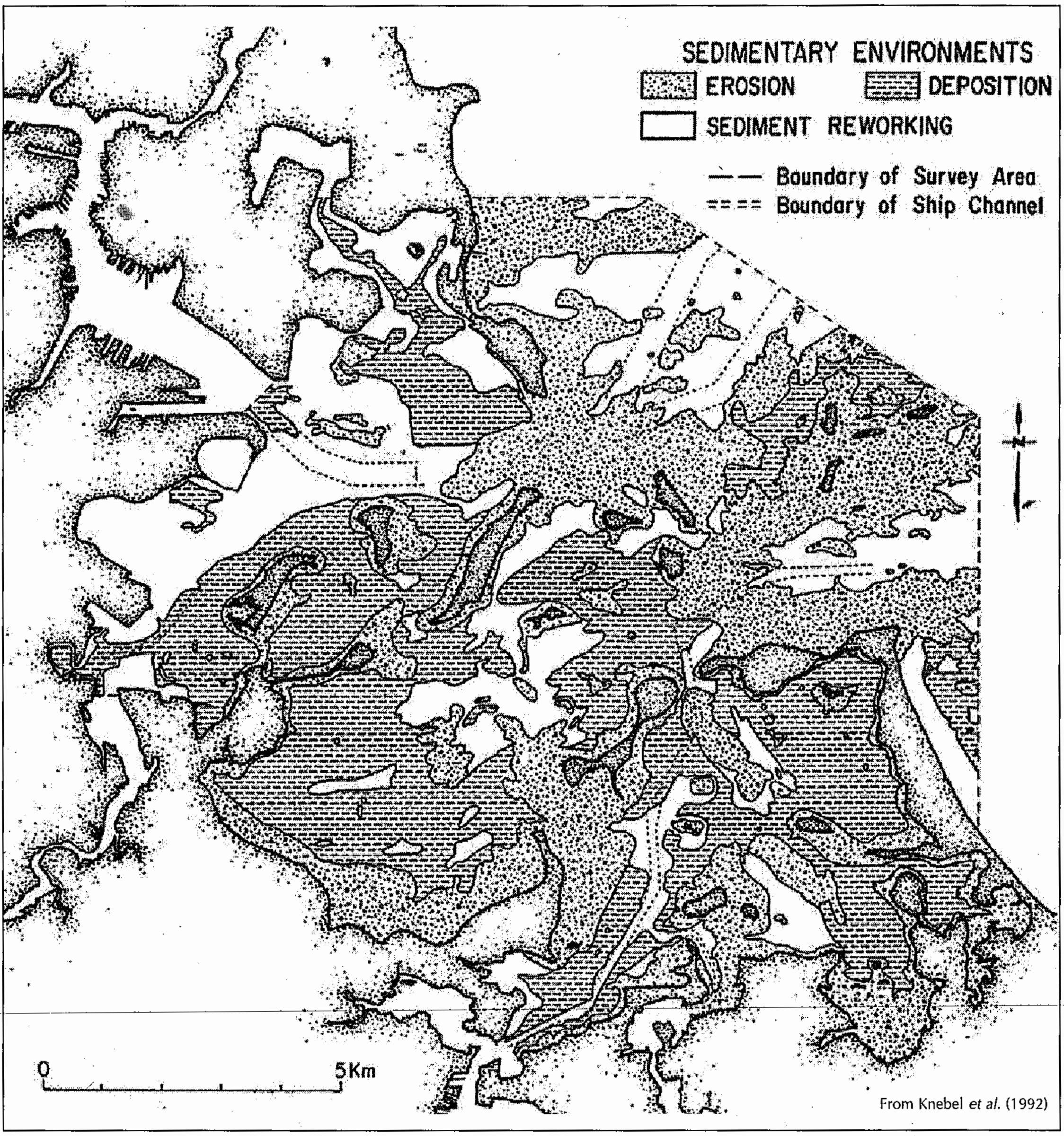



**FIGURE 3-112. Map of the Boston Harbor showing present sedimentary environments.**

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-

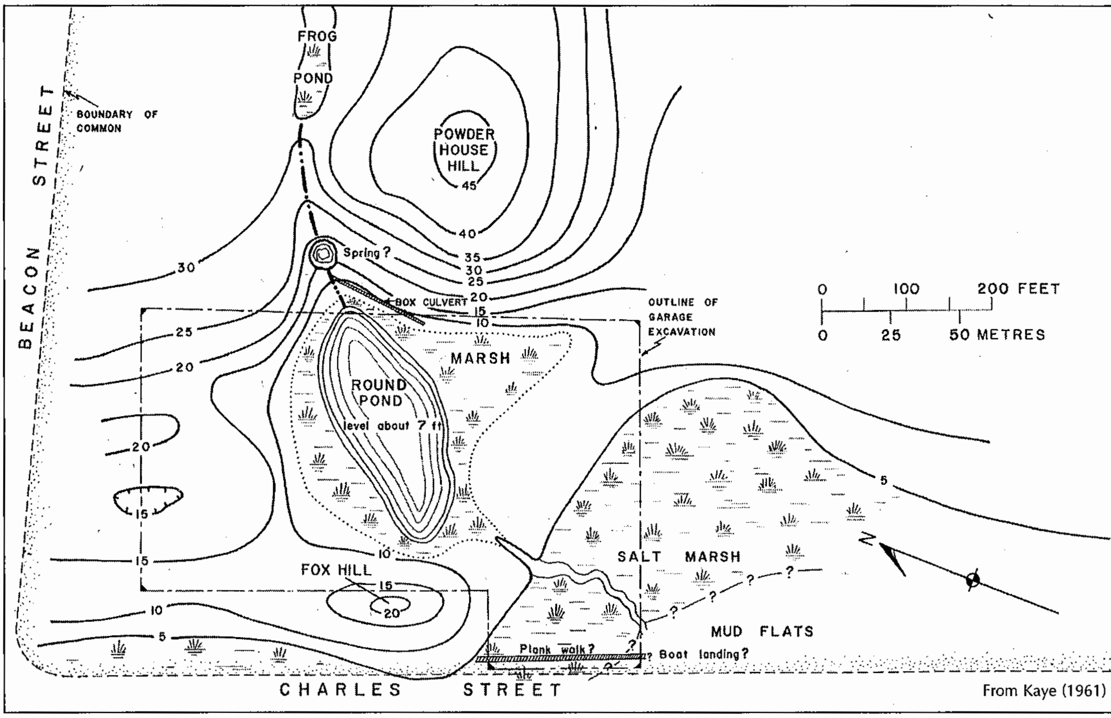



**FIGURE 3-113. Site of the Boston Common Garage showing the reconstructed shoreline features of 1630.**

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

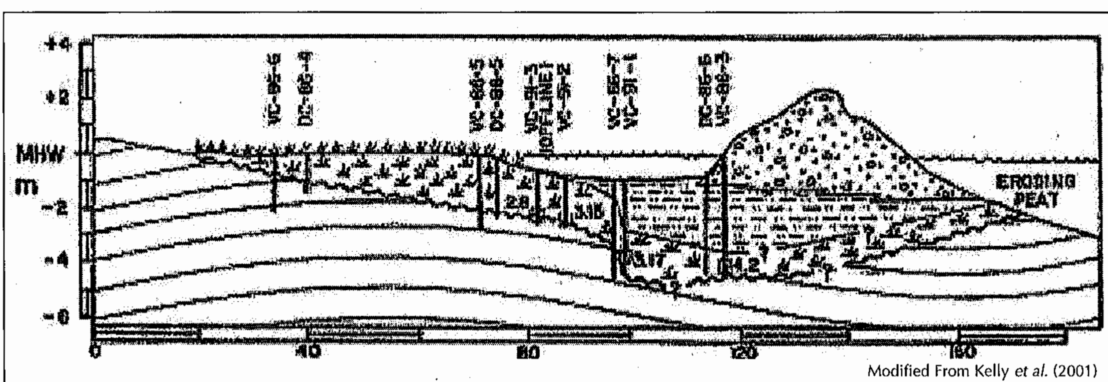



**FIGURE 3-114. Section of a barrier beach (Jasper Beach, Maine, view northeast) showing the transgression of barrier beach sand over lagoon and marsh deposits.**

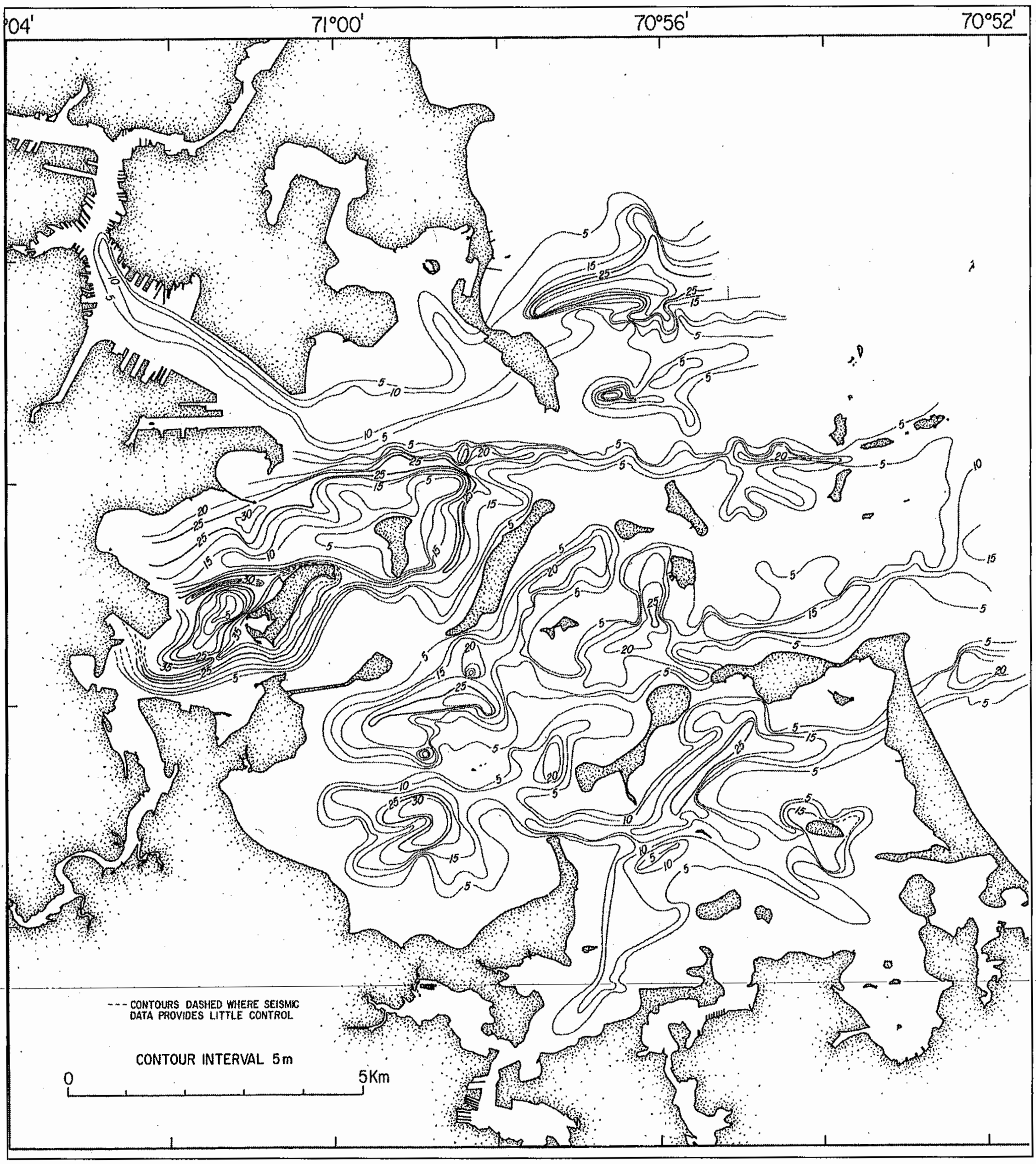



**FIGURE 3-115. Contoured thickness of Quaternary fill in the Boston Harbor interpreted from a subbottom acoustic survey (Rendigs & Oldale, 1990), which reflects the acoustic basement and may not include all of the dense till.**

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

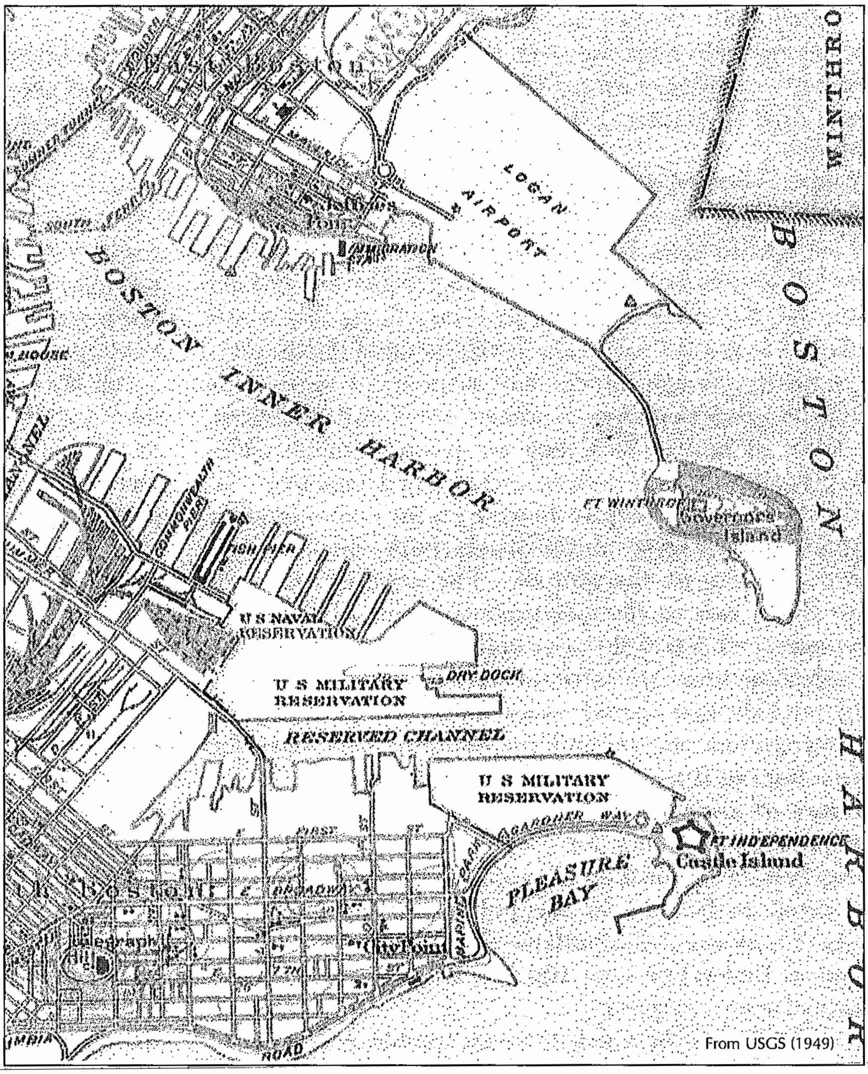



**FIGURE 3-116. Map showing the extent of the fill for Logan Airport in 1946 and the excavation of the drumlin till forming Governors Island for fill prior to the present expanded airport.**

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.

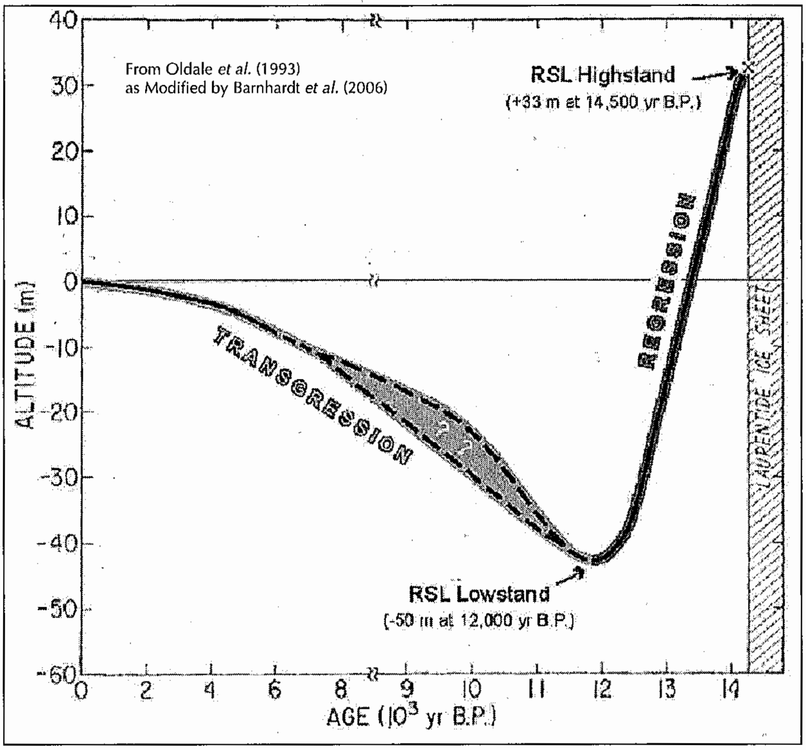



**FIGURE 3-117. Late Quaternary relative sea-level curve for northeastern Massachusetts.**

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

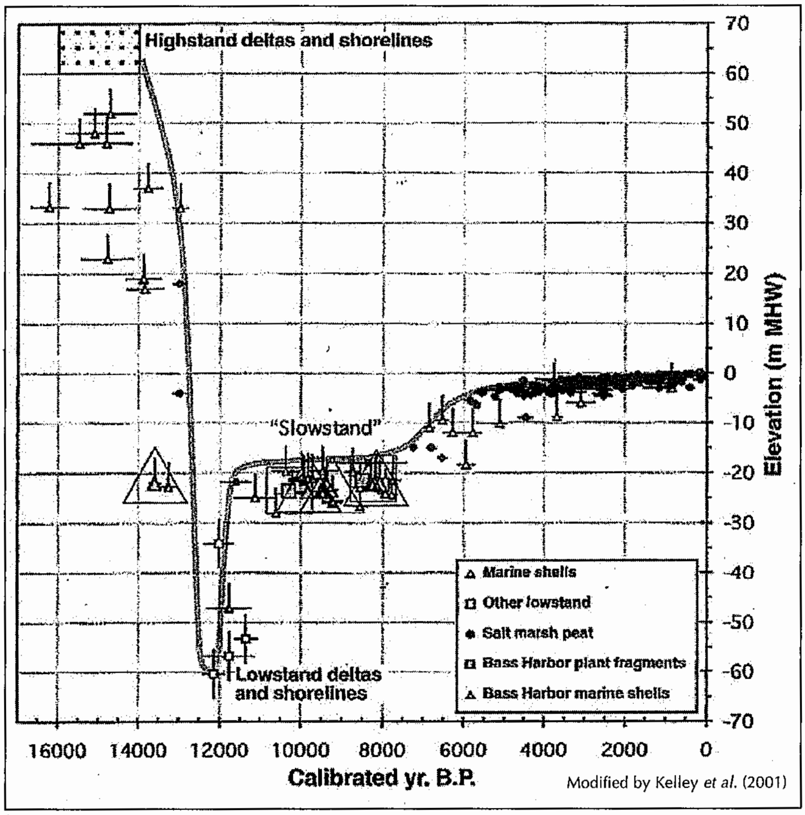



**FIGURE 3-118. Late Quaternary relative sea-level curve for Wells, Maine. (Note that the horizontal scale is reversed from Figure 3-117.)**

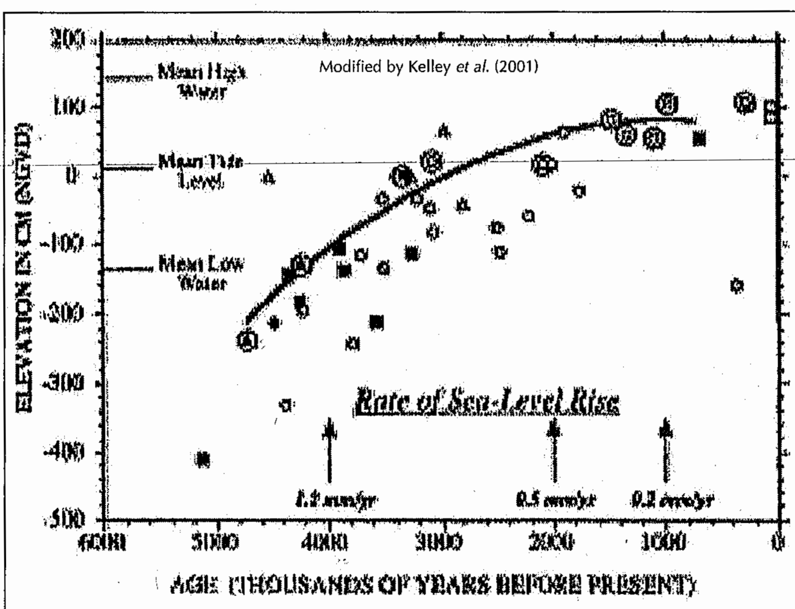



**FIGURE 3-119. Late Quaternary relative sea-level curve for southern Maine.**

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).

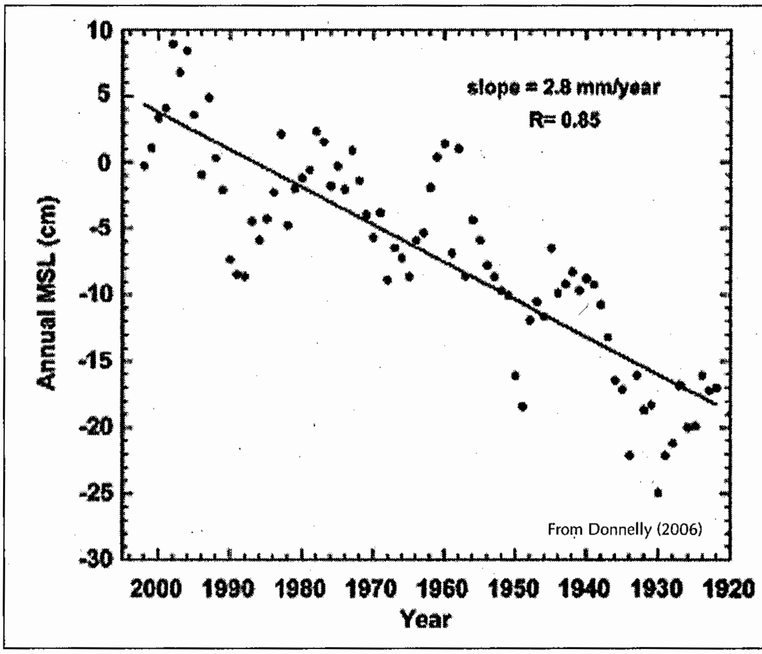



**FIGURE 3-120. Tidal records for Boston Harbor between 1922 and 2002. (Note that the age scale is opposite that on Figure 3-119.)**

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.