Geology of the Boston Basin & Vicinity

If the knowledge of the geology of an area is well known, the greater will be the ability to handle engineering and environmental problems with a higher degree of certainty.

PATRICK J. BAROSH, CLIFFORD A. KAYE & DAVID WOODHOUSE

Boston lies in a fault-bounded structural and topographic basin containing a wide variety of strata that have highly irregular stratigraphic and structural relations. Overlying these rocks are glacial and post-glacial soils of such complexity that their study ultimately led to the development of soil mechanics as a science in this country.

The extreme variety in bedrock and surficial deposits, and their structure, makes the region one of the most challenging anywhere for engineering geologists, since nearly every site is different. The growing need to understand more about water movement (both for water supply and hazardous waste management and cleanup), ground conditions for an ever-expanding variety of construction projects and the potential for earthquake hazards requires more detailed knowledge of the geology of the Boston area than ever before. The lack of detailed geologic data in the northeast United States, for example, has resulted in the unnecessary expenditure of millions of dollars and years of delay in the construction of nuclear power plants while seismologists attempted to relate earthquakes to geologic structures on maps that did not contain the critical data.

A virtual explosion of new information on the region has become available over the past 20 years. This new knowledge has radically changed earlier concepts of the regional geology. The data is mainly from mapping by personnel of the Boston Office of the Geologic Division of the U.S. Geological Survey (closed in 1976), investigations of the New England Seismotectonic Study and the work of the Water Resources Division and the Office of Marine Geology of the U.S. Geological Survey. Some excellent work also has been done by engineering geologists and geophysicists working on tunnels and nuclear power plant sites in the region. Much of the geologic literature on the area, unfortunately, reflects this understanding unevenly and is often contradictory. Also, obtaining the new geologic data is not always easy. The recent State Geologic Map of Massachusetts is, unfortunately, more of pictorial than scientific value and contains little practical information.[1] It contains far less information than the larger-scale preliminary compilation for this map.[2] However, most of the quadrangles in eastern Massachusetts have been mapped, although most of these maps are

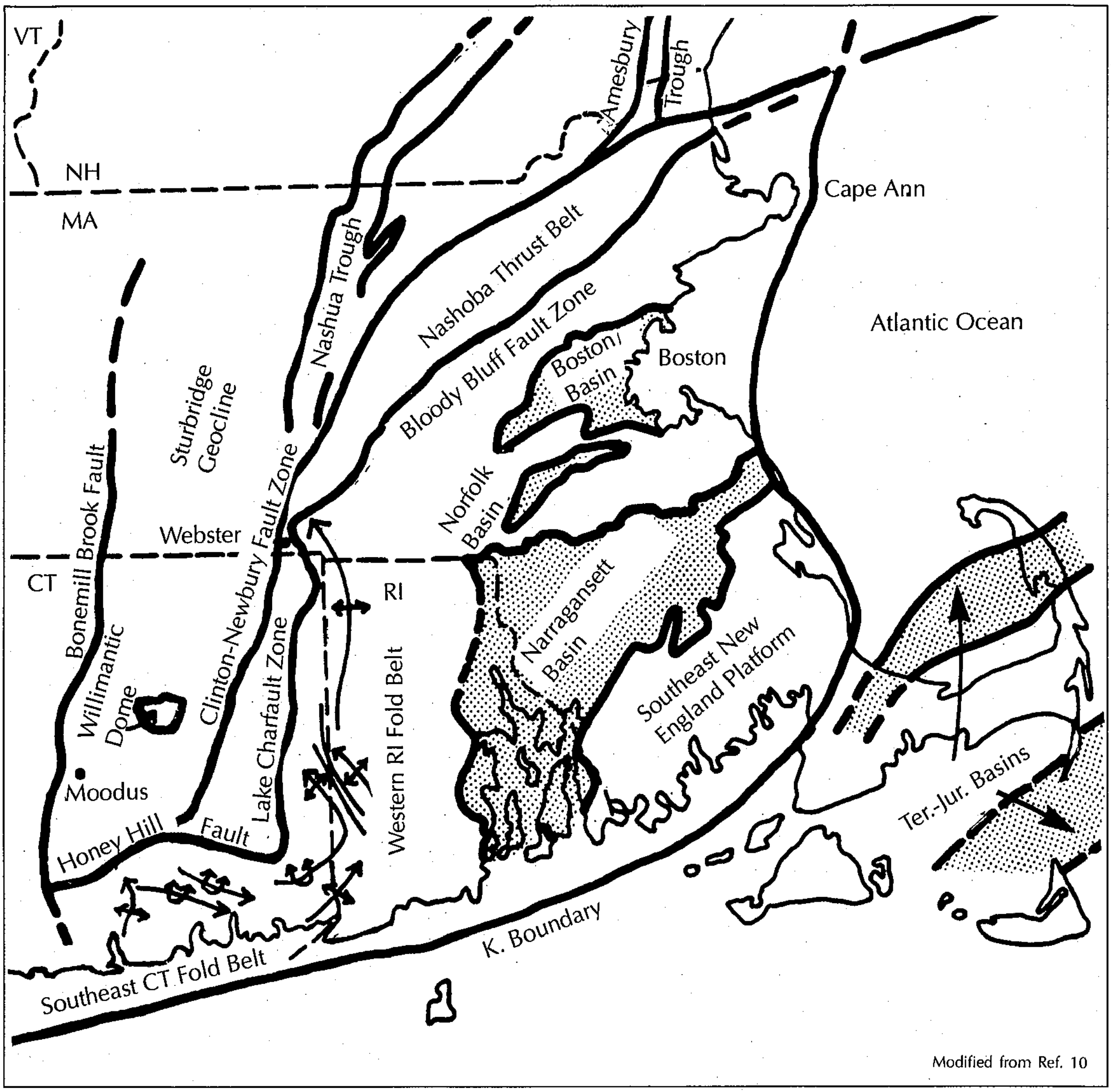


FIGURE 1. Map of southeastern New England showing the major tectonic provinces and structures.

as of yet unpublished and only available in open-file reports. Those that were prepared after 1970 generally have much more structural data, since it took time, preliminary work and excavation of new exposures before many structures were recognized.

Kaye has prepared several reports on Boston summarizing much of this complex geology,[3,4,5,6,7] building on the work of La Forge[8] and has produced a detailed geologic map of central Boston.[9] Information on the regional geology of eastern Massachusetts can be obtained in other recent works.[2,10,11]

Regional Structural Framework & History

Southeastern New England contains some of the most interesting, varied and complex geology in all of North America. It lies astride the eastern border of the Appalachian orogenic belt. This border is the greatest structural zone known in New England. It represents a zone of late Precambrian and early Paleozoic collision between Paleo-North American and Paleo-African plates, and now forms the Nashoba Thrust Belt (see Figure 1). The rifting that later

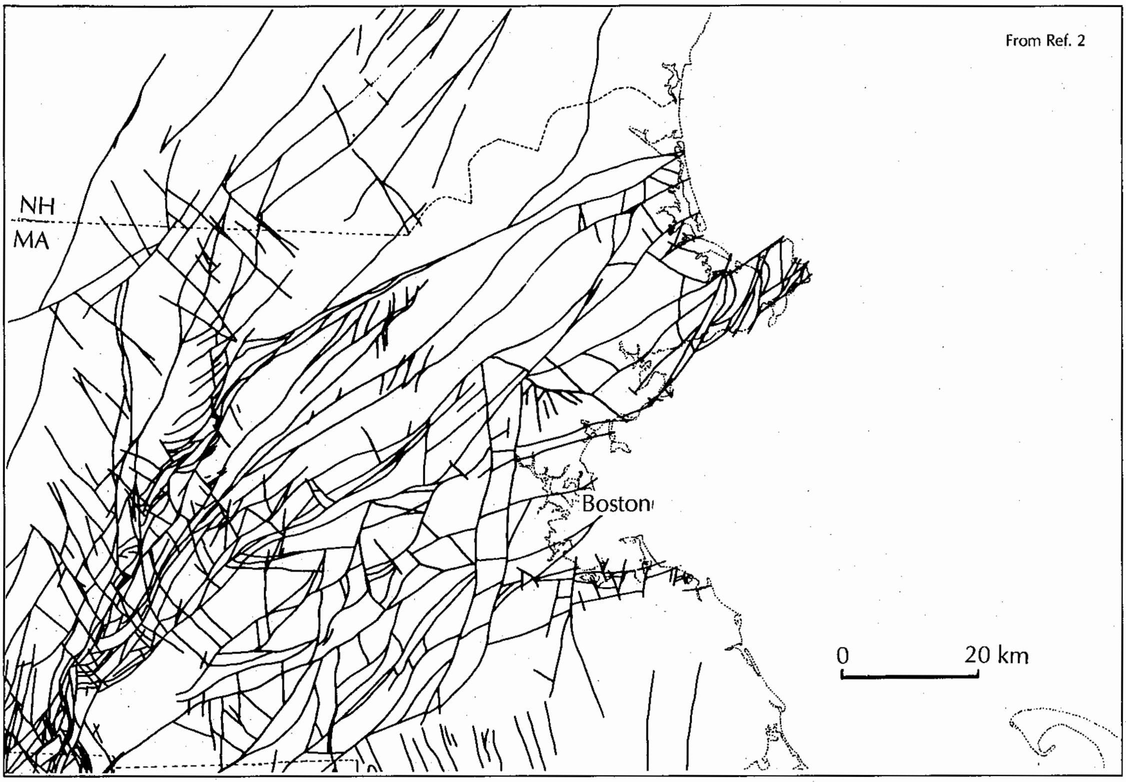


FIGURE 2. Map of eastern Massachusetts and southern New Hampshire showing mapped faults (Boston 2-degree sheet).

formed the present North Atlantic Basin generally followed this collision zone, but split off a piece of northwest Africa that clung to North America and now forms the southeast corner of New England.[10] This fragment became the foundation on which Boston was built. The Boston Basin, as well as other nearby basins, were formed by faulting in this ancient, largely granitic basement (see Figures 2 and 3). Subsequently, the eastern edge of this fragment sagged as the North Atlantic widened and was overlapped by the Cretaceous and Tertiary deposits that lie offshore and form the submerged northern extension of the Atlantic Coastal Plain.[12] Earthquake activity and other indications of crustal movement show that it is still a tectonically active region.

The Boston Basin

Bedrock Geology. The City of Boston is located near the center of the Boston Basin, an east-northeast-trending, wedge-shaped, down-faulted body of sedimentary and volcanic rock (see Figure 4).[7,8,9,13,14,15,16] Onshore, the basin is widest along the coast, where it measures about 24 kilometers (15 miles) north to south.

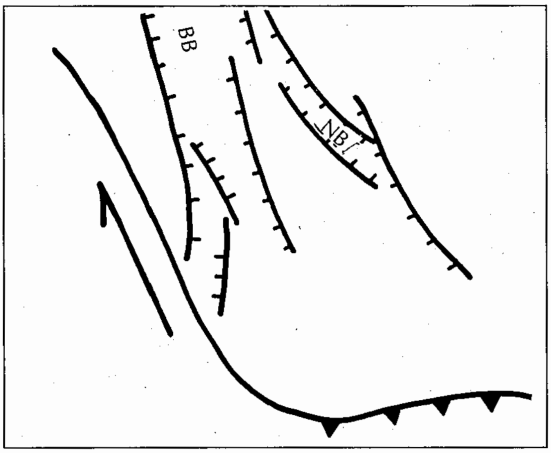


FIGURE 3. Sketch map showing the structural relations of the Boston Basin (BB) and the Norfolk Basin (NB) with the eastern edge of the Nashoba Thrust Belt.

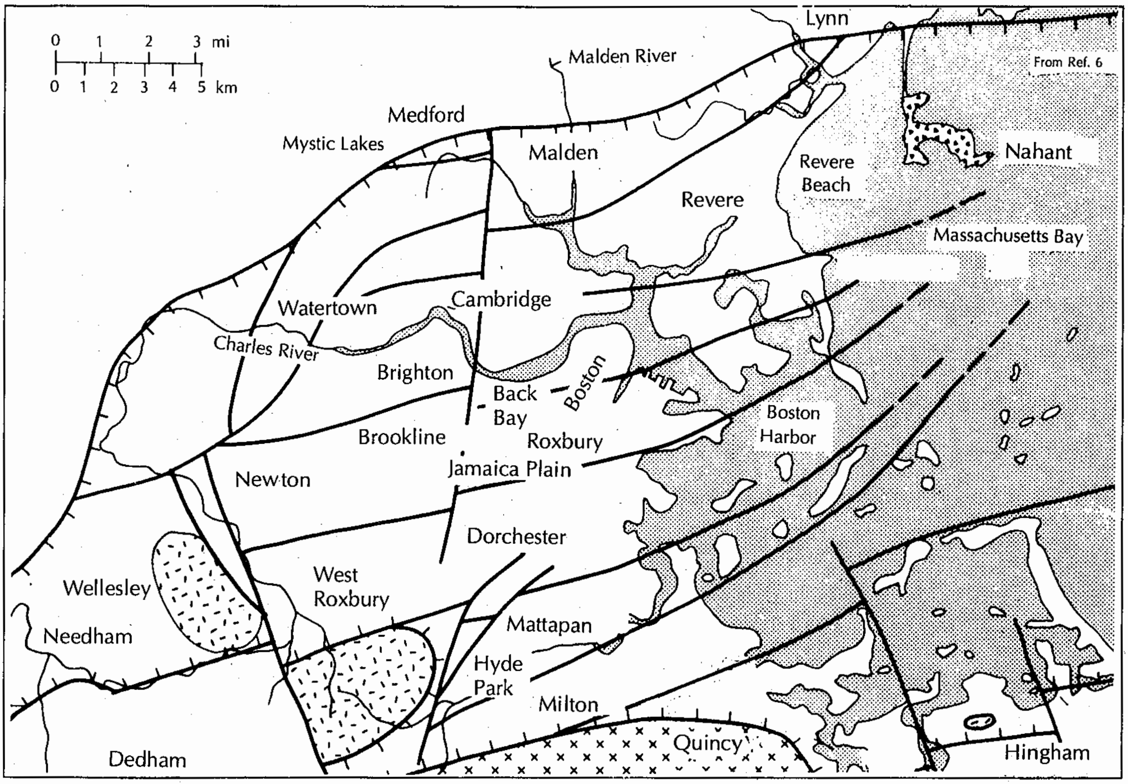


FIGURE 4. Map of Boston showing the limits of the Boston Basin (ticked line), generalized major faults (heavy lines, dashed where inferred) and inliers of plutonic rock (hatched = Dedham granite, crosses = Quincy granite, and triangles = Nahant gabbro).

Offshore, it extends to the east under Massachusetts Bay, where it appears to widen still more. On the west, the basin tapers to a point about 29 kilometers (18 miles) west-south-west of Boston.

The strata in the basin vary in age from the latest Precambrian to Middle or Late Cambrian and perhaps Ordovician.[17] The rocks of the Boston Basin appear to have been deposited in a basin complex that was undergoing active block-faulting. The highest relief and source areas lay to the south and west of the basin. Coarse-grained heterogeneous terrestrial deposits along these borders graded rapidly north and east into fine-grained marine deposits. The sedimentary rocks, therefore, consist of detritus that had been eroded from the surrounding highlands and fault scarps and that had been deposited as interfingering lithofacies. Conglomerate, sandstone, argillite and volcaniclastic sediment grade or interfinger into each other laterally and vertically over short distances. Thin limestones interbedded with argillite and sandstone are locally abundant.

Very late Precambrian volcanic activity was widespread and occurred in at least six intervals. Early eruptions were rhyolitic and later were spilitic and keratophyric. The volcanic rocks occur as flows, flow breccias, explosion breccias, pillow lavas, plugs, necks and diatremes.

Bottom conditions were unstable in the depositional basins. At many stratigraphic levels, the telltale evidence of submarine sliding and turbidity currents is present. This evidence includes convoluted bedding, intraformational breccia, graded-bedding and large lenticular slumped masses of pebbly to bouldery mudstone (mistakenly identified as glacial tillite). Bottom slumps and slides were probably triggered by earthquakes that originated from volcanic eruptions and block faulting.

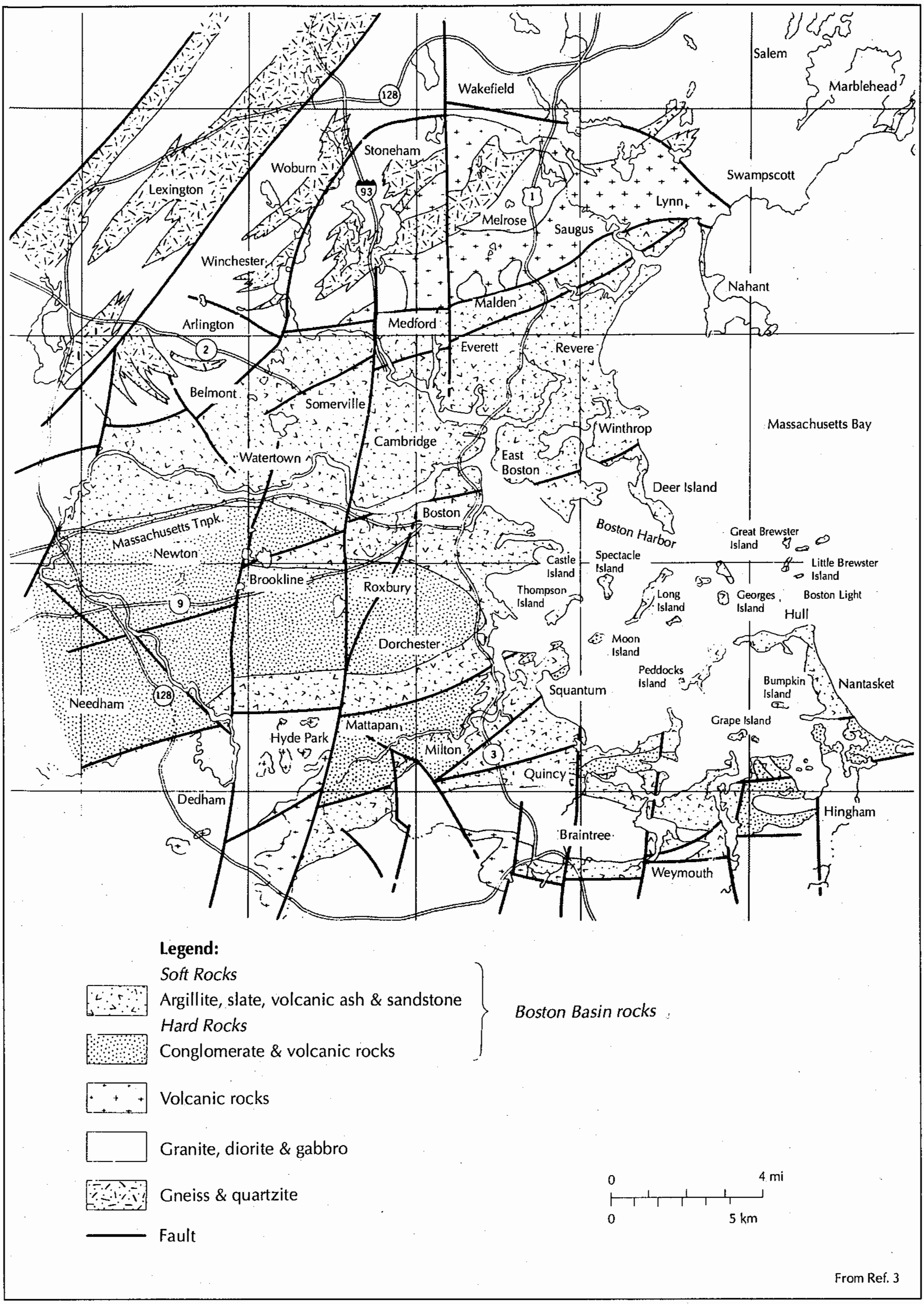


FIGURE 5. Generalized bedrock geologic map of the area surrounding Boston.

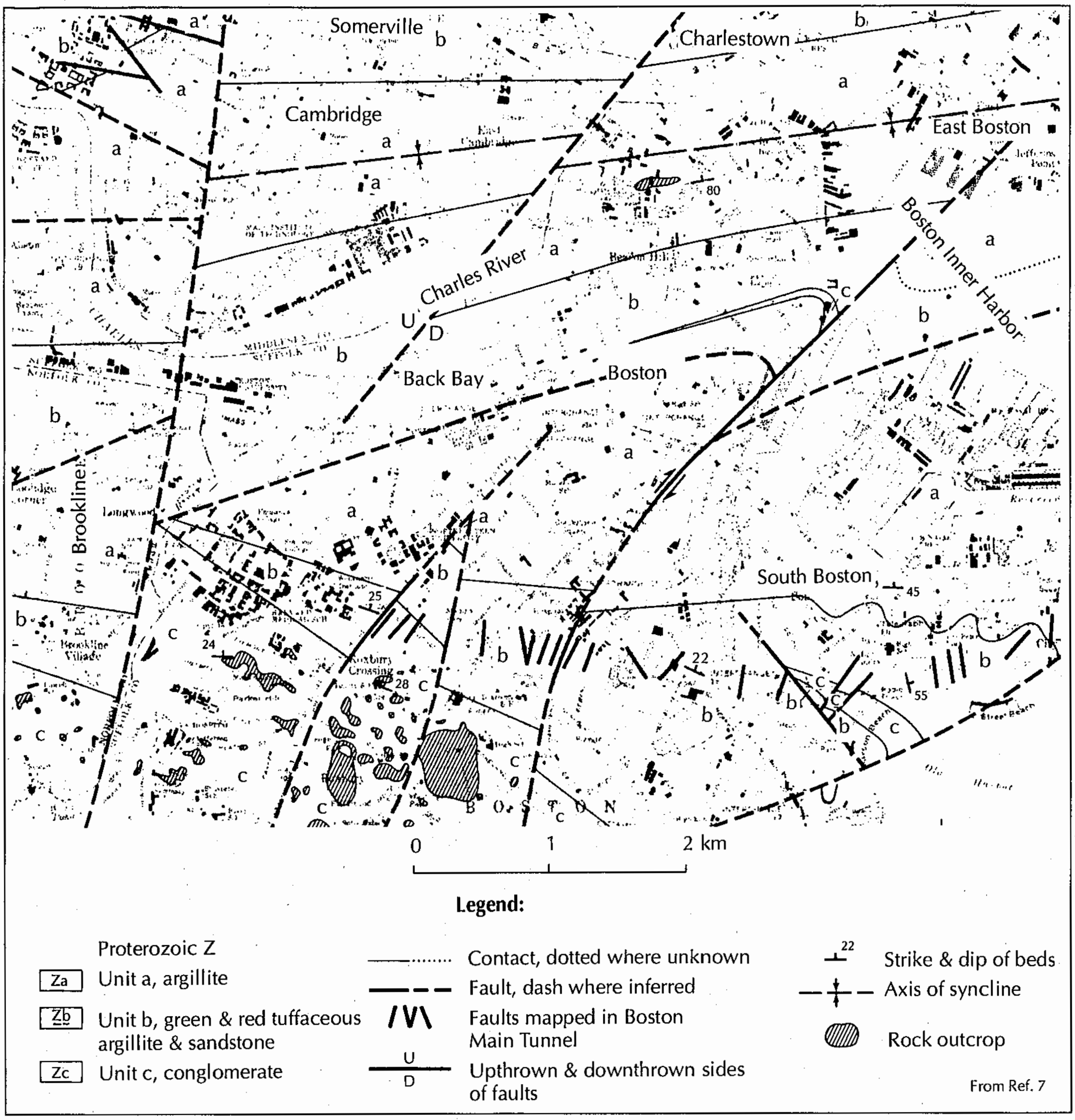


FIGURE 6. Bedrock geologic map of central Boston.

Large volcanic complexes developed on either side of the Boston Basin during the Ordovician period. The remnants of these complexes now comprise the Cape Ann Granite, Salem Gabbro-Diorite and Lynn Volcanics to the north and the Quincy Granite and associated ash-flow and other volcanic rock to the south. This activity probably ended marine deposition in the basin. Rock of this age might also be preserved locally in the basin.

The sedimentary rocks in the basin are divisible into three main facies: coarse-grained (conglomerate and sandstone), fine-grained (argillite) and a mixed facies consisting of maroon and green tuffaceous siltstone and sandstone (see Figure 5). Traditionally, these sedimentary rocks have been called the Boston Bay Group and have been given formational names: Roxbury Conglomerate and the Cambridge Slate, in that order of the previously ascribed Paleozoic age.[8,15]

The lower formation, the Roxbury Conglomerate, was traditionally subdivided into three members which are, in ascending order:

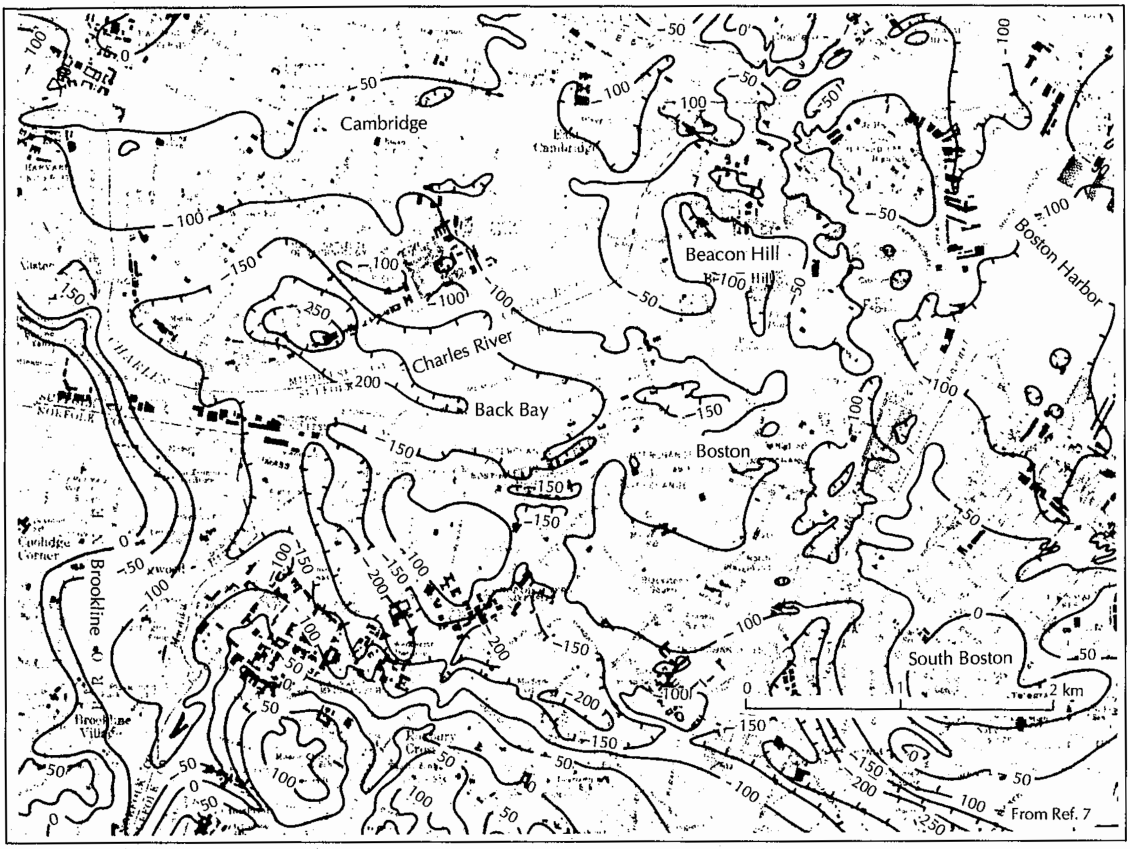


FIGURE 7. Bedrock surface of the central Boston area. The contour interval is 15 m (50 ft). Datum is mean sea level.

the Brookline Conglomerate, the Dorchester Shale, and the Squantum Tillite. The Brookline Conglomerate is comprised of conglomerate, sandstone, argillite, shale, and altered basalts and andesites that are sometimes called the Brighton Metaphyre. The uppermost member, a mudstone with "floating" clasts, has been called a tillite by some,[8,18] but is considered to be a subaqueous flow by more recent workers.[19]

The Cambridge Slate is now called the Cambridge Argillite. Thin quartzites are locally present within it such as the Tufts Quartzite in Medford, on the edge of the basin just north of Boston, and the Milton Quartzite, just south of the city.[14,15]

This simple stratigraphic concept of a layered sequence of decreasing age does not properly portray the complex intertonguing relations of different facies in which the same rock type may have been deposited at different times. The use of these formational terms perpetuates confusion in the basin and they have not been used on recent maps.[9] The assignment of a proper stratigraphic nomenclature awaits further mapping.

The fault boundary of the basin on the south is complex and consists in part of faults that were active during the period of deposition. The much straighter northern boundary fault formed later. The Boston Basin appears to be deformed by compression into a series of long, east-west to east-northeast-trending folds, overturned to the south and, as they can be seen today, plunging east. The southern part of the central Boston area appears to lie on the faulted northern flank of a large east-plunging anticline (see Figure 6).[8,9,14] Cutting across the northern tip of the Boston Peninsula is the east-northeast-trending axis of the large Charles River Syncline,[14] with argillite cropping out in the trough of this long fold. These folds are

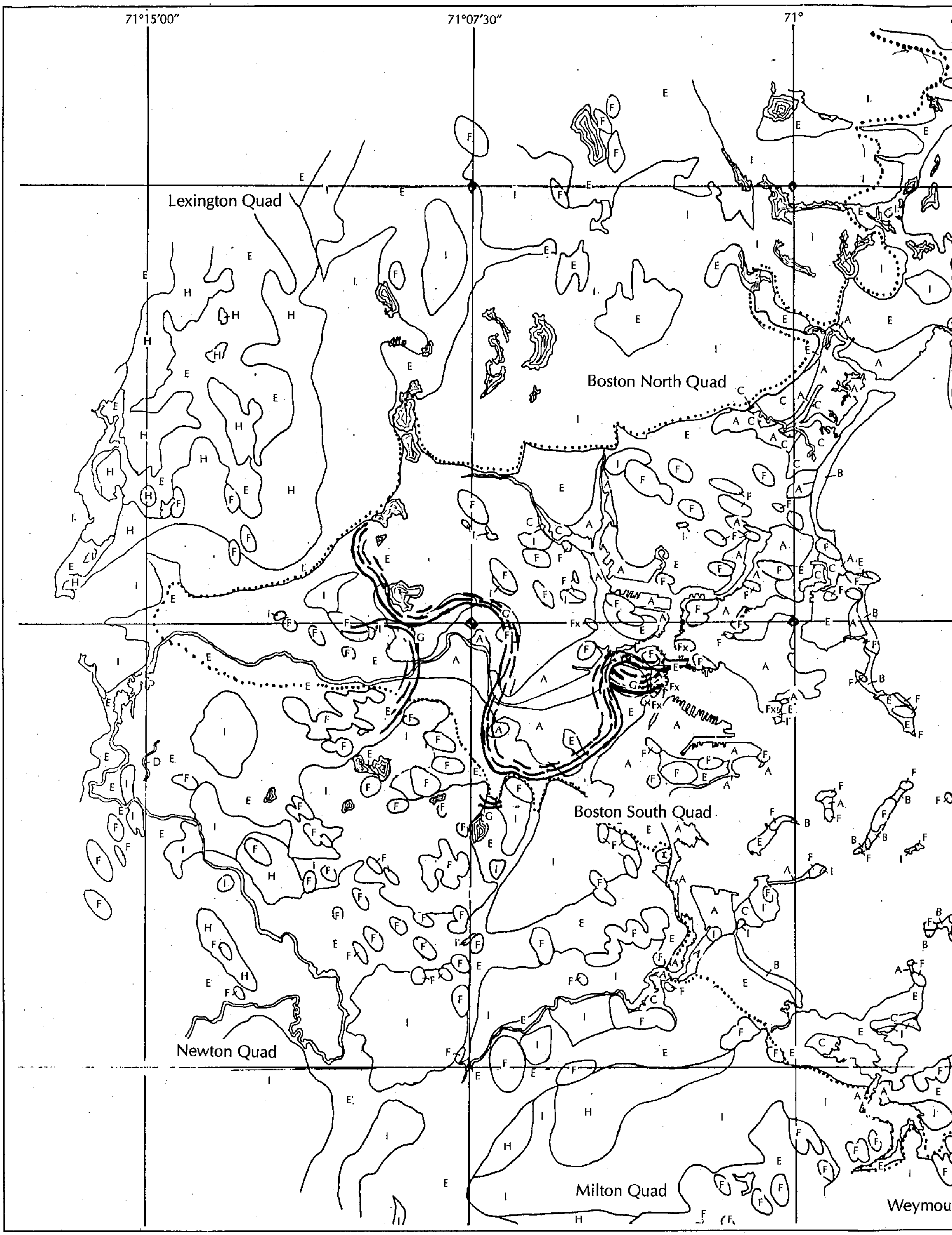
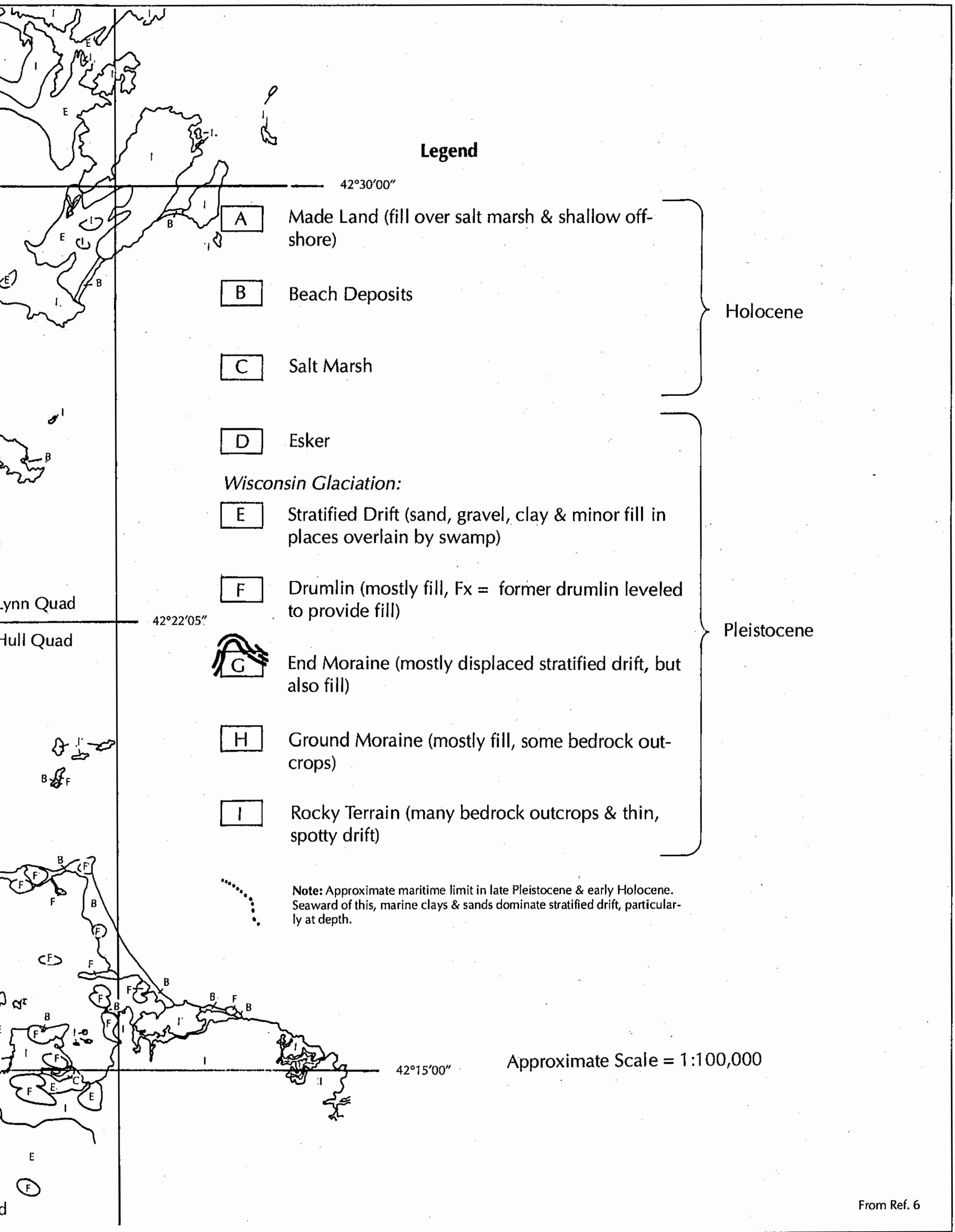


FIGURE 8. Surficial geologic map of the area surrounding Boston.



Legend
42°30′00″
A Made Land (fill over salt marsh & shallow off-shore)
B Beach Deposits
C Salt Marsh
Holocene
D Esker
Wisconsin Glaciation:
E Stratified Drift (sand, gravel, clay & minor fill in places overlain by swamp)
F Drumlin (mostly fill, Fx = former drumlin leveled to provide fill)
G End Moraine (mostly displaced stratified drift, but also fill)
H Ground Moraine (mostly fill, some bedrock out-crops)
I Rocky Terrain (many bedrock outcrops & thin, spotty drift)
Pleistocene
Note: Approximate maritime limit in late Pleistocene & early Holocene. Seaward of this, marine clays & sands dominate stratified drift, particular-ly at depth.
Lynn Quad
Hull Quad
42°22′05″
42°15′00″
Approximate Scale = 1:100,000
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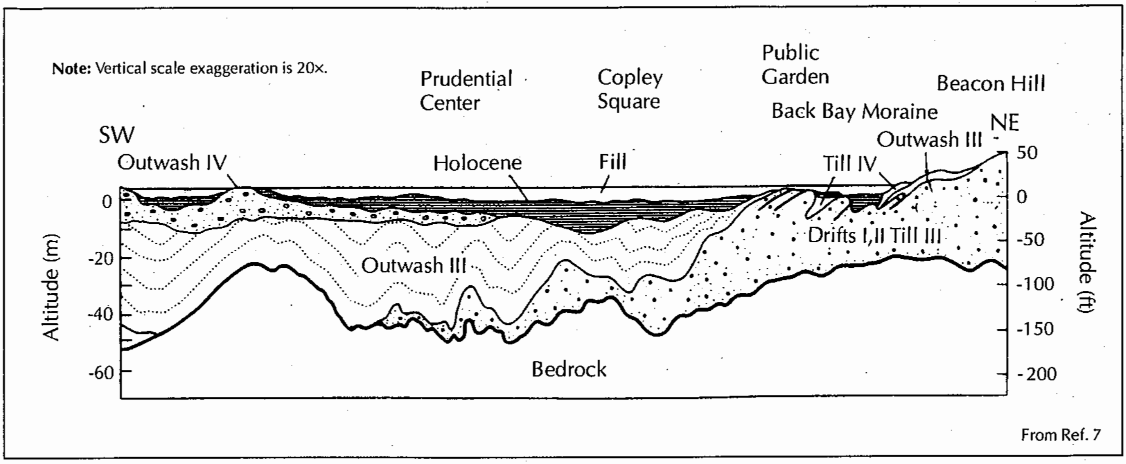


FIGURE 9. Geologic cross-section across part of the Back Bay, extending southwest from Beacon Hill and showing Quaternary deposits.

fragmented by longitudinal faults of large displacement. Recent mapping indicates that there are at least eight large faults, most of which are 15 kilometers (9 miles) or more in length.[9] They break the basin into long, narrow fault blocks, each of which consisting of a single fold, either an anticline, syncline or homocline. In addition, the rocks are broken by a complex of later faults, most of which are transverse to the longitudinal faults. Besides faults with large to small displacement, there are shear zones with various cataclastic effects, but with relatively small displacement. The longitudinal faults are mostly high-angle reverse in nature. Slickensides on fault surfaces show a strong strike-slip component of movement on many

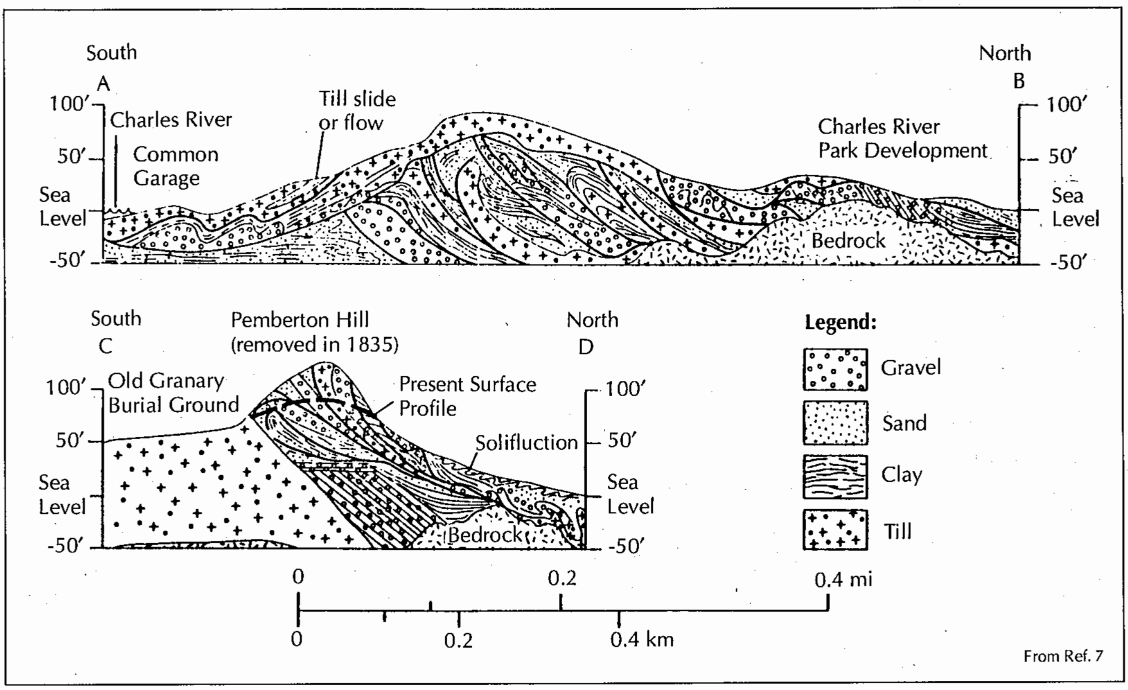


FIGURE 10. Two cross-sections of Beacon Hill showing the type of complexity revealed by deep foundation excavations.

of the transverse faults. There is surprisingly little to no unconsolidated fault breccia or gouge lining many faults. However, there is, in many of the faults, lithified cataclastic material that is difficult to characterize without petrographic study. The present data indicate an average lateral fault-spacing throughout the area of about 150 meters (490 feet) measured in any direction, although the density of faults varies from place to place.

The structural deformation within the Boston Basin probably is the result of latest Precambrian to Ordovician movements with lesser activity from the rest of the Paleozoic, when other nearby basins were formed, as well as faulting and dike-intrusion in the Triassic-Jurassic. The longitudinal faults may represent reactivation of the late Precambrian basin-range faults. The transverse faults are mostly post-Pennsylvanian. Northwest- and north-trending faults are the youngest in the region and some are still active north of the basin.

Bedrock Surface. More than 95 percent of the surface of the bedrock of the central Boston area lies buried beneath Quaternary deposits. The

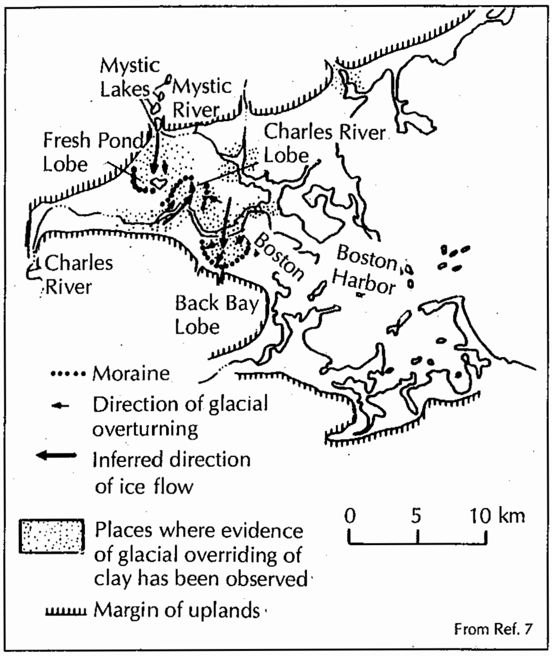


FIGURE 11. Map showing Fresh Pond, the Charles River and Back Bay moraines and areas that have yielded evidence of glacial overriding of clay.

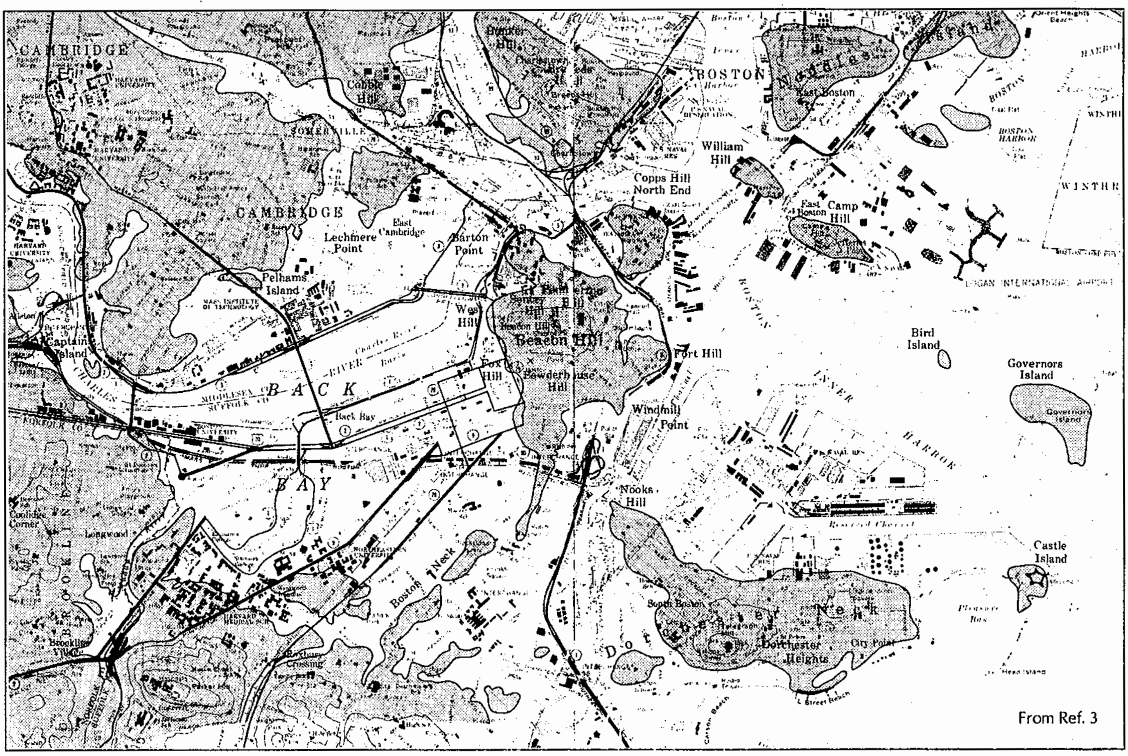


FIGURE 12. The Boston mean-high-tide shoreline as it probably existed in 1630 (shaded).

bedrock surface reflects rock erodibility. The deeper section under the Charles River and Back Bay is underlain by softer strata (argillite, siltstone and sandstone), and the high-standing area along the southern margin marks the outcrop of massive conglomerate (see Figure 7). In detail, the bedrock surface is highly irregular.[7] Dikes stand up as knobs and ridges, major joints are deeply grooved and closed depressions abound.

Pleistocene Geology. The last Wisconsin ice sheet covered the entire region and extended off-shore to the east. Extensive thick outwash plains and moraines developed across Cape Cod and the islands near its southern terminus. As the ice melted and retreated northward, a complex and often bewildering variety of till, drumlin, esker, outwash, delta and lake clay, and sand and gravel deposits were laid down. Sequences of many types of outwash, delta and lake deposits formed in the shallow valleys. Marine clays were deposited along the shore, and sand and gravel deposits lie off-shore. The outwash deposits are several hundred feet thick on outer Cape Cod, but usually the deposits are thin, although quite variable in thickness. Little geologic change has affected the area since the retreat of the ice other than man's activities and the filling of many lowland areas by lake and swamp material. This history has created a highly variable ground condition that may change over a short distance.

Glacial deposits overlie the bedrock almost everywhere in the central Boston area, attaining a maximum thickness of 90 meters (295 feet) in a few places under the Charles River Basin. These deposits include: drumlin till, ablation till, sand, gravel, and silt and clay.[3,4,5,7,20,21] Most of the clay is marine and referred to as the "Boston blue clay," although its moist color is typically light greenish-gray to medium-gray. The Boston area, lying close to or below sea level, was repeatedly flooded by marine waters. Variation in ice thickness, eustatic sea level and isostatic crustal levels were all interrelated factors that affected deposition and erosion (see Figures 8, 9 and 10). Four separate and distinct ice currents occurred in the Boston area. Major wastage of the ice took place about 18,000 years before the present. From that time to about 12,500 years ago, glacial re-advances, such as at Beacon Hill, Back Bay and Fresh Pond, have occurred in the Malden River, Mystic River and Charles River valleys (see Figure 11).

Holocene Geology. The melting and retreat of the glaciers from New England resulted in the surface of the land rebounding from the mass of the ice and a rise in sea level. These events changed the depositional regime in the Boston area. The rising and southward tilt of the land combined with the rise in sea level are in equilibrium just south of Boston, where the Late Pleistocene and present sea-level match. The sea level rise was not uniform, but had at least several fluctuations and was complicated by some crustal subsidence.[22]

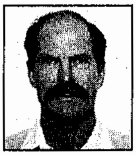
Unconsolidated reworked marine clay and organic silt mantle the low areas of Boston and the use of fill, dating back to colonial times, has been extensive around the city.[23] When Boston was first settled, the town lay on a high-tide island that was surrounded in many places by shallow mudflats (see Figure 12). As the town grew into a city, most of the shallow areas have been filled to provide land for the expansion of the city. A record of the stages of filling is reflected in the city's somewhat confusing street pattern, since when each area was filled, it was usually given a pattern of streets different from the earlier ones. Comparison of the area of construction at different times with the original shoreline also shows this phenomenon well.

Engineering & Environmental Considerations

At many places in the Boston Basin, the joints, faults, alteration or type of clay affect the engineering performance of the foundation material. Many rock types have distinct engineering characteristics.[7,16] Secondary alteration has weakened, softened and bleached all basin rock types in places.[24] It has changed the hard rock into a soft, white silty aggregate that can be dug with a hand shovel. These changes are due to the formation of sericite and kaolinite at the expense of all primary minerals, including quartz. 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, deep bedrock, and altered rock is notable. The alteration seems to occur in close proximity to certain faults. The cause of this soft-rock alteration is conjectural and may be the result of hydrothermal activity, but it may also represent the roots of lateritic weathering in Tertiary time.[24] Soft-rock alteration probably is responsible for the fact that most of the Boston Basin is ill-suited for tunnelling. Unfortunately, much of the alteration is restricted to relatively narrow zones or beds that are easily missed by exploratory borings. In tunnels, the altered rock almost always requires steel support. This altered rock is often referred to as "shale" in geotechnical reports.

Understanding the regional geology around Boston and its development is important in many ways. Faults of different ages have different trends and characteristics that affect their bearing strengths, and water-bearing and earthquake generating capabilities. They are important for water exploration and understanding the direction of flow of hazardous waste. Some stratigraphic units weather and loose their strength very rapidly in cuts so that they pose problems in slope stability; other units may contain natural groundwater contaminants such as arsenic and iron sulfides. Thus, their recognition and distribution is important. Granites with different ages and tectonic environments at time of intrusion vary greatly in degree of homogeneity, foliation, jointing and potential for radon gas production. These characteristics affect blasting, slope stability, the potential for high-level radioactive waste and other types of underground storage and indoor air quality. Understanding the early tectonic movements helps predict areas of high residual strain that may cause rock bursts in deep excavations. The type of Pleistocene deposit largely determines its water-bearing and groundwater flow characteristics, bearing strength, slope stability and potential for earthquake-induced liquefaction.

The general geology thus contains considerable practical data for construction, groundwater and hazardous waste projects in the region and needs to be considered even for very small sites.



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CLIFFORD A. KAYE *(1916-1985) was an uncompromising scientist and an outstanding geologist. He received his undergraduate degree from Cornell University in 1938 and performed graduate work at the University of California at Berkeley and at Harvard University. Virtually his entire professional career over a 40-year span was spent with the United States Geological Survey and most of that working as an Engineering Geologist in the Boston area. He devoted large amounts of time and energy, even after his retirement in 1981, trying to understand and decipher the complex geology underlying Boston.*

DAVID WOODHOUSE, *CPG, is Vice President and Principal of QUEST Environmental Sciences, Inc., located in Manchester, New Hampshire. Since receiving his undergraduate and graduate degrees in geology from Boston University, he has worked as an engineering geologist for over 20 years with major geotechnical firms in the Boston area. This experience has given him valuable insights into the complex geological and soil problems in the Boston area. He has also developed a keen interest in its history since the colonial times.*

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