# Transportation Tunnels in Greater Boston

*A summary of all major transportation tunnels in the Boston area, with notes on how their construction added to understanding Boston's geology.*

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In order to accommodate Boston's growth, and to facilitate commerce, a number of public works have been designed and constructed since the late nineteenth century. Tunnels have been built for vehicular traffic as well as for mass transit. The tunnels have largely been excavated by means of open-cut excavations, with notable exceptions for the trans-harbor crossings and the Massachusetts Bay Transportation Authority (MBTA) Red Line extension through Porter Square, Cambridge. Tunnel excavations offer a unique opportunity to examine soil and rock over a long cross-section not always afforded by building excavations.

## Subway Tunnels

More than a century has passed since state and local governments in Massachusetts first recognized the need for decreasing street congestion and for increasing the speed and capacity of public transportation in the Boston area. In 1888, there were more than eight thousand horses pulling streetcars in Boston. The many rapid transit facilities built since that time (Woodhouse & Barosh, 1991; Clarke & Cummings, 1997; Cheney, 2002; Cudahy, 2004; McKendry, 2005) formed the foundations of today's Red, Orange, Blue, Green and Silver subway lines of the MBTA (see Figure 6-1). This subway network, now 125 kilometers (77.4 miles) in length, carries an estimated 250 million riders annually, and has planned extensions. The system includes 50 kilometers (31 miles) of active subway tunnels. For a metropolitan area the size of Boston, its rapid transit system is large when compared to rapid transit facilities elsewhere in the United States. Boston has long been a leader in rapid transit development, starting with America's first subway — part of the Green Line, which opened in 1897, and the second undersea tunnel, the East Boston Tunnel on the Blue Line, put in service in 1904. Both lines remain in daily use and are augmented by the area's commuter rail system. The subway tunnels were largely constructed by cut-and-cover methods with three notable exceptions.

*Early Subway Construction History.* A three-person Board of Subway Commissioners, subject to approval of the Boston City Council and appointed by the mayor, was created in 1893 by the state legislature to report on the

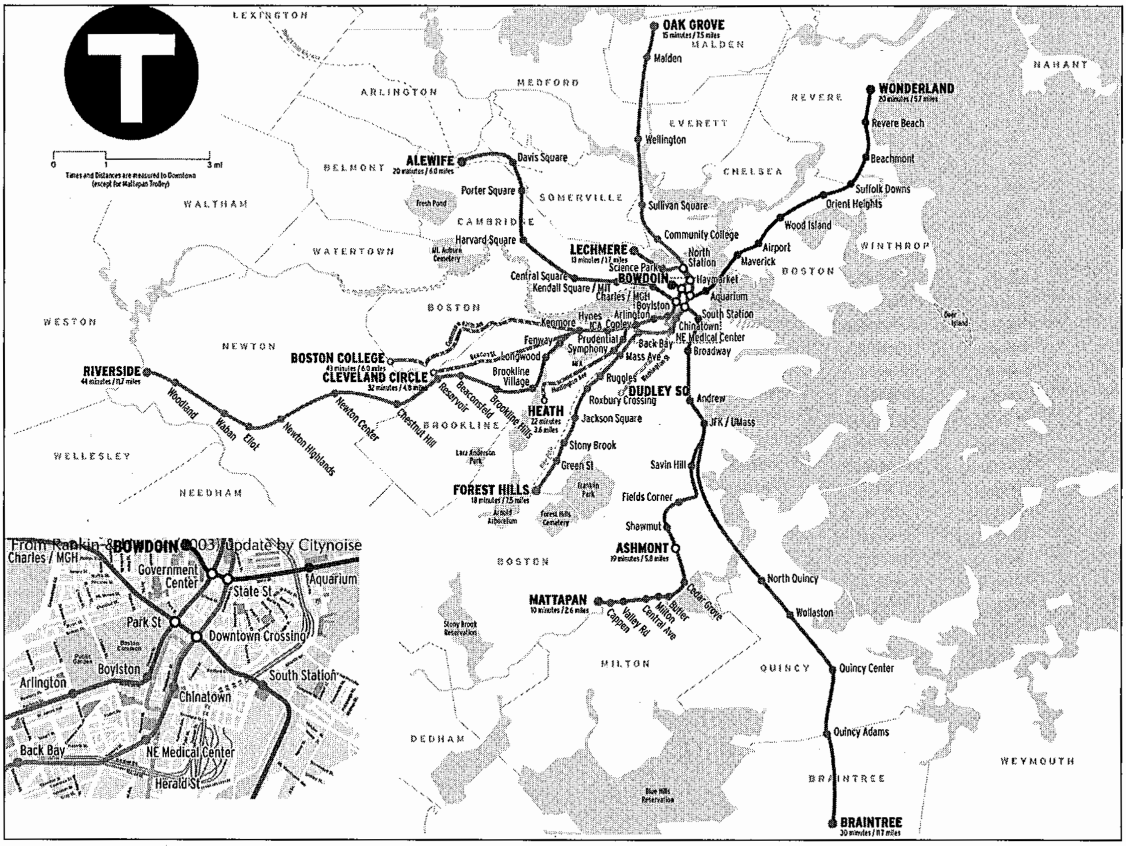



**FIGURE 6-1. Map of the Boston area showing routes of the MBTA system, July 2011.**

feasibility of building a subway under Boston Common for the purpose of removing streetcar traffic from Tremont Street. The council gave its consent, and the board was appointed on January 1, 1894. After hearing from critics and supporters of the subway, various technical experts in the construction, transportation and health fields, as well as from proponents of elevated railways, the legislature enacted a bill on July 2, 1894, to create the Boston Transit Commission and the Boston Elevated Railway Company. The Boston Transit Commission would be a governmental body whose primary function would be to construct the Tremont Street Subway, now part of the Green Line (see Figure 6-2). The Boston Elevated Railway Company, on the other hand, would be privately owned and charged with building elevated lines. The legislation required a local referendum, and Boston voters overwhelmingly approved the bill on July 24, 1894.

During the fall and winter of 1894-1895, the engineering staff of the Boston Transit Commission took the Tremont Street Subway from the planning phase to final design. Ground breaking took place on March 28, 1895, at a public ceremony presided over by the governor. Work progressed so rapidly that the first Tremont Street section beneath Boston Common was opened on September 1, 1897, from Park Street to a portal in the Public Garden, near Arlington and Boylston Streets. (see Figure 6-3). Two additional segments of subway were opened later. The leg under Tremont Street from Boylston Street Station to Pleasant Street (now Broadway in the Boston South End) opened on October 1, 1897, and on September 3, 1898, operations commenced on the final section to Haymarket near North Station (Whitehill, 1968) for streetcar traffic. The Haymarket end of the tunnel was connected by an elevated loop that circled to the east above Atlantic Avenue to connect South and North stations in 1901 (see Figure 6-4).

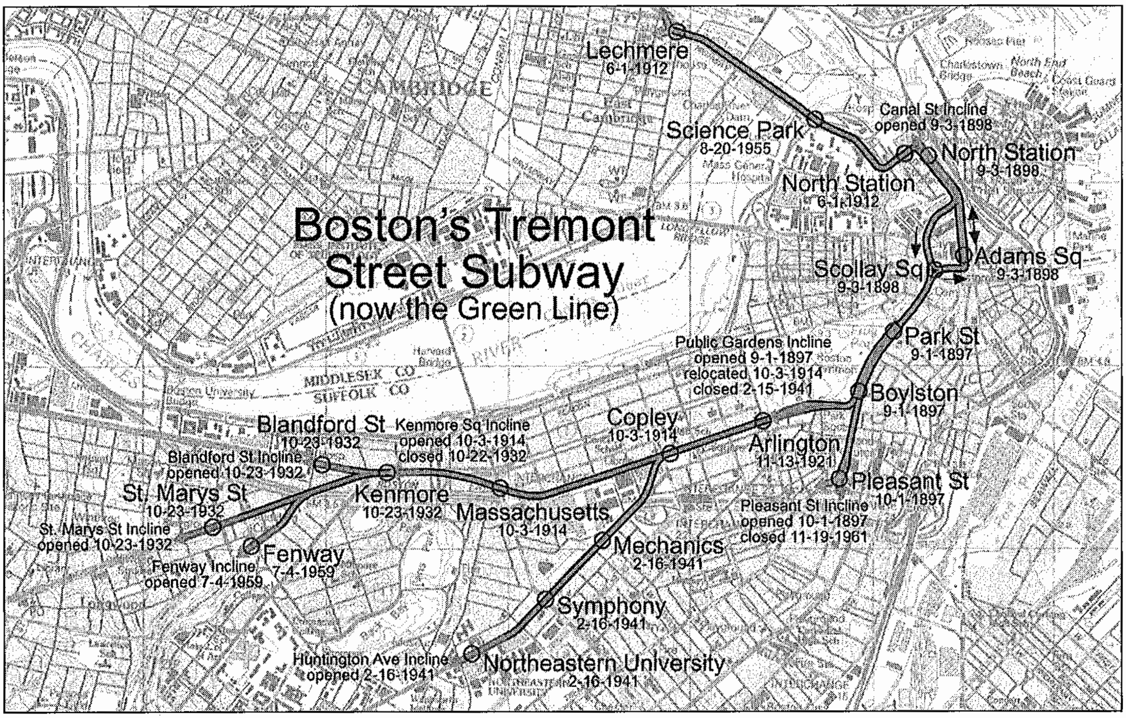



**FIGURE 6-2. Map of the Tremont Street subway (Green Line) showing gradual extensions and their dates of completion. (Courtesy of spuimap.)**

The original Boston Elevated Railway Act of 1894, which was amended in 1897, provided for a transit tunnel under Boston Harbor to East Boston and the Boston segment of a subway to Cambridge. The East Boston Tunnel, the first underwater transit tunnel in North America, opened for streetcar traffic in 1904. The tunnel, now part of the Blue Line, extended from Maverick Square, East Boston, to Court Street Station, near Scollay Square (now Government Center) in downtown Boston and allowed passenger transfer to the elevated train at a midway station at Atlantic Avenue and State Street.

A 2 kilometer (1.23 mile) long subway tunnel was then dug under Washington Street between 1905 and 1908 for the Sullivan-Dudley line and replaced the use of the Tremont Street Tunnel for service to Dudley Square. The Washington Street Tunnel, which follows the old Boston Neck, was opened for public use on November 30, 1908. Removal of high-platform and third-rail equipment (the third rail was never used) from the Tremont Street Subway began at once, and on December 4, 1908, streetcar service fully resumed through all parts of the subway that were formerly used by the high-platform trains of the elevated system.

The Boston Elevated Railway and the Boston Transit Commission shared joint responsibility for constructing a line to connect Park Street in Boston with Harvard Square in Cambridge. This line consists of a cut-and-cover Cambridge Tunnel from Harvard that rises on the Longfellow Bridge, crosses over the Charles River and then runs through a shield-driven, hand-mined tunnel under Beacon Hill and under the Park Street Station. This segment is now part of the Red Line (see Figure 6-1). The Cambridge section was built by the Boston Elevated Railway, but all sections in Boston were built by the Boston Transit Commission. Construction in Cambridge started July 12, 1909, on the first segment and the subway began operation on March 23, 1912. An extension to South Station, known as the Dorchester Tunnel, opened on December 3, 1916. A further extension, which opened on June 29, 1918, continued southward through a

**FIGURE 6-3. Construction trench for Tremont Street subway circa 1896. (Courtesy of the Society for the Preservation of New England Antiquities.)**

tunnel under Fort Point Channel to reach Andrew Square in South Boston.

The need for rapid transit service in the congested Back Bay area led to a proposal to construct a new subway line, which was approved by the state legislature in 1907. The bill specified that the facility be built under the Charles River Embankment and be known as the Riverbank Subway, with stations located at Charles Street, Dartmouth Street and Massachusetts Avenue. The Boston Elevated Railway strongly opposed the location of the Riverbank Subway, and abutting property owners, who were worried about the effects that the construction of the subway would have on sewers and other underground utilities, joined together and protested to the legislature. The protest succeeded and in 1911 the lawmakers abandoned the Riverbank Subway in favor of a line beneath Boylston Street. The Boylston Street Subway, now the Green Line, began construction in March 1912 for a two-track cut-and-cover tunnel, which would eventually run from a connection with the Tremont Street Subway near the Public Garden Incline to a portal in Governor Square, now Kenmore Square (see Figure 6-2). As part of the subway construction, the incline itself would be shifted to the middle of Boylston Street, parallel to its old location. The subway opened on October 3, 1914.

A short extension of the East Boston, streetcar based subway system took place between 1912 and 1916. The East Boston Tunnel, when originally opened, ran downtown to Court Street Station, which was a stub-end single-track terminal. Traffic volume through the tunnel increased tremendously over the years, and this single-track turn-back became an operational nuisance. The answer was a short 796 meter (2,610 foot) extension to Bowdoin Square. The tunnel runs through the deformed Pleistocene soil deposits of Beacon Hill (Boston Transit Commission, 1913; Kaye, 1976b), where an underground station, a loop and a surface incline to Cambridge Street were built. The loop allowed a quick turnaround for streetcars from East Boston, while the incline permitted cars to come to the surface and travel all the way through from Cambridge to East Boston. Streetcar tracks were laid across the Longfellow Bridge along with the subway in the center. The East Boston Tunnel Extension was opened on March 8, 1916. The Boston Transit Commission had by this time opened the East Boston Tunnel and its extension to Bowdoin, the Washington Street Tunnel, the Boylston Street Subway and the Tremont Street Subway.

In the late 1930s, the Boston Transit Department (which succeeded the Boston Transit Commission in 1918) began the Huntington Avenue Subway (see Figure 6-2), now a branch of the Green Line, through a variety of deposits (Aldrich & Lambrechts, 1986). This subway was a Work Projects Administration (WPA) program and was one of the first examples of major federal funding for local mass transit construction. Prior to the subway, the Huntington Avenue streetcar line ran from Forest Hills, past Northeastern University on Huntington Avenue to Copley Square and then on Boylston Street as far as the block between Arlington and Charles streets. At that point, the streetcars entered the portal to the Boylston Street Subway. The Huntington Avenue line was the last major surface streetcar route to run through this heavily congested section of the Back Bay, and its diversion into the new subway portal south of Massachusetts Avenue on February 16, 1941, shortened the running time considerably.

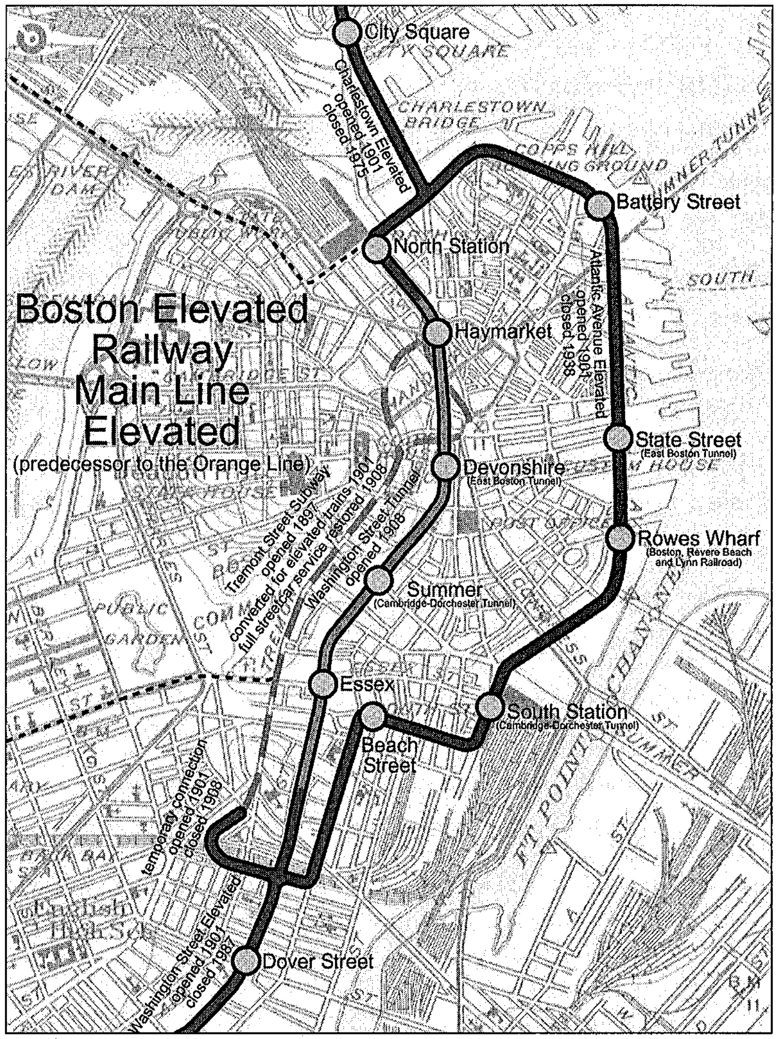



**FIGURE 6-4. Map of how the Boston Elevated Railway tied into the Tremont Street subway between Haymarket and south of Essex stations to make a transit loop through Boston. (Courtesy of spuimap.)**

The Public Control Act of 1918 was extended in 1931 under new terms, which reduced the rate of payment to the private owners of the Boston Elevated Railway and, among other things, provided for the eventual purchase of the company by the Commonwealth of Massachusetts. Popular sentiment grew over the years against publicly assisted payments to private shareholders for the use of a facility that was providing an essential public service and for which a fare was also demanded. The state purchased the Boston Elevated Railway in 1947 and reorganized it as the

Metropolitan Transit Authority (MTA). Two years later, on July 2, 1949, the functions, powers and personnel of the Boston Transit Department were transferred to the MTA, along with the title to the subways and other transit properties formerly held by the city of Boston. The MTA was an effective agency for the area it served, but its activities were limited to fourteen cities and towns. To form a mass transit operation with metropolitan responsibilities, the state legislature created the Massachusetts Bay Transportation Authority (MBTA), which superseded the MTA on August 3, 1964. The MBTA has much broader powers than its predecessor and greatly expanded responsibility, and it now serves seventy-nine cities and towns.

*Recent History of Subway Construction.* The Orange Line subway was extended from the end of the Washington Street Tunnel at Haymarket northward through a new immersed tunnel under the Charles River to Charlestown to replace the old Charlestown Elevated Railway, which had been in operation since June 10, 1901. The new tunnel, the Haymarket North Extension, opened April 7, 1975, and the elevated line through the center of Charlestown in Thompson Square to Sullivan Square was torn down the same year. Once through the tunnel under the Charles River, the Orange Line runs at grade along an existing railroad right-of-way to Oak Grove in Melrose. A major expansion of the MBTA took place between 1981 and 1987, with the construction of the Northwest Extension of the Red Line in Cambridge and Somerville and the Southwest Corridor for the Orange Line through Back Bay and Roxbury. A new subway station at Tufts New England Medical Center and a southwest relocation of the Orange Line (from the old 1908 Washington Tunnel at Kneeland Street and the Washington Street elevated line to Forest Hills in Jamaica Plain [see Figure 6-4) to the old Boston and Providence [Penn Central] railroad embankment) was part of a plan to redevelop the South Cove area (the area surrounding Back Bay Station) for urban renewal. The plan made use of land previously intended for the Interstate 95 highway extension into Jamaica Plain and Roxbury that was abandoned in 1972. The first part of the corridor was the South Cove Tunnel to carry the line beneath the Massachusetts Turnpike without interrupting the traffic flow during construction. The idea for the Southwest Corridor was conceived in 1964, the planning done in the period 1972 to 1979, the construction started in 1979 and the relocated Orange Line opened on May 4, 1987.

A Northwest Extension of the Red Line from Harvard Square was planned to go underground to the west edge of Cambridge and from there rise up to travel along an abandoned commuter rail line through Arlington to Lexington. Objections in Lexington and Arlington about concerns for increased traffic congestion succeeded in limiting the extension to present terminus at Alewife Brook at the western edge of Cambridge. The opening of the last segment of this extension took place on March 30, 1985.

The most recent tunnel construction was for bus and rapid transit travel between South Station and Logan Airport via the South Boston Seaport area, by passing under Russia Wharf, the Fort Point Channel and part of the South Boston flats. The Silver Line Bus Rapid Transit System was planned as part of improvements and expansion of the MBTA to link the Roxbury section of Boston with the downtown and the South Boston Convention Center area. The further link from Logan Airport to transport passengers to the Red Line subway at South Station uses the roadway of the Ted Williams Tunnel of the Central Artery/Tunnel Project. The surface section of the Silver Line from Roxbury was constructed as Phase I and uses buses along Washington Street. It was followed by the Phase II tunnel section from South Station to South Boston. Phase II originally was planned as the South Boston Piers Transitway and part of environmental mitigation for the Central Artery/ Tunnel Project (see Figure 6-1). It opened in December 2004, with a new name — the Silver Line, Waterfront Phase. The final route of a planned Phase III tunnel section to connect South Station with Boylston Station of the Green Line is controversial and yet unfunded. Ambitious plans have been in the works for two decades to extend the Blue Line from Bowdoin Station to connect with the Red Line at Charles/MGH Station.

During the Central Artery/Tunnel Project, the elevated Green Line near North Station was placed underground and the Canal Street incline and elevated railway along Causeway Street were demolished. This project principally consisted of a joint North Station Superstation for both the Green and Orange lines, as well as re-routing the Green Line beneath the new TD Garden arena to a new portal near the Zakim Bunker Hill Bridge.

## Geology & Construction Methods of Subway Tunnels

The subways were constructed chiefly in a variety of soft ground conditions that vary from marine clay to lodgement till as they passed under the Shawmut Peninsula and the filled areas of the Back Bay and the Boston Neck. Only rarely were subways dug through bedrock.

*Tremont Street Tunnel of the Green Line.* A surface excavation method was chosen for the Tremont Street Tunnel rather than a deep tunnel as used for the London subway. The innovative building of a tunnel in a ditch, dug by pick and shovel, established what is now called the cut-and-cover method (see Figure 6-3), which has since been widely used. A framework of steel beams and concrete was constructed in the excavation, and covered by an arched roof of brick and concrete and then buried. The 2.4 kilometer (1.5 mile) long tunnel between Boylston and Haymarket skirts the edge of Beacon Hill and is through deformed till, clay and outwash (Kaye, 1961). It encountered some difficulty with sand flowing into the trench, but this problem was solved by bulkheads. Another quite unusual problem developed in the discovery of 910 bodies in unmarked colonial graves off the edge of the Granary, or Old Common, Burial Ground (Cudahy, 2004). At the other end near Haymarket, the tunnel is through a filled tidal flat area. It took three and a half years to complete the entire tunnel between 1895 and 1898.

*East Boston Tunnel of the Blue Line.* Construction on the East Boston Tunnel, which passes under Boston Harbor to connect Boston with East Boston, began in 1900 and was completed on December 30, 1904 (see Figure 6-1). The original tunnel was 1,600 meters (5,280 feet) in length, of which 823 meters (2,700 feet) are under water. It was originally used for streetcars, but it was converted over one weekend to rapid transit subway cars in 1924. One end of the tunnel was located in Maverick Square in East Boston, where a portal (now closed) allowed the streetcars to run as a surface line. From East Boston, the tunnel runs under Boston Harbor to Long Wharf and up State Street and ended at what was then called Court Street Station (also now closed). The streetcars could exit onto Cambridge Street near Russell Street in Bowdoin Square through a portal (closed in 1924, and abandoned and filled in 1952), and then travel to and across the Longfellow Bridge. The tunnel was dug using a tunnel shield under pressure. The shield rolled forward on concrete footings laid down ahead in two small pilot tunnels. The tunnel was the first to be built entirely of concrete with no steel framing (Cheney, 2002). The tunnel leaked and had to be grouted nightly for many years following construction.

The tunnel was constructed in mainly Pleistocene glacial sediments varying from marine clay under the harbor and the glaciomarine deposit along both waterfronts, to the deformed clay and sand around Beacon Hill (Crosby, 1903; Kaye, 1976b). From Bowdoin (including the Cambridge Street portal) to State and Court streets, the tunnel encountered a till consisting of mostly silty sand; stratified sand; deformed and mixed deposits made up of pervious outwash and deltaic sand, marine clay and till; and argillite in the West End, which included Bowdoin Square, where the bedrock is close to the surface. From State Street easterly to the Aquarium Station (formerly the Atlantic Avenue Station) on the waterfront, the tunnel was constructed through the till on the east side of Beacon Hill to Court Street and a variety of deposits found under the original shoreline of Boston. These deposits consist of fill, organic sediment, marine clay, outwash sand, glaciomarine sediment and till. The Central Artery/Tunnel Project cross-sections show these complex deposits well. The tunnel from the filled-in waterfront was constructed under the Boston Harbor through the marine clay and entered Maverick Square Station in East Boston. In this area, the underlying material is similar to the west side since Maverick Square is also located on filled land just northwest of the Camp Hill drumlin. The Blue Line was extended under the north end of the Camp Hill drumlin in 1952 to provide a station for the expanding Logan Airport (see Figure 3-92). The Blue Line tunnel was connected (from 1952 to 1954) to the old narrow-gauge Boston-Revere Beach-Lynn Railroad.

*Beacon Hill & Cambridge Tunnels of the Red Line.* The 5,183 meter (17,000 foot) long subway system between Park Street Station and Harvard Square had tunnel construction on either side of the Charles River (see Figure 6-1). In order to connect the recently built Tremont Street subway to the new Cambridge subway, the Boston Transit Commission constructed a tunnel through Beacon Hill as the Cambridge Connector, during the period 1909 to 1911. The Longfellow Bridge had previously been built in 1907 over the Charles River from Charles Circle in Boston to the Cambridge side just east of Kendall Square. The bridge was intended to convey trains, in addition to vehicular and pedestrian traffic. The Cambridge trains entered the subway just before Kendall Square and traveled westerly underground past the Central Square Station to terminate at Harvard Square.

The Beacon Hill tunnel extended from the Park Street Station to Phillips and Grove streets, a distance of 762 meters (2,500 feet) along a 1,453 meter (4,000 foot) radius arc. The tunnel passed diagonally from the southeast to the northwest under the remnants of the original Mount Vernon and Beacon hills. Historical records reported that "it was constructed through a very hard mixture of sandy clay containing numerous small stones, and occasionally boulders" (Colby, 1912). This description best fits the slices of lower till found in Beacon Hill. The tunnel intercepted "artesian" wells dating back to colonial times that necessitated the use of a 578 kilonewton (65 ton) thrust hydraulic roof shield pushing a 9.8 meter (32 foot) diameter bore. Two tubes 6 meters (16 feet) high and 7.5 meters (25 feet) wide were constructed with an arched roof of concrete. The deepest point of the tunnel was 30 meters (100 feet) below the ground surface where it passed beneath the hill.

A 90 meter (300 foot) long open cut was dug where the tunnel exited what was once the northern slope of Mount Vernon. The deposits encountered would be expected to be similar to both the organic silt and marine clay associated with the original shoreline of Boston found in the area of the Massachusetts General Hospital and the northern edge of Mount Vernon, and the sand and till found under Strong Place and the nearby Holiday Inn. The tunnel would then have been bored through the lower till, deformed lower outwash sand and clay under Trimountain and the Boston Common to Park Street Station. Pictures of the excavations at the State House and at Park Street, as well as observations of the deposits encountered during excavations to construct the Under Common Garage on Charles Street, support this conclusion (see Figures 3-81 & 3-83). The artesian wells encountered also indicate that pervious sand and gravel is present under Trimountain.

The tunnel between Kendall and Harvard squares on the Cambridge side of the river (for the Cambridge Main Street Subway) was built by the cut-and-cover technique developed fifteen years earlier. The work force averaged 2,500, but up to 4,000 workers at a time were employed. Near Harvard, the finished tunnel consisted of two stacked tunnel boxes, each 4.9 meters (16 feet) high by 7.6 meters (25 feet) broad, with the outbound track the higher one (Anon., 1911). The Cambridge tunnel crosses an area consisting primarily of marine clay, with varying amounts of upper outwash sand and gravel. The subway to Harvard Square opened March 23, 1912.

*Boylston Street Tunnel of the Green Line.* The Boylston Street Subway crosses Back Bay from the south end of the Tremont Street Tunnel to Governor (now Kenmore) Square several blocks west of Massachusetts Avenue (see Figures 6-3 & 6-5). The excavation became well known because of the discovery of fish-weirs near Dartmouth Street (Boston Transit Commission, 1913) and its depiction in the novel *Back Bay* by William Martin (1979). The invert of the subway varies from approximately an elevation 0.9 meters (3 feet) Boston City Base (BCB) at Massachusetts Avenue, to its lowest point at elevation –5 meters (–19 feet) BCB between Arlington Street and Hadassah Way, thence to elevation –3 meters (–10 feet) BCB at Charles Street (Aldrich & Lambrechts, 1986) (see Figure 6-5). Ground surface along Boylston Street is generally elevation 17 BCB from Charles Street to Gloucester Street.

The structure is underlain by a wide variety of deposits including the fill, organic silt and upper sand and gravel outwash (see Figures 4-5 & 6-5, & Table 6-1). Peat encountered between approximately Hadassah Way and Charles Street — a distance of 140 meters (460 feet) — necessitated wood piles to support the structure (Aldrich & Lambrechts, 1986). Aldrich and Lambrechts (1986) researched the engineering geology and reported on the geologic conditions as described by L.B. Manley, Assistant Engineer for the Transit Commission:

"As is well known, the land reclaimed from the Back Bay consists of sand and gravel filling resting on a bed of silt whose upper surface lies at about grade 0, Boston City Base, or grade 100, Boston Transit Commission Base. This layer of silt is continuous throughout the length of the subway, and attains a thickness of about 5.2 meters (17 feet) at Dartmouth Street, and over 6.1 meters (20 feet) in the Fens. Between Exeter Street and Charlesgate East and between Clarendon Street and Charles Street, where it finally disappears, it averages about 2.4 meters (8 feet) in thickness. Below the silt between Massachusetts Avenue and Hereford Street, and at Exeter Street, are pockets of peat from 0.6 to 1.2 meters (2 to 4 feet) in thickness. Another extensive body of peat occurs between Arlington and Charles streets, where it attains a great depth.

"Below the silt and peat is a stratum of sand and gravel which also extends throughout the length of the subway excavation except for a length of about 488 meters (1,600 feet) between Exeter and Clarendon streets. This sand and gravel carries large quantities of water laden with sulphurated hydrogen, which has been offensive to passersby and injurious to the health of those working in it. This gas, as it leaves the surface of the water, is particularly destructive to metal, and copper floats in several of the temporary pump wells have been corroded through at the surface of the water in a few weeks' time by the action of this gas. It is supposed that this layer of gravel is the same as that which appears in the bed of the Charles River and affords an underground water course which tends to equalize the level of the ground water in the Back Bay."

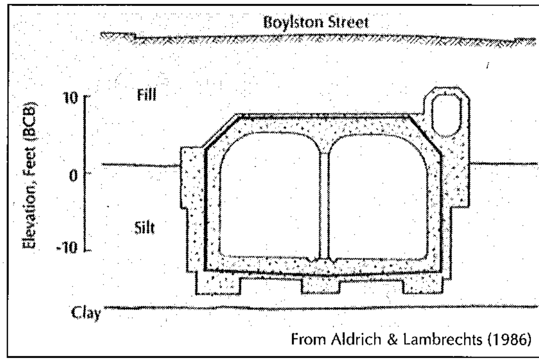



**FIGURE 6-5. A section of the Boylston Street Subway between Berkeley and Clarendon streets at Station 58+00.**

The sand and gravel layer is part of the same Lexington Outwash found at the nearby Gravelly Point on Massachusetts Avenue. A temporary drawdown of water levels both in the fill and in the lower sand and gravel stratum would have occurred during construction (Aldrich & Lambrechts, 1986). The drawdown in the sand stratum is estimated to have reached elevation –3 meters (–10 feet) BCB where the subway route passed opposite to what is now the Prudential Center.

Special care was needed alongside the Old South Church to prevent a further tilt of its tower, which was taken apart and rebuilt due to excessive settlement (Boston Transit Commission, 1913). Problems with its foundations had caused the tower to lean soon after it was built from 1872 to 1873.

*Dorchester-Fort Point Channel Tunnel of the Red Line.* The Boston Transit Commission completed the Dorchester Tunnel in 1915 from

**TABLE 6-1.**
**Geologic Material Along the Boylston Street Subway**

| Location | Approximate Station | Elevation Top of Rail (ft, BCB) | Soil Conditions at Bottom of Subway |
|---|---|---|---|
| Kenmore Street (at Commonwealth) | 0+00 | 16.2 | Sand & gravel fill underlain by silt |
| Charlesgate West (at Commonwealth) | 6+00 | –8.7 | Silt underlain by sand and gravel |
| Charlesgate East (at Commonwealth) | 10+00 | –18.9 | Sand & gravel, short section of clay |
| Massachusetts Avenue (at Newbury Street) | 19+32 | 7.5 | Sand & gravel fill underlain by silt |
| Hereford Street | 27+15 | 7.7 | Silt over sand & gravel |
| Gloucester Street | 31+55 | 1.9 | Sand & gravel |
| Fairfield Street | 37+15 | 4.8 | Sand & gravel |
| Exeter Street | 43+75 | –6.4 | Silt over sand & gravel |
| Dartmouth Street | 49+80 | –6.5 | Silt over thin peat over thin sand & gravel |
| Clarendon Street | 56+05 | –8.8 | Silt over thin peat |
| Berkeley Street | 62+25 | –13.0 | Sand & gravel |
| Arlington Street | 69+10 | –14.5 | Clay |
| Hadassah Way | 73+35 | N –14.0<br>S –11.2 | Fairly hard blue clay<br>Peat between Hadassah Way & Charles Street |
| Charles Street | 78+00 | N –4.2<br>S –5.0 | Blue clay & gravel |

**Notes:** From Aldrich & Lambrechts (1986). All elevations BCB. Information was obtained from Boston Transit Commission Plans Nos. 10219, 10386, 10091, 10418,11157, 11159, 11161 & 11162 of the "Boylston Street Subway." The bottom of subway structure varies from 1.2 to 1.7 meters (4 to 5.5 feet) below top of rail. The subway is supported on wood piles from Station 71+82 to 76+41.

Park Street Station to South Station (then called Dewey Square) and from there beneath the Fort Point Channel to the Broadway Station in South Boston (Boston Transit Commission, 1914), with service on the surface initially from Broadway to Ashmont. The tunnel was later extended to Andrew Station (see Figure 6-1). The Dorchester Tunnel, which intersected the Washington Street Tunnel at Summer Street, is 3.6 kilometers (2.3 miles) long and was constructed as a cut-and-cover tunnel on land, with shield-driven segment under the Fort Point Channel for 0.5 kilometers (0.3 miles). New subway stations were constructed at Chauncey Street (now Downtown Crossing) and Dewey Square (now South Station). The materials removed from the tunnels were used to fill in South Boston or were dumped at sea.

The cut-and-cover tunnel encountered clay with sand and what was called hardpan consisting of sand, gravel and clay. These findings are consistent both with the glaciomarine deposits found in the South Station area in the Central Artery/Tunnel Project borings and the hard clayey till observed by Woodhouse in the caissons for the 100 Summer Street (the Blue Cross-Blue Shield Building). The tunnel under Fort Point Channel was driven using a 7.3 meter (24 foot) shield, hydraulic jacks and compressed air pressure (Cohill, 1916). The depth of the tunnel is approximately 6 meters

**TABLE 6-2.**
**Geologic Material Along the Huntington Avenue Subway**

| Location | Approximate Station | Elevation Top of Rail (ft, BCB) | Soil Conditions at Bottom of Subway |
|---|---|---|---|
| Massachusetts Avenue | 13+85 | –6.0 | 12 ft hard packed coarse sand |
| Cumberland Street | 21+50 | –10.9 | 11 ft hard packed coarse sand & gravel |
| West Newton Street | 26+65 | –13.0 | 7 ft hard packed sand & gravel |
| Garrison Street | 32+00 | –13.1 | 4 ft hard packed coarse sand |
| B&A Railroad Tracks (Massachusetts Turnpike Extension) | 37+50 | –13.6 | Hard yellow clay (sand pinches out at Station 37+50) |
| Blagden Street (& Exeter Street) | 41+30 | –10.7 | 4 ft silt over medium blue clay & sand |
| Boylston Street (& Exeter Street) | 44+50 | –6.9 | 4 ft peat over 8 ft fine sand over stiff blue clay |

**Notes:** From Aldrich & Lambrechts (1986). All elevations BCB. Information was obtained from Boston Transit Commission Plans Nos. 17947, 17943, 17936, 17933 & 17914 of the "Huntington Avenue Subway, Plan & Profile." The bottom of subway structure varies from 1 to 1.8 meters (3.5 to 6 feet) below top of rail. Footings, pedestrian passageway (Massachusetts Avenue) and bottoms of catch basins are deeper.

(20 feet) below the bottom of the channel at an elevation –15.2 meters (–50 feet) BCB, according to the Boston Transit Commission report of 1916. Soil under the Fort Point Channel consists of fill and harbor mud overlying stiff blue marine clay and the hard sandy clay till (Cohill, 1916). The tunnel excavation was primarily through the clay.

*Huntington Avenue Tunnel of the Green Line.* The Huntington Avenue Subway, which is now a branch of the Green Line, was constructed between 1937 and 1940 (see Figure 6-2). The surface Green Line enters the subway at Northeastern University just west of Massachusetts Avenue, crosses under Massachusetts Avenue as it enters Back Bay, and joins the Boylston Street subway at Exeter Street in Copley Square (see Figure 6-1). Within this area, the invert of the subway structure varies from elevation –3 meters (–10 feet) BCB at Massachusetts Avenue down to elevation –5.8 meters (–19 feet) BCB where the structure passes below the railroad tracks and under the Massachusetts Turnpike Extension (Aldrich & Lambrechts, 1986).

Aldrich and Lambrechts (1986) described the surficial deposits along the subway (see Table 6-2). The upper outwash sand and gravel, which is the Lexington Outwash, extends from 1.5 to 3.7 meters (5 to 12 feet) below the bottom of concrete from Massachusetts Avenue to the Massachusetts Turnpike. North of the turnpike to Boylston Street, the structure bears without piling on the organic deposit and the marine clay typically found in the Back Bay. During construction, it was necessary to dewater the highly permeable outwash for the entire length of the subway along Huntington Avenue to elevations as low as, or even below, –6.1 meters (–20 feet) BCB. It was noted that a very significant drawdown of the water level for a period of two to three years occurred over a wide area. The level in an observation well at Massachusetts and Commonwealth Avenues 0.6 kilometers (0.4 miles) away was reported to have dropped from elevation 2.1 meters (7 feet) to elevation 0 BCB in 1939. In fact, construction for the Huntington Avenue Subway required extensive and prolonged dewatering to levels below any known construction before or since (Aldrich & Lambrechts, 1986), which is significant because major construction around Copley Square has occurred since the subway was built, including the Prudential Building and Center, the Christian Science Complex, the John Hancock Building, and the Westin Hotel and Copley Place Development. Only one major additional building in the Prudential Center on Huntington Avenue has been constructed after 1986 and it had no significant impact on water levels. In addition, drains installed in the tunnels of both subway lines have undoubtedly collected groundwater that leaks into the structure, but data on groundwater levels reported in the section on the Boston Groundwater Trust information website (www.bostongroundwater.org) have not shown notable lowering in the period 2000 to 2012.

*Haymarket North Extension Tunnel of the Orange Line, Green Line Tunnel & North Station "Superstation."* With the construction of the Washington Street Tunnel, completed in 1908, the end of the MBTA Orange Line exited the subway tunnel at Friend-Union Station and climbed the Canal Street incline subway alongside the Green Line to the elevated portion over Causeway Street at North Station. The elevated Orange Line then proceeded across the Charles River over the North Washington Street Bridge (see Figure 6-4) toward Charlestown and followed above Main Street and Thompson Square to the terminal at Sullivan Square. The Green Line used the same incline from Haymarket Square Station to North Station, where it continued northwestward by another elevated viaduct to Cambridge.

The expansion and modernization of the Orange Line included the construction and expansion of the line to Melrose along with construction of a "superstation" at North Station. The first phase, the Orange Line Extension, was carried out between 1966 and 1977, which at that time was considered to be the most complex transit engineering project ever undertaken in the country. The expansion of the Orange Line was called the Haymarket-North Extension Project and it had a total length of 9.5 kilometers (5.9 miles) from Haymarket Square to the Malden-Melrose line. The first construction phase of the Orange Line ran underground through a two-track tunnel built in two sections for a total length of 1,380 meters (4,520 feet). It consisted of a cut-and-cover tunnel that followed Haverhill Street from Haymarket north to Causeway Street where the original complex for the future North Station "Superstation" was built. The cut-and-cover tunnel then continued down Accolon Way until it reached the Charles River. This area from Haymarket to Causeway Street was once a part of the old Mill Cove and Mill Dam that was filled in the early 1800s with the city's street sweepings, shells and till excavated from the top 12 meters (40 feet) of the west and north sides of Beacon Hill. Soils encountered in the tunnel consisted of the fill, organic silt and clay, which locally appeared to be glaciomarine in origin. The Orange Line was constructed under Accolon Way to Charlestown and then on the surface to Melrose. Problems developed with the open cut along Accolon Way that resulted from the use of steel sheet piling for excavation support. The Empire Carpet building that was next to the cut, and to the rear of the Railway Express building on Accolon Way, settled. Lateral movement of the Empire Carpet sheeting was 13 centimeters (0.5 feet) and settlement was 27 centimeters (0.9 feet). The structure was on timber piles and the first floor slab was an asphalt on grade. The silts washed out under the slab and the carpets that had been stacked on end collapsed and fell through the masonry wall.

H. Russell recollected in 2012 that the sheeting had numerous holes, and Lambe (1970) considered the role of groundwater to be most important. Lambe also found that significant movement occurred below the bottom of the excavation, and he attributed these movements to clay consolidation. In addition, Lambe showed that:

- The thrust from water pressure and the effective soil stress were significant.
- Groundwater flow analysis was complicated by the soil layering that caused differing permeabilities, and that there was leakage of water through the sheeting.
- The measured pore pressure was far below the static values, but that steady state seepage analysis gave reasonable prediction of water pressure.
- Groundwater levels affected key factors in excavation support design such as pore

pressure, soil stress, strut loads and wall movement.

Because the 12 to 18 meter (40 to 60 foot) deep Orange Line Tunnel excavation through Accolon Way was in close proximity to the foundations of the old Boston Garden and the Anelex Building, these structures had to be underpinned using one-hundred and fifty-five 890 kilonewton (100 short ton) piles driven to a depth of refusal at 14 to 20 meters (45 to 65 feet) where they penetrated into the glacial till. Uncovering and examining the old Simplex piles supporting the buildings, Woodhouse found that some of these original cast-in-place piles showed "necking" and, hence, had provided little or no foundation support to the original building.

The Charles River crossing was accomplished by the use of twin prefabricated steel tunnels lined with reinforced concrete and separated by concrete. Construction took place between October 1971 and July 1973. Dimensions of the tunnel sections were 9.8 meters (32 feet) in length, 11.4 meters (37.5 feet) wide and 6.9 meters (22.5 feet) high. Their tops were submerged 5.5 meters (18 feet) below low tide. Dredging for the immersed tubes was through river muck and clay. The tunnel exited to the surface at the Prison Point Bridge and Community College Station in Charlestown. Since it was in close proximity to footings for what was then the elevated Central Artery, these foundations had to be underpinned using caissons drilled 3.7 meters (12 feet) into the bedrock. The Charles River Tunnel was opened to subway traffic on April 7, 1975. The seventy-four-year-old elevated Orange Line structure was considered a "black serpent of blight" on the landscape through Charlestown and was demolished between 1975 and 1976.

The second major part of the work was making a better connection with the existing underground station of the Orange Line by building the so-called "superstation" adjacent to North Station. This superstation, which was constructed in stages between 1991 and 2005, involved the demolition of the old Boston Garden arena, the removal of the east Cambridge viaduct on Causeway Street and the enlargement of the underground station at North Station to include a common station for the Orange Line and the Green Line. The Green Line connection to the Lechmere Viaduct was placed underground around North Station as part of the Central Artery/Tunnel Project. The old Canal Street incline from the Haymarket Station and the remaining 0.8 kilometers (0.5 mile) of elevated railway along Causeway Street that was built in 1912 were taken down. As part of the project, a six-story underground garage was constructed under the arena with the use of slurry walls and load bearing elements for the future Boston Garden (now called the TD Garden).

The two lines were built adjacent and parallel through the station in order to allow cross-platform transfers and access to North Station and the sports arena. The station was excavated more than 15 meters (50 feet) deep through mainly old fills north of Haymarket. A Green Line tunnel was excavated farther north before swinging west under the new TD Garden arena and rising to cross over the viaduct. Caissons drilled 3 meters (10 feet) into the argillite bedrock for TD Garden, and the Green Line below it, encountered hard diabase dikes within the argillite bedrock that were reported to have slowed drilling from as much as 8 meters per day to less than 1 meter per day (25 feet per day to 3 feet per day) (Haley, 2013; Cardoza, 2013).

*Southwest Corridor Tunnel of the Orange Line.* A proposed extension of Interstate 95 into Boston was abandoned in 1972 due to public opposition and a moratorium imposed by then-Governor Sargent on further highway construction in Boston. This change left the acquired right-of-way, from which many structures had been cleared, unused. Money set aside for this cancelled Southwest Expressway Highway Project then was redirected by the Massachusetts Legislature for the construction of a relocation of the Orange Line from the elevated structure over Washington Street to this right-of-way (see Figure 6-6). Construction began in 1979 and the Southwest Corridor opened to much fanfare in 1987. This project finally allowed the elevated Orange Line and the remaining old Washington Street Elevated railway (which ran from Forest Hills

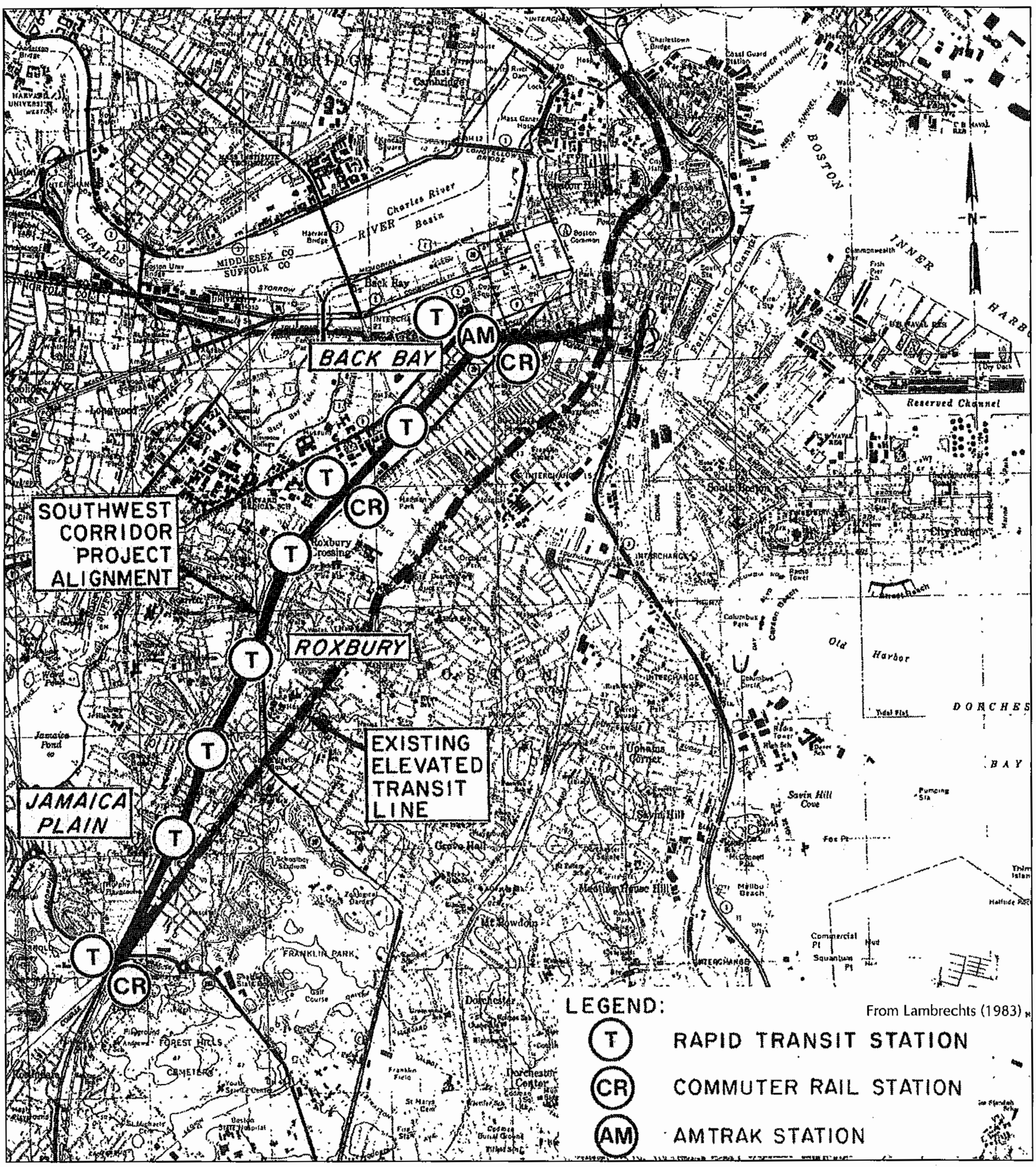



**FIGURE 6-6. Location of the Southwest Corridor Project of the Orange Line Subway. The Amtrak station is the Back Bay Station.**

through Roxbury to downtown Boston) to be demolished. The old Washington Street Tunnel was re-routed into the new corridor in May 1987 via the South Cove Tunnel. The corridor is a shared route with two tracks for the relocated Orange Line subway and three tracks for MBTA commuter rail and Amtrak service. The alignment through Back Bay follows parts of two original railroad embankments that were constructed across the Receiving Basin in the mid-1830s. From Massachusetts Avenue to Dartmouth Street (Back Bay Station), the new concrete structure was built below ground (see Figure 6-7) in a 915 meter (3,000 foot) long cut-and-cover tunnel that required excavations as deep as 11.6

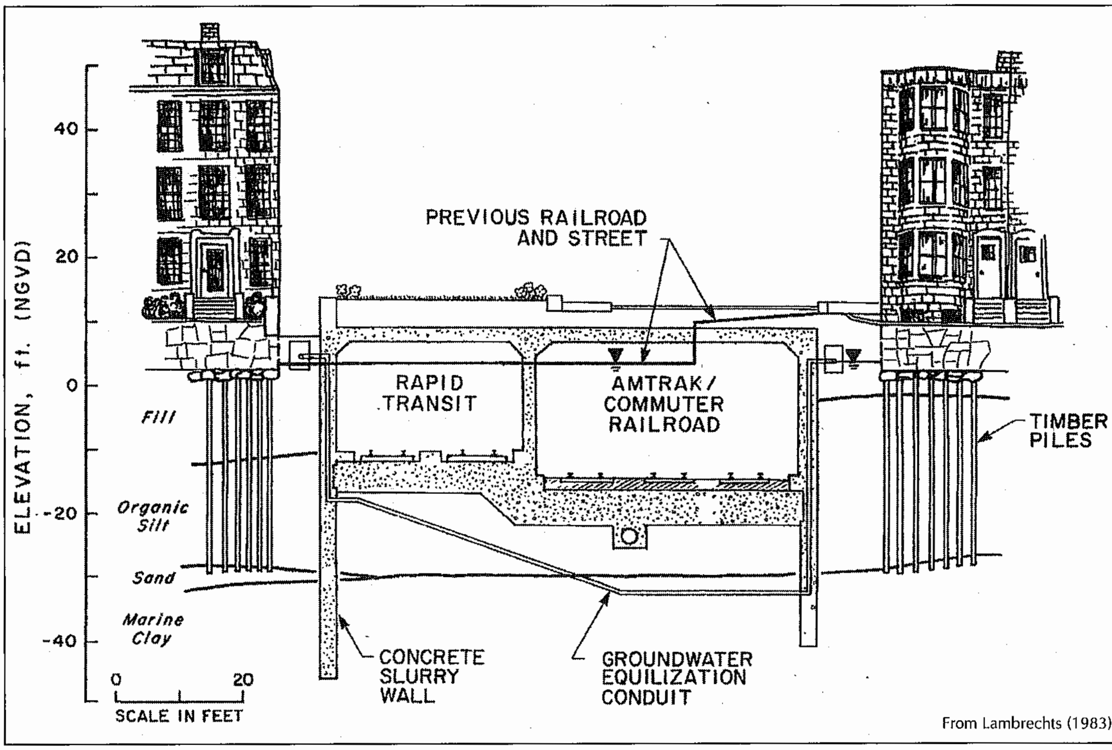



**FIGURE 6-7. Typical section of the Southwest Corridor Project of the Orange Line through the Back Bay.**

meters (38 feet). East of Dartmouth Street, the structure extended about 3 meters (10 feet) below the former grade. The 7.25 kilometer (4.5 mile) long project is 24 to 30 meters (80 to 100 feet) wide. About 30 percent of the corridor is roofed over and buried, and the rest of it has been designed to accommodate a future deck.

The corridor tunnel traverses the Boston Pleistocene sequence in the Back Bay (see Figure 6-8) and into the inland glacial sequence in Roxbury and Jamaica Plain (Lambrechts, 1983). The soft marine clay and organic deposit of the Back Bay were particular concerns in the project and layers of very peaty silt up to 1.5 meters (5 feet) were encountered in the latter.

Reinforced concrete slurry walls were used for lateral support for about 640 meters (2,100 feet) of the tunnel excavation (see Figure 6-7). The 1 meter (3 foot) thick concrete walls penetrated 2.4 to 4.6 meters (8 to 15 feet) into the clay stratum of the Back Bay and serve as the tunnel's permanent walls. Depth of slurry wall penetration was established depending on strength of the crust of the marine clay that was determined by test borings made for each of the 6 meter (20 foot) long slurry wall panels. The crust has superior end-bearing support properties (see Figure 6-9), where present. Some minor amounts of water leakage occurred through a few of the vertical joints between wall panels. This leakage is common and has been observed on other construction projects in Boston with similar excavation support walls, but there was no appreciable lowering of groundwater levels in adjacent areas. In other deep excavation areas where adjacent structures were farther away from the excavation or absent, steel sheet-piling was used for temporary lateral support of the excavation. East of Dartmouth Street, excavations were shallower and soldier piles with wood lagging were used. Water seepage into these excavations temporarily lowered groundwater levels (Aldrich & Lambrechts, 1986) in adjacent areas as much as 3.7 meters (12 feet).

According to Aldrich and Lambrechts (1986), where concrete slurry walls were used,

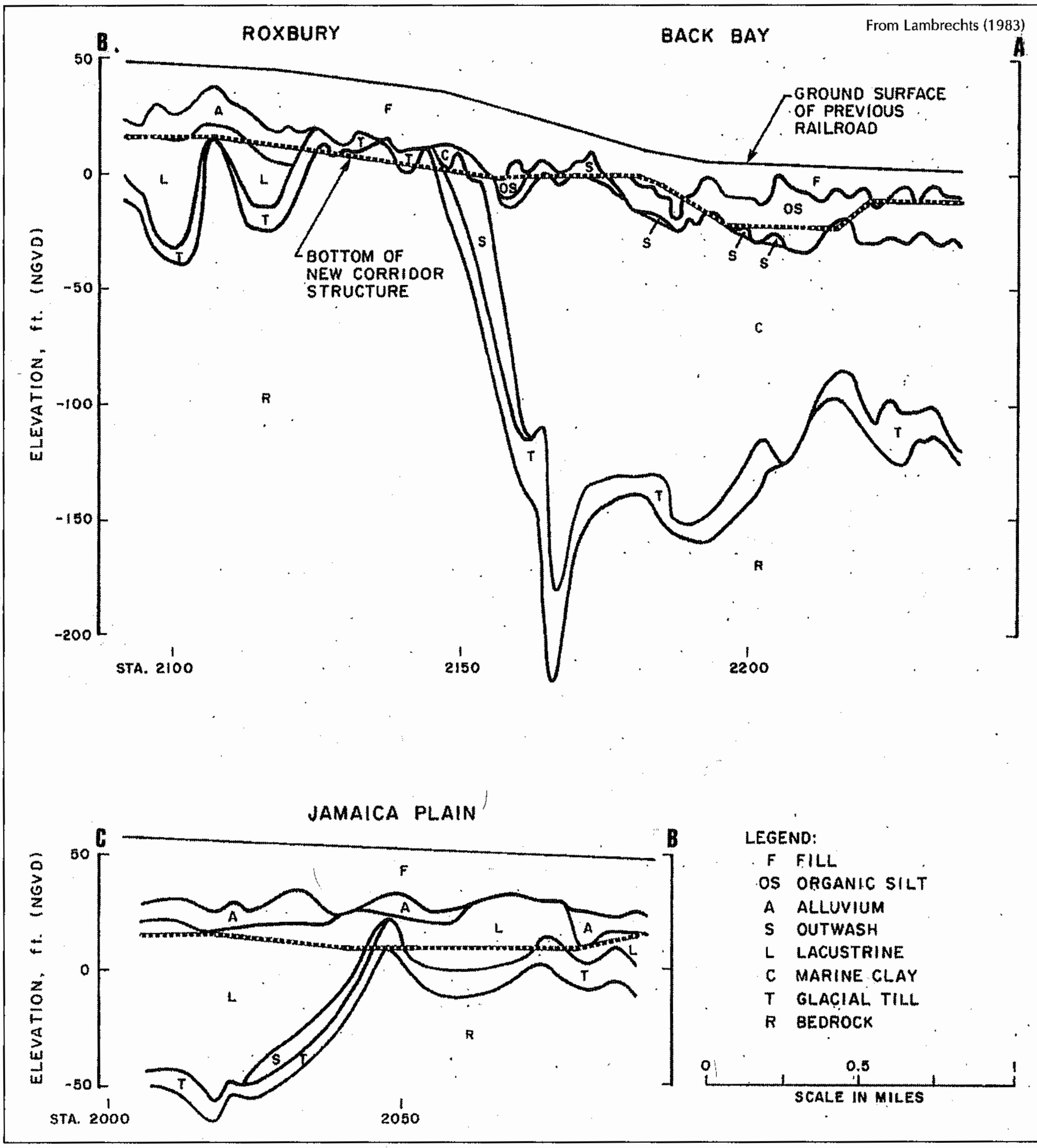



**FIGURE 6-8. Section along the Southwest Corridor from the Back Bay to Jamaica Plain showing geologic units and tunnel depth. The Back Bay portion shows the Pleistocene sequence of Boston: undivided upper and lower till (T), local lower outwash (S), marine clay (C), patchy upper outwash (S) and organic deposit (OS). The Roxbury to Jamaica Plain portion shows inland sequence of till (T), lacustrine silt and fine-grained sand and minor clay (L) and alluvium (A). The lacustrine deposit is approximately the same age as the lower outwash.**

the tunnel is supported on a thick concrete invert slab bearing on compacted sand and gravel fill, which was used to replace compressible and unsuitable organic soils (see Figure 6-9). East of this portion of the tunnel, the structure was supported on pre-cast, prestressed concrete piles driven through the clay to end bearing on till or bedrock.

In order to allow the natural groundwater flow across the corridor structure (which

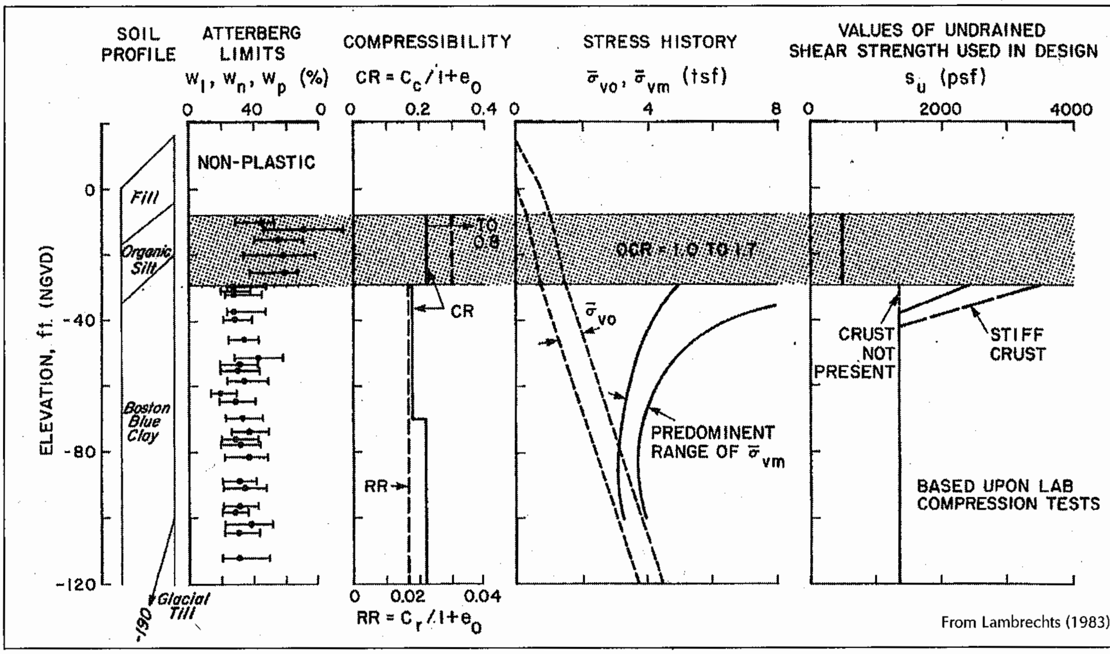



**FIGURE 6-9. Engineering characteristics of the surficial deposits along the Southwest Corridor.**

would form a hydraulic barrier), a groundwater equalization under-drain system was installed (see Figure 6-7). This system consisted of longitudinal drains placed 0.6 to 1.2 meters (2 to 4 feet) below the pre-construction groundwater level along either side of the structure. Where slurry walls formed the tunnel walls, 20 centimeter (8 inch) diameter header pipes surrounded by crushed stone were connected to 20 centimeter (8 inch) galvanized steel pipes cast into the walls and connected beneath the invert slab. In other areas, rectangular drains of crushed stone wrapped in filter fabric were constructed beneath the invert slab and up the outside of each wall in order to allow water to flow between longitudinal drains on either side (Aldrich & Lambrechts, 1986).

The Southwest Corridor Project includes the large Back Bay Station, which extends from Clarendon Street to Dartmouth Street, for combined Amtrak, commuter and subway train service. The station construction extended under part of an eight-story building (see Figure 6-10) and replaced some caisson support of the building by a "C"-shaped load transfer (Lambrechts, 1983).

*South Cove Tunnel of the Orange Line.* The Orange Line beneath Washington Street connects to the new Southwest Corridor (see Figure 6-11) by way of the South Cove Tunnel and the previously constructed South Cove Station (now called the Tufts New England Medical Center). The tunnel is approximately 0.77 kilometers (0.5 mile) long and consists of 444 meters (1,450 feet) of cut-and-cover on the north end, 107 meters (350 feet) of twin tunnels under the Massachusetts Turnpike and 221 meters (725 feet) of cut-and-cover on the south end (Stacho, 1968). Because of the concern for settlement of the overlying roadway, the top of the 4 meter (12 foot, 11 inch) high tunnel box (inside height) was to be no less than 0.46 meters (1.5 feet) from the underside of the roadway. The tunnel under the turnpike was a twin-bore that used both a roof shield driven by hydraulic jacks and a 7.3 meter (24 foot) diameter compressed air shield.

Construction of the northern part of the tunnel passed very close to existing buildings and had to preserve their structural integrity. Two designs to protect the foundations from settlement included underpinning with piles driven to bedrock and the construction of a 1 meter (3

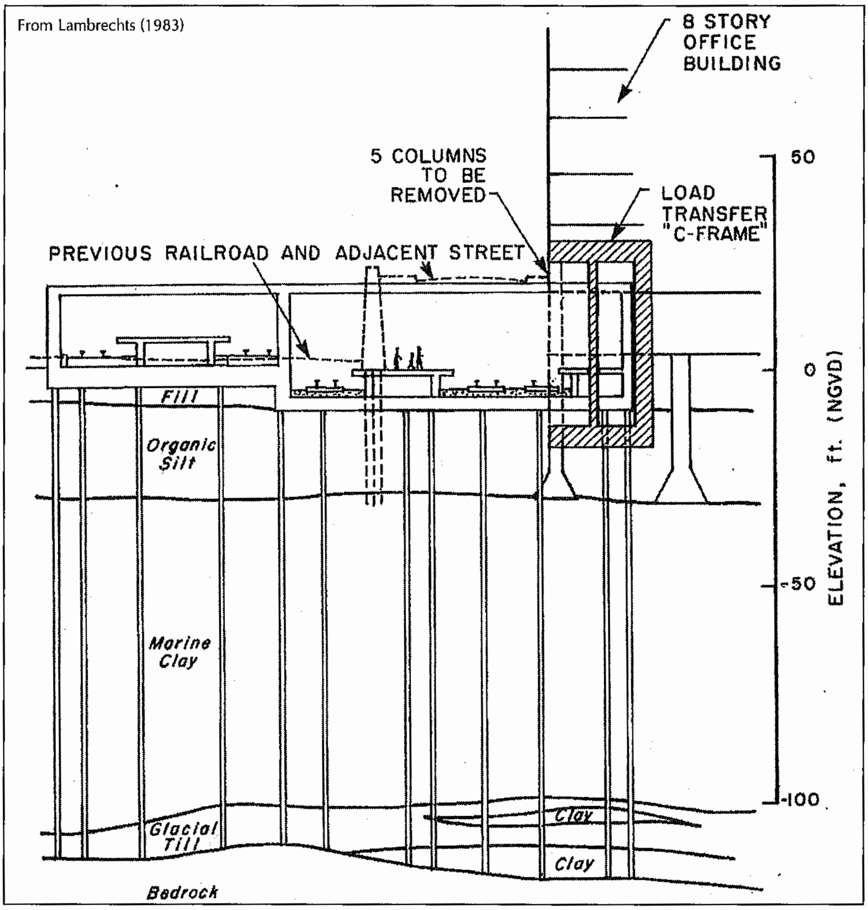



**FIGURE 6-10. Section through the Back Bay Station showing the underpinning and the load transfer "C"-frame building support.**

foot) thick reinforced concrete wall. The wall was constructed using a bentonite slurry cutoff wall that was then filled by tremie concrete. The concrete slurry wall was successful in minimizing settlement. A study by Lambe (1970) compared the performance of the excavation for the South Cove Tunnel using steel sheet piling and concrete slurry wall. The Don Bosco School was protected from the South Cove Tunnel excavation by a concrete slurry wall, which reverted to steel sheet piling just past the school. The concrete slurry wall moved inward 2.5 centimeters (1 inch) and settled as much as 1.5 centimeters (0.6 inches), which was very much less than the ground moved behind the adjacent steel sheet piling section that moved laterally 15 centimeters (6 inches). In addition, it was required that the tunnel be designed to support the new buildings that were planned by the Boston Redevelopment Authority to be built above the tunnel north of the Massachusetts Turnpike. Also, the groundwater levels in the area had to be maintained and recharged if deemed necessary.

The geology along this 805 meter (2,640 foot) tunnel is highly variable (see Figure 6-12), as described by Stacho (1968). The underlying material consists of 1.5 to 3 meters (5 to 10 feet) of miscellaneous fill originally brought in from Roxbury, Dorchester and Brighton about one hundred years ago when the South Cove was filled and developed. Beneath the fill under the former tidal flats of the cove is a layer of peat and organic silt, which ranges in thickness from a feather edge to as much as 6 meters (20 feet). Marine clay with a thickness of 18 to 30 meters (60 to 100 feet) underlies the organic deposit and consists of an upper approximately 1.4 meter (5 foot) thick soft blue clay (the hard crust is reduced and softened by the overlying organics) and a lower stiff pre-consolidated weathered yellow clay crust that is normally soft and gray at depth. Identified as "gray clay" on the profile, a thin till layer about 1.5 meters (5 feet) thick and made up of clay, sand, gravel and argillite fragments was found on top of the bedrock. The argillite was encountered at depths approaching 35 meters (115 feet), at elevation –35 meters (–115 feet) MSL, at the south end of the tunnel and rising to a bedrock high at a depth of 20 meters (65 feet), at elevation –20 meters (–40 feet) MSL or less, under the Washington Street portion of the Orange Line Tunnel at Kneeland Street.

*Northwest Extension Tunnel of the Red Line.* The 5.0 kilometer (3.1 mile) Northwest Extension of the MBTA Red Line beyond Harvard Square to Alewife Station (see Figure 6-1) was constructed between 1979 and 1985, and consists of two deep rock tunnel sections and shallower cut-and-cover sections in the overburden. The first section, which is 1,342 meters (4,400 feet) long, connects the new cut-and-cover Harvard Square Station to the 46 meter (150 foot) deep Porter Square Station (Dill, 1986). The five-level deep station and approach tunnels were built into the argillite because of the high cost of constructing a shallow tunnel in clay and the consequent surface disruption it would have created according to the MBTA. The Porter Square Station is, in turn, linked to the cut-and-cover Davis Square Station by the second deep bedrock tunnel section, which is 884 meters (2,900 feet) long (Cullen *et al.*, 1982). Beyond the Davis Square Station, the Northwest Extension continues as cut-and-cover tunnel along a railroad right-of-way to the Alewife Brook Station, which is its present terminus. Considerable exploration was done for the project and a thorough evaluation of the results of the exploration was made for design (Stimpson & Thompson, 1981; Keville & Sutcliffe, 1983; Waggoner, 1984).

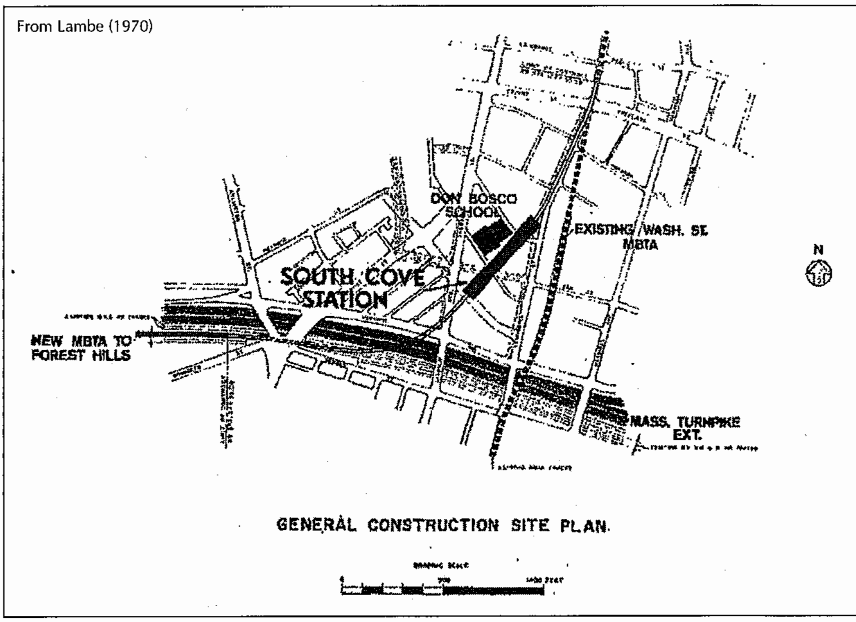



**FIGURE 6-11. Map of the Southwest Corridor Tunnel and the South Cove Station.**

The deep tunnels are twin bores, with each excavated to 6.7 meters (22 feet) in diameter. The construction access shafts now serve as ventilation and emergency egress shafts at intervals along the alignment. A variety of excavation and support techniques was utilized during the construction of the shafts and tunnels. The minimum support requirements originally specified for lengths of the tunnels, based on the expected subsurface conditions, were as follows: circular steel ribs and wood lagging for soft ground and mixed-face conditions — 1,479 meters (4,850 feet); steel sets for moderately sound rock conditions — 1,085 meters (3,560 feet); and rock bolt support or other appropriate support at the contractor's option in sound rock — 1,866 meters (6,120 feet).

The primary rock type along the tunnel alignment is the Cambridge Argillite, with lesser amounts of intrusive rock. The engineering properties of the bedrock and that of the overburden were determined (see Tables 4-4 & 4-5) for the project (Hatheway & Paris, 1979; Cullen *et al.*, 1982). The argillite is not uniform in appearance, but it does not show any significant variations from a geotechnical standpoint, except where it is significantly faulted or sheared and degraded by groundwater. The bedding characteristics in the argillite are extremely variable (Cullen *et al.*, 1982), although the bedding generally dips gently to moderately (20 to 45 degrees) to the south and repre-

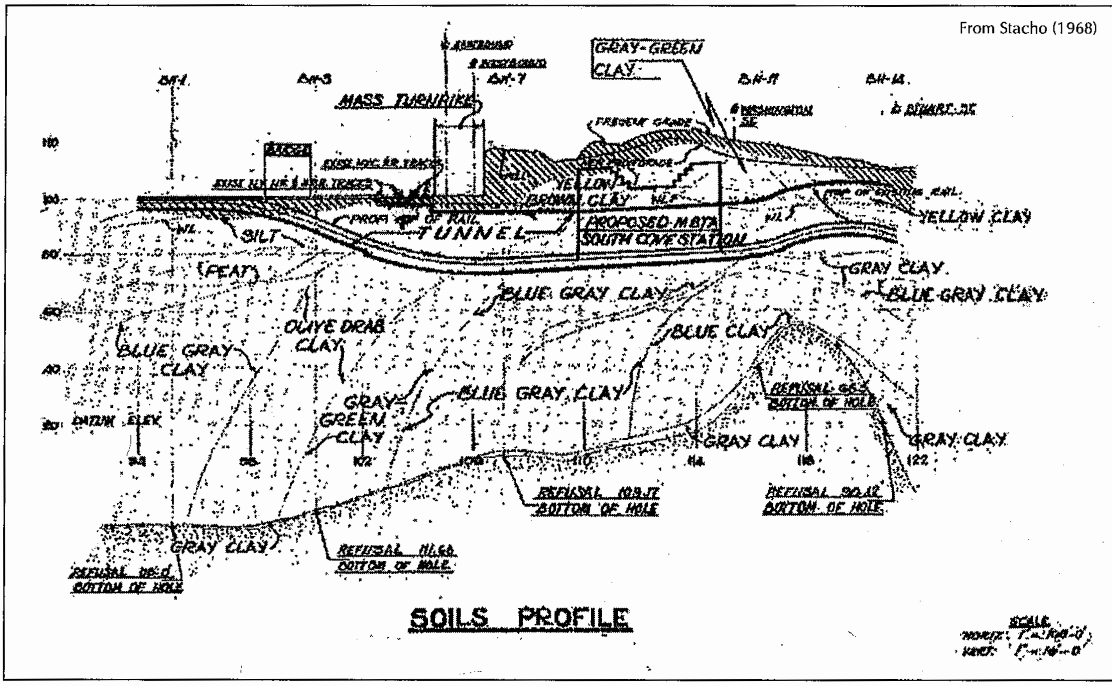



**FIGURE 6-12. Section of the Southwest Corridor Tunnel near the South Cove Station at Follen Street.**

sents the tilted fault block north of the Charles River. The bedrock varies from a massive dark to medium-gray, fine-grained argillite to one exhibiting rhythmic bands of light-gray layers alternating with medium- to dark-gray layers. The coarser-grained and generally lighter colored layers display well developed bedding structures such as graded sequences, cross-bedding and ripple marks. Mafic to felsic intrusive bodies are not uncommon and the characteristics of each occurrence vary greatly. They differ in composition, texture, orientation and contact relations.

The tunnel alignment is obliquely down or up-dip, depending on the direction of its orientation. On the curved tunnel section from Porter Square Station to the Davis Square Station, the alignment swings around almost parallel to the strike of the beds (Cullen *et al.*, 1982). This gradual change resulted in a varying response by the bedrock to the boring of the tunnel, which translated into a differently shaped tunnel opening (Hathaway & Paris, 1979). Joints are usually spaced 30 to 50 centimeters (12 to 20 inches) apart along bedding planes and their presence or absence did not normally affect the stability of the tunnel opening. The exception exists near faults, or the top of the rock, where very closely spaced joints, usually 10 to 25 centimeters (4 to 10 inches), developed parallel to the bedding surfaces. Three major joint sets were encountered during construction. The major joint sets, other than bedding plane joints, along the alignment generally strike north-northeast. In addition, the joints have nearly vertical dips (angle measured from the horizontal surface at right angle to the strike of the rock). Jointing parallel to bedding is also commonly developed and strikes nearly east-west with gentle to moderate dips, either north or south. A well-developed set of joints was found nearly parallel to shear zones, which are usually oriented more east-northeast. These joints tend to decrease to become non-existent with increasing distance from a shear zone and did not contribute to major support problems because most were oriented nearly normal to the tunnel alignment. Locally, overbreak occurred if these joints were parallel to the alignment (Cullen *et al.*, 1982). Shear or fault zones without associated clay gouge did not have much effect on tunnel construction. Where gouge is present, however, the stability is affected owing to the reduction of the frictional forces binding blocks of rock together around the tunnel opening. The integrity of the tunnel opening was further affected where these zones nearly parallel the alignment (Cullen *et al.*, 1982).

The Pleistocene section along the alignment west of (but not including) the Davis Square Station contains moderately thick and variable deposits. The units and their thicknesses are, in ascending order from the bedrock (Bechtel, 1978): till 0 to 21 meters (0 to 70 feet), marine clay 0 to 18 meters (0 to 60 feet), upper outwash sand and gravel 0 to 15 meters (0 to 50 feet), and miscellaneous fill 0 to 4.5 meters (0 to 15 feet). It is noted that, at Davis Square, the slurry wall encountered problems when it was discovered that a portion of the wall was not keyed into the argillite, but was bearing on a boulder in the till. Woodhouse observed that a thick slab of the argillite about 1.5 meters (5 feet) thick had been dislodged by the glacier and deposited in the till. This case points out the need to core no less than 3 meters (10 feet), but preferably 6 meters (20 feet), of the bedrock to confirm that the top of the rock has been encountered.

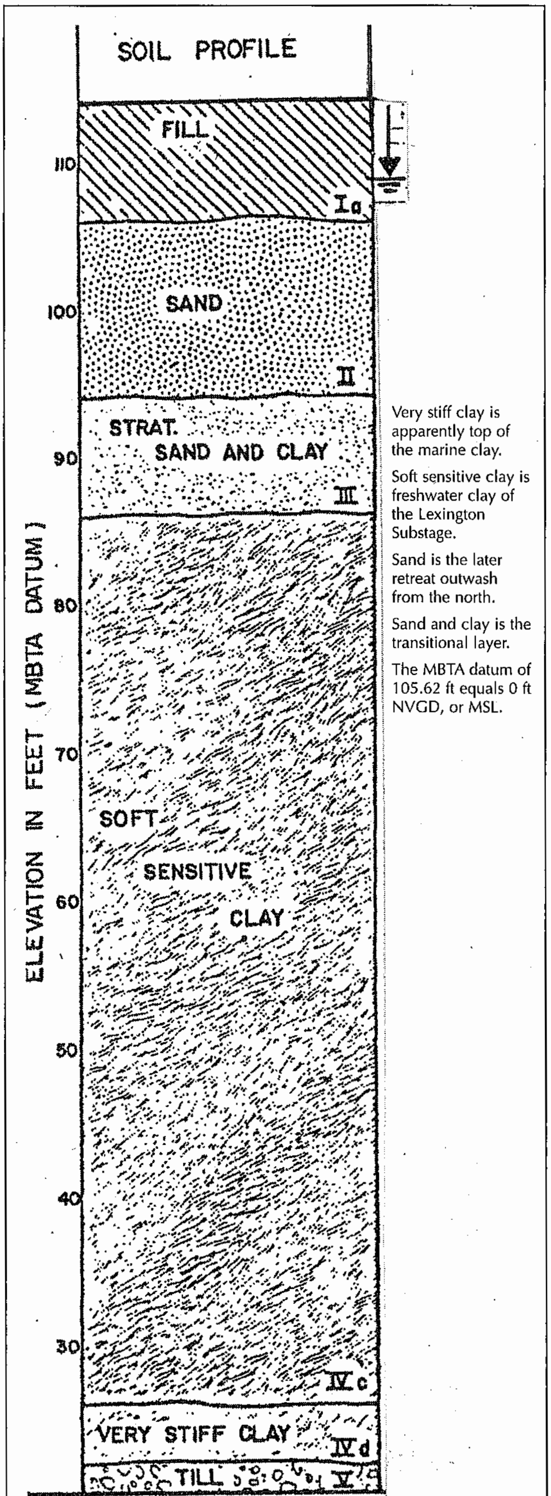
Excavation for the Alewife Station, which is the location of the station garage complex at the end of the Red Line, encountered an anomalous deposit of soft sensitive clay that caused several problems. The unusual complexities posed by this clay were thoroughly considered in design. The station design consisted of an 18 meter (60 foot) wide by 11 meter (37 foot) deep excavation with cast-in-place slurry walls used for cofferdam construction and permanent walls for the station. The presence of the sensitive clay caused problems with the slurry wall. The test borings found about 2.4 meters (8 feet) of miscellaneous fill overlying stratified sand and clay to 6 meters (20 feet). At this depth, soft sensitive clay was encountered to a depth of 24.4 meters (80 feet) where very stiff yellow clay from 24 to 27 meters (80 to 90 feet) was found overlying the till layer of only limited thickness, less than 3 meters (10 feet) The top of bedrock is generally about 30 meters (100 feet) deep (see Figure 6-13).

The following discussion is adapted from Goldberg-Zoino Associates's *Slurry Wall Test Panel Report, MBTA Red Line Extension Davis Square to Alewife*, and from personal communication (Barvenik, 2012).

The sensitive-like clay at the Alewife Station area in West Cambridge was recognized to be somewhat different that the "usual" Boston Blue Clay. The Alewife blue clay had lower than normal strength relative to the Boston Blue Clay, sensitivity greater than 20 versus 4 to 8, a lower plasticity index and liquid limit, and a higher liquidity index with natural water content greater than the liquid limit. The possibility of large strength loss with disturbance during excavation resulted in the selection of cast-in-place diaphragm walls (slurry walls) for cofferdam construction. This method provided rigid walls extending below the bottom of the excavation to prevent excessive lateral displacements and improve base stability. The slurry wall also provided a permanent wall for the station platform excavation area and the tunnels leading into the Alewife Station from Davis Square.

Because of the unusual character of the soft sensitive-like clay, a test section was undertaken to reveal inherent potential construction problems, resolve uncertainties and reduce contingencies in the bid prices. The test section results showed that the sensitive clay deposit appears to be over-consolidated by at least 71 kilopascals (1.0 kips per square foot) throughout its entire depth. The deposit did not exhibit any consistent trends of increasing or decreasing strength with depth but a high degree of strength variability actually exists throughout the deposit. Based on field and lab testing, average undrained strength for the clay is 43 kilonewtons (900 pounds per square foot). The clay anisotropy is as much as 175 percent. Wick/sand drains were used both to speed up drainage for rebound and to foster more drained-strength conditions during excavation. The excavation was made in sequential benched steps, thereby providing some drainage time.

The station wall bottoms rotated inward during excavation, resulting in the top of the walls moving away from the excavation and, thus, leaving a gap between the top struts and




From Goldberg, Zoino, Dunnicliff & Associates (1978)

**FIGURE 6-13. Columnar section in Alewife Station area of the Red Line.**

the wale. This rotation indicated that the clay inside the excavation was not providing sufficient resistance to withstand the soil pressures outside the walls prior to the installation of the lower struts in the station excavation area.

Problems also developed with the installation of piles to support the parking garage and station mezzanine areas (see Figure 6-14). All the inclinometers and piezometers installed indicated that the slurry walls were moved by the pile driving. The piles were to be pre-augered through the sensitive clay to limit disturbance. Sufficient water was required to flush out the cuttings during augering so that only clear water remained in the hole before pile insertion. If this operation were not done, it was feared that the clay would remain in the pre-auger hole and would turn into a thick liquid because of its high sensitivity and not rise up to the ground surface, escaping through the small space between the hole wall and the pile when the pile was placed in the pre-augered hole. The contractor apparently did not figure in the cost of dealing with all the water and a settling pond that would be required to meet the specification. Instead, only a small volume of water was used during drilling, which did not flush out the cuttings. The result was that very little soil/clay cuttings came out of the hole when the pile was inserted, and a spike in pore pressure in the clay surrounding the pre-auger hole developed, leading to disturbance.

Alterations to the auger allowed more water to be pumped in temporarily, which cured this problem. The problem redeveloped, however, when the contractor again resumed the practice of using very little water. Each time a pile went in, it acted like a piston and displaced the viscous clay remaining in the lower portions of the hole out into the formation as a volume change. The end result was that the pile installation outside the already placed concrete diaphragm walls pushed the walls laterally about 15 centimeters (6 inches). This displacement was enough to cause the two cast-in-place slurry walls (which were to be the permanent tunnel walls) to move toward each other, thereby impinging on lateral train clearances. The contractor was then allowed to drive the internal piles between the two slurry

**FIGURE 6-14. Aerial view (from west) of the Alewife Station of the Red Line during construction. (Courtesy of M. Barvenik, Goldberg-Zoino Associates.)**

walls in the same manner to push the walls back out. That, plus requiring removal of all the imperfections (bulges) in the concrete walls, provided just barely enough clearance for the trains not to "rub the walls" on their way through the station.

Further problems with the 35.5 centimeter (14 inch) square, 42.5 meter (140 foot) long precast concrete piles developed when the hammer was found to be delivering less energy, resulting in a pile load test failing. However, the new hammer broke and the contractor again used the flawed hammer to drive a large number of piles with insufficient energy. The pile driver was unable to get back into the area to re-strike or further advance the piles to required design capacity due to all the piles already being in place. Subsequent calculations concluded that there was reduced pile load capacity but that the resulting factor of safety less than the specified standard 2 would be sufficient. Monitoring of the garage as it was being constructed found that it did not settle an unacceptable amount because of lower ultimate pile capacity. Another consideration was that only five stories of the garage were constructed, although it was designed to take seven stories, which is problematic for any future proposed addition to the original constructed height of the garage at Alewife (which would require adding piles similar to that done at Central Parking Garage at Logan Airport).

The Route 2 Bridge (which originally crossed the previous railroad alignment) now crosses over the subway storage tunnel that is beyond the Alewife Station. The bottom of the clay was very deep in this area. Bridge abutments on either side of the tunnel roof slab were underpinned with top-down construction. The tunnel roof is supported on the slurry walls, which then had to be deep (more than 24 meters [80 feet]) to pick up sufficient load-carrying capacity through side friction. Given the stiffness of the walls, the calculations showed that the long walls extending far below the bottom excavation support strut (which was a meter [several feet] above the thick tunnel invert slab) would impose very large loads on the bottom strut due to the rigidity of the support system relative to the strain required in the clay to develop its shear strength and the passive resistance between the walls. A "hinge" was therefore formed in the slurry walls below the bottom strut by crossing the inside and out-

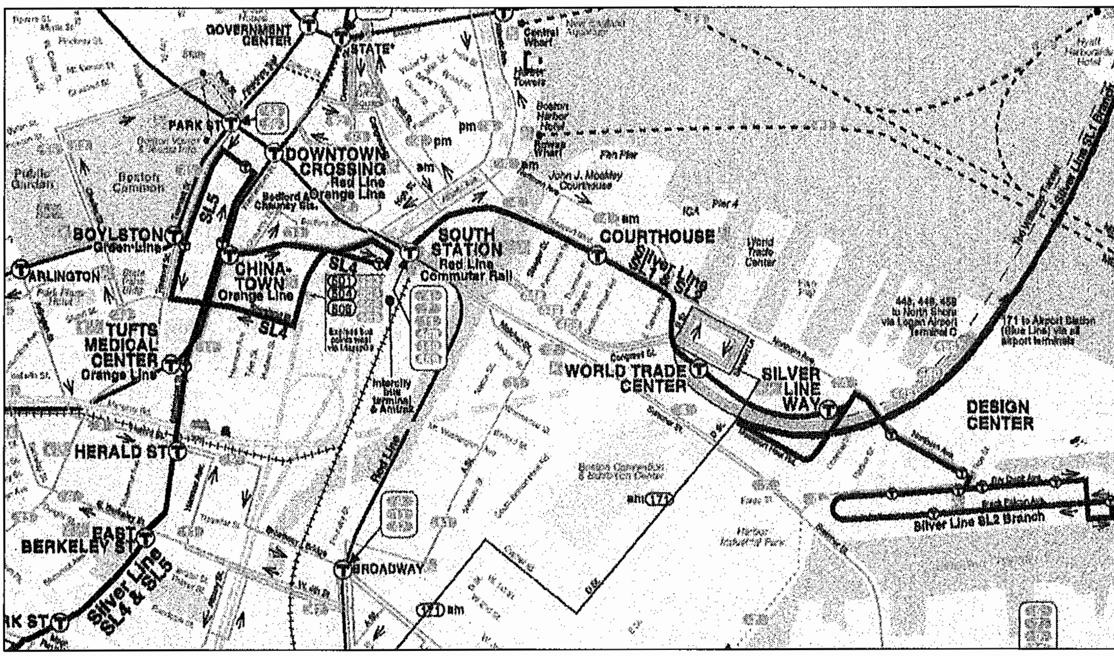



**FIGURE 6-15. Map of the Silver Line through central Boston and South Boston. (Courtesy of the MBTA.)**

side reinforcing bars to opposite sides of the wall, thus reducing the moment-carrying ability of that point in the wall. This solution maintained the vertical load carrying capacity needed for the underpinning, while eliminating the moment in the wall and, thus, the otherwise high lateral loads on the bottom strut.

The high sulfate and low pH (as low as 1) in the soils and groundwater that originated from the Grace Chemical sludge lagoon affected the concrete and steel. There were health claims by MBTA transit workers alleging that the Grace Chemical groundwater contamination was causing headaches, etc. However, an investigation discovered a small leak in an elevator hydraulic hose that was atomizing the hydraulic oil and dispersing it into the air. The issue disappeared once the leak was found and repaired. However, this investigation uncovered the fact that the contractor never installed the cutoff slurry wall that was supposed to be installed below the floor slab between the tunnel slurry walls. This wall would have separated the boat slab section through the stratified sand deposits in the Grace Chemical area to the east of Alewife Brook Parkway from the relieved slab in the clay deposits of the station area to the west of Alewife Brook Parkway. The lack of this wall resulted in far more groundwater coming into the relieved slab drainage system, which was contaminated by the groundwater from the boat slab section through Grace being pumped from the station area.

*Silver Line Tunnel.* The Silver Line was originally planned as a subway in 1948, but ended up as a hybrid rapid bus line that provides service at street grade from Dudley Square Station in Roxbury to South Station, and then with transfer to a tunnel, continues on to South Boston Seaport and Logan Airport. Although it has a normal subway line designation, the Silver Line is largely a bus on city streets (see Figure 6-15). The line runs on the surface from Dudley via Downtown Crossing Station or Chinatown to South Station. At South Station, a second segment has its terminus below ground and it runs in a tunnel that passes above the Central Artery northbound from Essex Street to Congress Street and goes under Fort Point Channel to emerge just east of the World Trade Center in the South Boston Seaport area, where the line splits at the Silver Line Way Station. One route continues on the surface northeastward through the Ted Williams Tunnel to the airport and another eastwards to the Boston Design Center. Plans to extend the tunnel from South Station westward to the Boylston Station on the Green Line are currently on hold. The construction of the existing Silver Line Tunnel section, which opened December 17, 2004, demonstrated some excellent innovative engineering techniques in both its onshore and sub-channel portions.

The tunnel passes through an area of old docks and mostly nineteenth century infilling that encroached on Fort Point Channel. The line extends through the Russia Wharf area at Atlantic Avenue and Congress Street (which is near the original Boston shoreline) and is underlain by 3 to 5 meters (10 to 16 feet) of granular fill and debris from old harbor-front structures that had been dumped on organic sediment that ranges in thickness from 1.5 to 3 meters (5 to 10 feet) thick (Boscardin *et al.*, 2005). The tunnel is built mainly within the underlying 3 to 15 meter (10 to 49 foot) thick layer of marine clay that overlaps a 1.5 to 10.5 meter (5 to 12 foot) thick dense upper till, which forms part of the east base of the Fort Point drumlin (see Figure 6-16). Very soft to medium hard argillite occurs below at depths of 19.5 to 24 meters (64 to 79 feet). Particular care was needed to seal off groundwater because the porous fill had many open voids. This goal was accomplished using a slurry cutoff wall. The groundwater level is that of the nearby Fort Point Channel and fluctuates between 0.3 to 1.0 meters (1.0 to 3.3 feet) with the tide.

Special design considerations had to be made in constructing the tunnel below Russia Wharf, which contains historical buildings dating back to the late 1800s that remained occupied during construction (Lacy *et al.*, 2004; Boscardin *et al.*, 2005). The buildings have steel frames and masonry facades supported by granite caps and wood piles, and the tunnel had to pass through the piles, fill and abandoned wharf structures (see Figures 6-16 & 6-17). A 13 meter (43 foot) wide by 8.5 meter (28 foot) high tunnel 100 meters (328 feet) long was constructed using the New Austrian tunneling method and the sequential excavation method. These methods were selected to protect and preserve the buildings of Russia Wharf and mitigate any ground and building movements (see Figure 6-17). These efforts included soil freeze cycling, raising and lowering the buildings, the installation of temporary and permanent underpinning, and the installation of mini-piles supported by the underlying argillite bedrock. There was full geotechnical instrumentation of the buildings and the tunnel to monitor movements before, during and after the tunnel construction. The wood piles that were cut out for construction of the tunnel were supported by the tunnel walls designed to carry the loads.

The Fort Point Channel portion was constructed as an immersed tube with cut-and-cover tunnel sections on the sides of the channel (Leifer, 2006). The tunnel in this location remains mostly in the marine clay, except for a small part in the middle that reached downward into the upper till. During dredging for the immersed tube placement, a 6 by 6 by 2.4 meter (20 by 20 by 8 foot) glacial erratic boulder was found at the clay-till contact and had to be broken up in place before dredging could be completed. The deeper parts of the dredged trench penetrated sand and clay, and the shallow ends were located in granular fill or cohesive fill consisting of dredged clay and harbor sediments. The tunnel tubes were prefabricated nearby and floated into place, lowered into the trench and then assembled, connected and backfilled.

The South Boston section was constructed as a cut-and-cover tunnel that begins at a depth of about 11.6 meters (38 feet) deep at the Fort Point Channel and ramps up to the ground surface east of the World Trade Center. The deeper part lies in outwash sand and marine clay, and the shallower part in granular fill or cohesive fill, which consists of dredged marine clay and harbor sediment (Leifer, 2006).

*Red Line/Blue Line Connector Tunnel (Proposed).* A new extension of the Blue Line subway, designated as the Red Line/Blue Line Connector, has been proposed to run from Bowdoin Station, currently the end of the Blue Line, to the Charles/MGH Station located at Charles Circle on the south side of the Charles

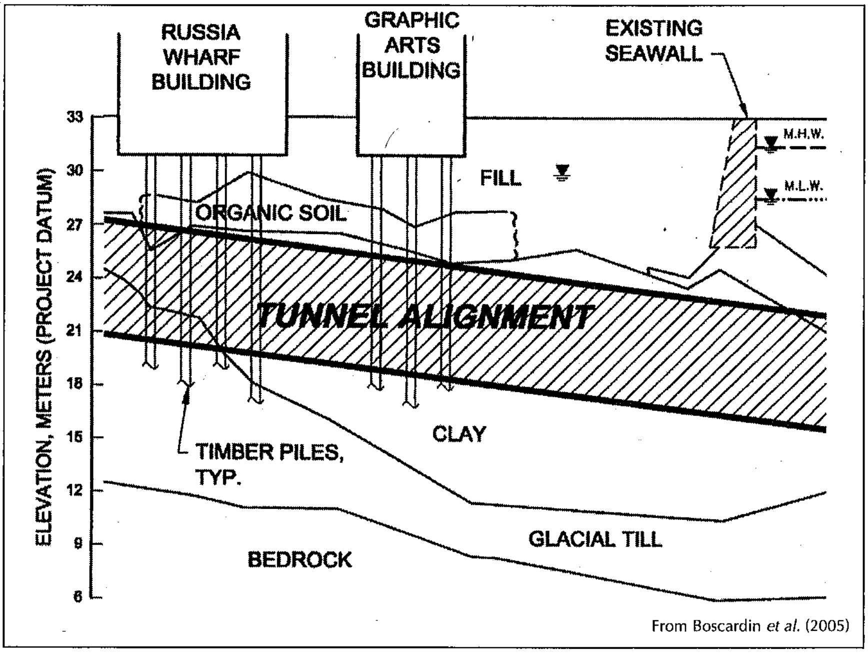



**FIGURE 6-16. Section along the Silver Line Tunnel between the corner of Atlantic Avenue and Congress Street and the edge of Fort Point Channel passing beneath the Russia Wharf Building (view north).**

River (see Figure 3-95). It would be an east-west tunnel lying beneath Cambridge Street. The MBTA Blue Line, which is the only subway line that does not connect to the Red Line, currently terminates at the Bowdoin Station located on Cambridge Street in the West End at the base of Beacon Hill. The preliminary plans and explorations for the proposed construction would have the connector extend a distance of approximately 990 meters (3,250 feet) in twin 6.4 meter (21 foot) diameter north and south tunnels with invert depths between 15 and 18 meters (50 and 60 feet). These tunnels would be cut-and-cover or mined and have a tunnel invert at elevation 19.2 meters (63 feet) at Charles/MGH Station and elevation 25.9 meters (85 feet), based on MBTA datum of 32.2 meters (105.62 feet) equals 0.0 MSL, at the Bowdoin Station. Surface elevations based on test boring data (MBTA datum) are about 43.6 meters (143 feet) at Bowdoin Station and 32.6 meters (107 feet) at Charles/MGH Station. Design Alternative 1 would eliminate the existing Bowdoin Square Station and Alternative 2 includes the construction of a new Bowdoin Station. The tunnel design incorporates vent shafts, station connections and egress stairways.

The tunnels are proposed to be constructed by a combination of technologies: the sequential excavation method for the two tail track tunnels at Charles/MGH Station; and, earth pressure balance tunnel boring machine for the running tunnels from near the Charles/MGH Station to the shaft near Bowdoin Station at Cambridge Street. Cut-and-cover construction would be used from this point to the nearby Blue Line/Green Line Government Center Station. The tunnels will run from the Charles River to the Beacon Hill and West End area. To avoid settlement of old brick homes and other shallow foundation buildings that bear on the till and glaciomarine deposits under the higher Bowdoin Square area of Cambridge Street, special attention would be placed on pre-construction underpinning. In addition, several buildings are supported by wood piles and dewatering close to the tops of the piles would need to be addressed to protect the piles.

Previous foundation investigations and exposures in construction excavations from the Charles River to Bowdoin Station encountered stratified sands on Strong Place on the south side of Cambridge Street at the base of Beacon Hill. North of this location on Cambridge Street at the Massachusetts General Hospital, fill, organic silt and marine clay were found. However, stratified and faulted sand and gravel were exposed in the excavation for the Holiday Inn 152 meters (500 feet) east of this location. Farther east up Cambridge Street is an area dominated by till and glaciomarine deposits. Shallow argillite was found to underlie the till at the Saltonstall Building across Cambridge Street from Bowdoin Station.

The north and south tunnel profiles (Haley & Aldrich, 2010) were constructed from extensive drilling in the area (see Figures 3-85, 3-91 & 3-95). These profiles show that the surface is underlain by 3 to 4.6 meters (10 to 15 feet) of granular fill mixed with cinders, ash, bricks and other miscellaneous materials. In the low-lying area of Charles Circle and running east up to Massachusetts General Hospital, from 3 to 7.6 meters (10 to 25 feet) of compressible organic silt, delineating the previous tidal flats of the Charles River, were found. A thin discontinuous layer of upper outwash sand up to 2.4 meters (8 feet) thick underlies the organic silt in the area of Charles Circle. This sand, which overlies the marine clay, represents the upper outwash. A layer of marine clay was encountered at a depth of 6 to 15 meters (20 to 50 feet) and has a thickness from 3 to 18 meters (10 to 60 feet). The clay thickens and thins, pinching out in the higher elevations of Bowdoin Square. The thin clay is shown to be underlain in some areas by what appears to be the glaciomarine deposit. The tunnels run mostly through marine clay, with lower sections in the glaciomarine deposit and into a short section of till on the south side of Cambridge Street near the Massachusetts General Hospital. Discontinuous sand, which lies at the base of the clay, reaches a thickness of 9 meters (30 feet) in a channel in the till north of Cambridge and Grove streets. This sand is called *marine sand*, but it apparently represents the lower outwash. The deposition may have continued as marine waters rose. The till overlying the argillite and sandstone bedrock reaches a thickness on the order of 18 meters (60 feet) southward on the flanks of the Beacon Hill drumlin and thins down to less than 1.5 meters (5 feet thick) to the north (see Figure 3-85). The till merges with the glaciomarine deposit that is up to 21 meters (70 feet) thick. This finding again demonstrates that the glaciomarine deposit is difficult to distinguish and classify. Elevation of the top of the bedrock varies from 1.5 meters (5 feet) MSL near the Charles River to –14 meters (–45 feet) MSL as Bowdoin Square is approached. The rock is severely to moderately weathered Cambridge Argillite.

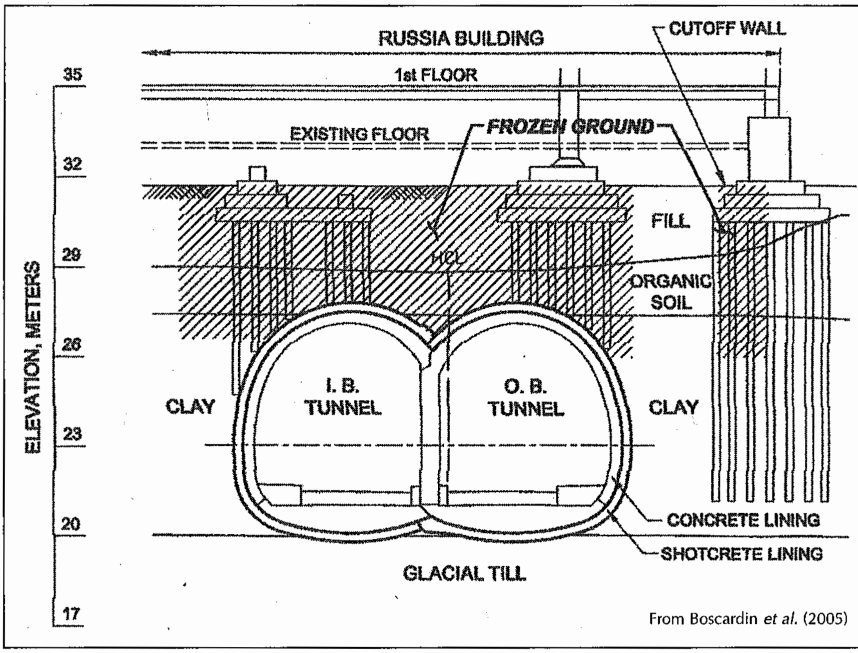



**FIGURE 6-17. Section through the Silver Line tunnel beneath the Russia Wharf Building (view west).**

## Trans-Harbor Highway Tunnels

Three major subaqueous highway tunnels, as well as the East Boston Tunnel on the Blue Line subway, connect downtown Boston with the communities northeast of the harbor, exiting in East Boston (formerly Noddle's Island). The highway tunnels were constructed in three phases since the need to accommodate

**FIGURE 6-18. The shield at the Boston vent shaft of the Sumner Tunnel on June 20, 1932. (Courtesy of the University Archives & Special Collections Department, Joseph P. Healey Library, University of Massachusetts–Boston.)**

increased traffic grew, and eventually they became incorporated into the Central Artery/Tunnel Project.

*Sumner Tunnel.* The Sumner Tunnel was constructed under Boston Harbor between 1931 and 1934 at a cost of 19 million dollars in order to access East Boston and Logan Airport other than by ferry or a circuitous land route. The deep bore tunnel has a base elevation inside the tunnel of –37 meters (–120 feet) MSL and is 9.1 meters (30 feet) in diameter with a length of 1,723 meters (5,651 feet). It was constructed by using a conventional pressurized shield through the marine clay and mud under Boston Harbor, with the muck being removed by hand (see Figure 6-18) and shipped to Logan Airport for fill (Loveland, 1932). The tunnel crosses over a 100 meter (328 foot) deep bedrock valley that underlies Boston Harbor. Circular steel rings were pushed 80 centimeters (32 inches) at a time by the shield, which circled the edge of the rings. Electricity and gasoline instead of steam were used in the pressurized air in order to advance the tunnel — a major advancement for its time.

Two concrete box sections 125 and 132.7 meters (410 and 435 feet) long were constructed at the two ends of the tunnel using open cut-and-cover methods. On the East Boston side, materials encountered consisted of the harbor fill and the till associated with the Camp Hill drumlin; on the North End side, harbor fill, organic sediment and marine clay were encountered. The tunnel lay chiefly in the marine clay. Repairs of tunnel deterioration were made in the 1960s. Other work in the 1990s found that the original contractor had skimped on steel supports, but the tunnel by then had lasted over fifty years. Recent major repairs to the ceiling tiles and their supports occurred in 2007.

*Callahan Tunnel.* The State Highway Master Plan of 1948 declared the Sumner Tunnel "overtaxed." Ten years later in 1958, the Massachusetts Legislature authorized the parallel Callahan Tunnel be built to alleviate traffic to and from Logan Airport in East Boston. The tunnel is 1,545 meters (5,068 feet) long and 9.1 meters (30 feet) in diameter, and was constructed at the end of the 1950s and opened in 1961. Its construction covered a period of only nineteen months. It was of similar construction to the Sumner Tunnel and was deep bored at the same depth through the harbor sediment using the shield method (see Figure 6-19). A full-sized shield started from the Boston side and a pilot bore started from the north to eventually meet beneath the channel. The tunnel was lined with bolted steel rings that were covered by a concrete liner. The ends of the tunnel were constructed of 18.3 to 24.4 meter (60 to 80 foot) concrete box sections using open cut-and-cover methods. Similar deposits as at the Sumner Tunnel were encountered. In the 1990s, repairs were made primarily to the ceiling panels and tiles that had been deteriorating. Repairs made in 2006 included the replacement of 418 loose ceiling bolts and the installation of diagonal steel beams in the ceiling to meet current seismic code requirements.

**FIGURE 6-19. Callahan Tunnel showing front end of the tunnel shield on March 23, 1961. (Courtesy of the *Boston Globe*.)**

*Ted Williams Tunnel.* Soon after the Callahan Tunnel was opened, the state recognized that a third harbor crossing would be necessary. It was not until 1968 that plans were drawn up for the new third tunnel to connect the Massachusetts Turnpike to Logan Airport, which was then estimated to cost 144 million dollars. In the early 1980s, the design of a tunnel to East Boston at Route 1A near the terminus of the other two tunnels was advanced by then-Governor King's administration. However, the location and function of the third tunnel eventually constructed as part of the Central Artery/Tunnel Project expanded greatly in the 1980s under Governor Dukakis's administration. The third tunnel was constructed from September 1991 to March 1994 from the far easterly end of the South Boston flats to the area of Bird Island flats at Logan Airport, and forms part of the Interstate 90 extension. The tunnel initially opened to commercial traffic on December 15, 1995, and was named the Ted Williams Tunnel. The tunnel was opened fully to all traffic in 2003.

The Ted Williams Tunnel has a total length of 2,575 meters (8,448 feet), including approaches. It is a twin-tube tunnel, with two lanes in each tube, which are each 12.2 meters (40 feet) in diameter. Length of the twelve immersed tubes totaled 1,207 meters (3,960 feet) under water. Requirements for the tunnel were that it had to pass under the elevation –10 meters (–30 feet) MSL deep boat anchorage in East Boston and the elevation –12 meters (–39 feet) MSL deep anchorage for the container shipping channel in South Boston. The existing two navigation channels were to be deepened by up to elevation –12 meters (–39 feet) MSL. Two bores were originally considered in preliminary design, but the chosen tunnel design consisted of twelve sections of double full circle, "binocular" steel sections or immersed tube tunnels sunk into a 1.2 kilometer long by 15.2 meters deep by 30.4 meters

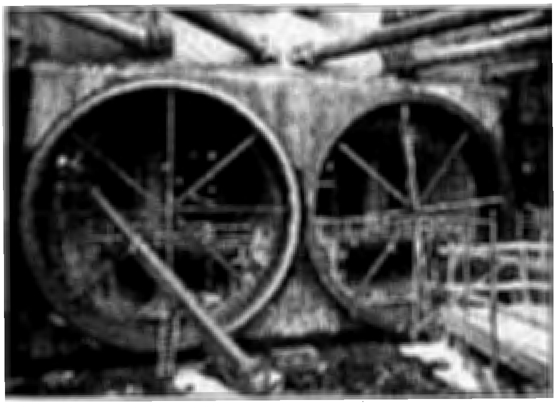


**FIGURE 6-20. Connection of the south end of the Ted Williams Tunnel to the covered roadway leading to Logan Airport. (Courtesy of the Massachusetts DOT.)**

wide (0.75 miles by 50 feet by 100 feet) trench excavated into bedrock, glacial till, clay and harbor sediments (see Figure 6-20). The trench was excavated by the "super scoop" clamshell excavator on a barge. About 1,000 meters (3,280 feet) of hard rock were encountered that required drilling and blasting to prepare the rock for excavation. Special environmental precautions were necessary to drive fish and lobsters away prior to each blast. Each of the 12 by 24 by 100 meter (39 by 79 by 328 foot) immersed tube elements were coupled together and made watertight by special gaskets. The tunnel was designed to meet a seismic design of a horizontal ground acceleration of 0.15 g operating design event (ODE), 0.3 g maximum design event (MDE) and an accidental load from a sinking ship or dragging anchor.

Eleven test borings in the water had shown that the top of the bedrock was just 1.5 to 2 meters (5 to 7 feet) below the harbor bottom for about two-thirds of the immersed tube tunnel. The top of the argillite is at about elevation –14 meters (–45 feet) MSL at the South Boston end. A soft to stiff clay comprised the rest of the harbor bottom. Sixty additional borings and a bathymetric survey confirmed the original findings. Chemical analysis of the harbor sediments found that the top 1.5 to 2.1 meters (5 to 7 feet) were contaminated and did not meet the criteria for disposal twenty miles at sea in the designated and regulated area. These contaminated sediments were dredged and disposed of at a newly designed and regulated facility at Logan Airport. Some of the approach excavations in South Boston encountered hazardous waste, which was excavated and dumped at the Spectacle Island disposal facility after being treated. The East Boston cofferdam constructed for the Logan Airport approach was the largest in North America, being 216.5 meters long by 25.9 meters deep (710 by 85 feet). In South Boston, the junction excavation was free-standing circular cofferdam using slurry wall and continuous ring beams (Kirmani & Highfill, 1996).

## Utility Tunnels

Shallow utility tunnels have been constructed around Boston for more than a century, especially for river and short bay crossings. These tunnels are mostly in the marine clay and organic sediment, and generally use a shield method under compressed air. For example, in 1898 and 1899, the Massachusetts Pipeline Gas Company excavated three tunnels: under the Mystic River at Malden Bridge in Charlestown near Everett, under the Charles River at the then new bridge on Washington Street between Charlestown and Boston, and under the Charles River at the River Street Bridge between Cambridge and Brighton (Cummings, 1901). These 122 to 137 centimeter (48 to 54 inch) diameter steel-lined pipes were advanced from riverside shafts under a minimum safe cover of only 2.4 meters (8 feet) and flooding occurred on occasion. A similar 2.7 meter (9 foot) diameter tunnel was driven under the channel between Chelsea and Charlestown by the Metropolitan Water Board from 20 meter (65 foot) deep shafts 43 meters (140 feet) apart, also at this time in the early 1900s.

*Mystic Cable Tunnel.* In 1941, the Boston Edison Company constructed a cable tunnel through soft ground from the Mystic Generating Station at Alford Street in Everett under the Mystic River to the Charlestown side at depth of about 20 meters (65 feet) (Bray, 1945). On each side of the river a 4.6 meter (15 foot) square shaft with 5.5 by 9 meter (18 by 30 foot) underground splicing chambers mounted on top were sunk and a 335 meter (1,100 foot) long circular tunnel driven between them. The tunnel is lined with 35 centimeter (15 inch) thick cast-in-place concrete with an inside diameter of 2.4 meters (8 feet). The invert of the tunnel on the Everett side is elevation –14.2 m (–46.5 feet) MSL and slopes down to elevation –15.8 meters (–51 feet) MSL on the Charlestown side. The shafts were constructed under compressed air because of the potential for heavy water inflow from saturated silty sand and the concern that this inflow could lead to loss of ground and settlement of nearby structures. The tunnel was excavated by hand methods and air spades under 172 kilonewtons per square meter (25 pounds per square inch) of compressed air.

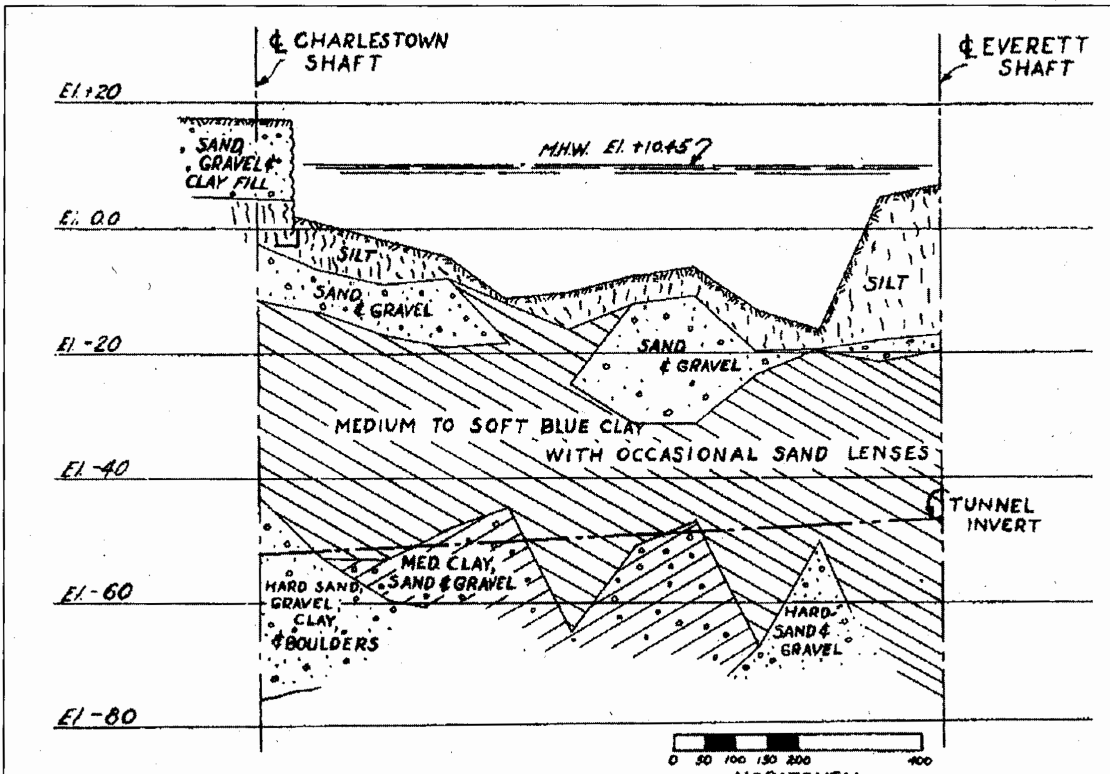
Twelve exploratory test borings were drilled, one at each shaft and every 30 meters (100 feet) near the alignment (see Figure 6-21). The 30 meter (100 foot) long borings reached an elevation of approximately –24 meters (–80 feet) MSL, and were terminated in till or an overlying clay with some sand and gravel on the Charlestown side. The borings there encountered about a 10 meter (30 foot) thick till. Above this till is the marine clay with scattered sand layers that have a soft to medium stiff consistency. The bottom elevation of the clay ranges from between elevation –12 meters (–40 feet) MSL to over elevation –24 meters (–80 feet) MSL and the top is between elevation –3 and –6 meters (–10 and –20 feet) MSL, yielding thicknesses between 10 and greater than 18 meters (35 to more than 60 feet). The tunnel alternates between the till and marine clay on the south to all clay on the Everett side. A 6 meter (20 foot) thick (but discontinuous layer of sand and gravel) corresponding to the Lexington Outwash fills channels cut into the top of the clay. Capping this deposit is an irregular layer up to 6 meters (20 feet) thick of organic silt and river alluvium. Test borings for a wind turbine generator testing facility located about one-half mile downstream on the Little Mystic Channel in Charlestown (Miller, 2009) found the bedrock at a depth of 43 meters (140 feet), at an elevation of –39 meters (–127 feet) MSL. Upson and Spencer (1964) thought that the Mystic River in this area represented the ancestral buried Malden River with the bedrock found at elevation –37 meters (–120 feet) MSL at the nearby Tobin Bridge and as deep as elevation –73 meters (–240 feet) MSL at Deer Island.

## The Central Artery/Tunnel Project: The Big Dig

The original Central Artery (Tsipis, 2001), also known as the John F. Fitzgerald Expressway, ran from Andrew Square in South Boston to the Mystic River Bridge (later renamed the Tobin Bridge) access, a distance of 5.12 kilometers (3.18 mi). It consisted of a surface roadway, a tunnel and an elevated section. The entire highway actually comprised about 12.6 kilometers (7.8 miles) of roadway surface, ramp and tunnel construction, and connected at its middle to the Callahan and Sumner tunnels, which run under Boston Harbor to East Boston. The elevated six-lane section from High and Broad streets to the Tobin Bridge was constructed during the period 1951 to 1954 and opened in Boston in 1954 with much political fanfare. Because of the public outcry concerning the unsightliness of the steel structure, called the "Green Monster," the southern half-mile was constructed underground as the Dewey Square Tunnel or the South Station Tunnel and opened in 1959. This tunnel was the first major interstate highway tunnel beneath an inner city area in the United States.

The highway was designed to alleviate downtown Boston's traffic for several decades to come. However, within a decade of its opening, the Central Artery reached its designed capacity of 75,000 vehicles daily, which increased to 200,000 daily by the late 1970s. This growth, coupled with some major flaws in the pre-interstate exit/entrance ramp design and positioning, resulted in considerable traffic congestion.

The chosen solution to alleviate the congestion and to remove the aging and deteriorating elevated freeway, originally called the Central Artery/Tunnel (CA/T) Project, was to construct a new depressed eight- to ten-lane expressway in a tunnel by cut-and-cover methods under the existing elevated road while not disrupting the economic viability of the city (see Figure 6-22). The project was widely referred to as the Big Dig (Vanderwarker, 2001). The project's centerpiece is the




From Bray (1945)

**FIGURE 6-21. Section along the Mystic Cable Crossing Tunnel.**

Thomas P. O'Neill, Jr., Tunnel, which extends 2.4 kilometers (1.5 miles) between Kneeland Street and Causeway Street, and opened in 2003. Other major components of the CA/T Project include the new Seaport Access and Ted Williams tunnels beneath South Boston and Boston Harbor to link the extension of the Massachusetts Turnpike (I-90) to Logan International Airport and Route 1A, and connecting the downtown elements to Interstate 93 north to a two-bridge crossing of the Charles River at the expressway's northern limit (see Figure 6-23). The larger of the two Charles River bridges, the Leonard P. Zakim Bunker Hill Bridge, is a ten-lane, cable-stayed hybrid bridge, the widest ever built and the first to use an asymmetrical design. The CA/T Project started construction in 1991 and was declared complete at the end of 2007.

The initial concepts for depressing the Central Artery were formed in the late 1970s. Preliminary designs began in 1980 when a working paper was produced that evaluated the geological and geotechnical conditions of the Leverett Circle Connector. The connector was a part of the "trumpet interchange" — a series of tunnels, surface roads and bridges linking Storrow Drive, Interstate 93, the Route 1 Tobin Bridge, the Craigie Bridge over the Charles River and a new underground Central Artery. The initial Environmental Impact Report for the Third Harbor Tunnel from downtown Boston to the Bremen Street area of East Boston was developed in 1982. The Central Artery depression was added in 1983, with the new Seaport Access South Boston location for the Third Harbor Tunnel. So, the CA/T Project started in 1982 and the Environmental Impact Statement process was underway in 1983. The CA/T Project was authorized by U.S. Congress in 1988. The joint venture of Bechtel and Parsons Brinckerhoff was assigned to be project design and construction management consultant. The final design began in 1989.

The first part of the CA/T Project to be designed and constructed was the new Third Harbor Tunnel. A South Boston by-pass road from the Southeast Expressway to the South Boston portal of the Ted Williams Tunnel opened in 1993. The tunnel itself opened in 1995. A bridge (then known as "the little bridge") across the Charles River connecting Interstate 93 and Leverett Circle/ Storrow Drive was opened in 1999. The Zakim Bridge, which carries Interstate 93 over the Charles River and into the new Central Artery Tunnel, opened in 2003. The underground artery partially opened in 2003, and the Massachusetts Turnpike extension to the Logan Airport and Route 1A opened in 2004.

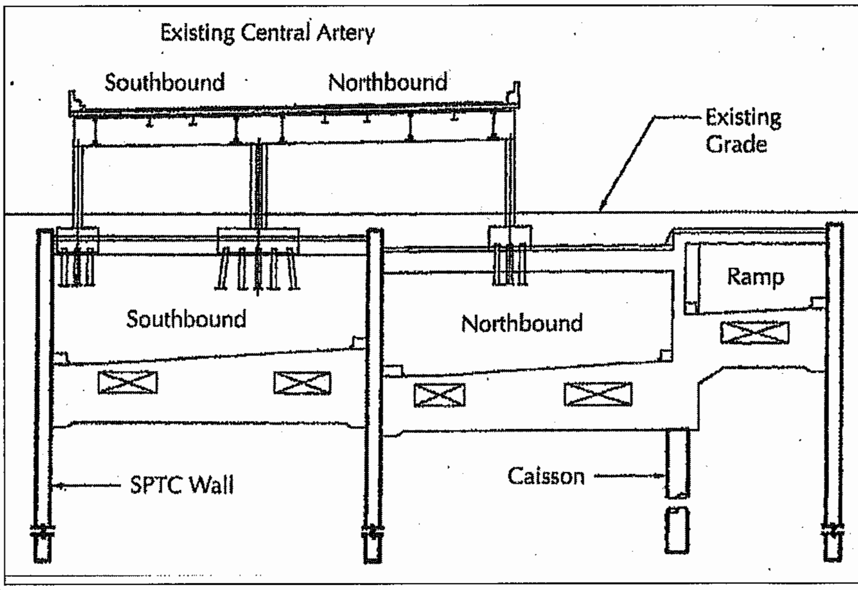



**FIGURE 6-22. Relation between the pre-existing Southeast Expressway viaduct and the new Central Artery Tunnel. (Courtesy of the Massachusetts Department of Public Works.)**

*Overview of Project Requirements & Constraints.* The design engineers were faced with formidable challenges of:

- building a new highway through the heart of Boston beneath the existing elevated highway (see Figure 6-22);
- keeping the existing highway operating to maintain traffic flow;
- avoiding disruption of a very old infrastructure, some dating from the 1600s, but expanded and updated in the 1800s when Boston experienced significant growth; and,
- not causing any damage to or disturbing historic buildings.

The underground route of the road and its ramps were crisscrossed with numerous century old utility lines (whose locations were sometimes unknown), ninety-year-old subway tunnels and several generations of old seawalls, piers and foundations (see Figure 6-24). In addition, the highway had to pass under a major confluence of rail lines that lead to the railhead at South Station, and cross beneath the Fort Point Channel.

A cut-and-cover tunnel was selected for the 30 meter (100 foot) wide highway. Preliminary work consisted of utility relocation, an ongoing rodent control program necessitated by the disturbance of their habitat, underpinning of the existing 1,128 meter (3,700 foot) long end-bearing, pile-supported elevated highway and an on-going archeological survey. In order to control the groundwater and tidal flow (and at the same time provide support for the tunnel), 7,927 linear meters (26,000 feet) of steel-reinforced concrete slurry wall were constructed along the downtown Central Artery route as combined excavation support wall, underpinning supports and final tunnel structure wall. Concrete immersed tunnels were used in the crossing of the Fort Point Channel because of shallow water depths and low clearance of existing bridges, and because of the existing transit tunnels that had to be crossed. These concrete segments were made on-site in a casting basin at the edge of Fort

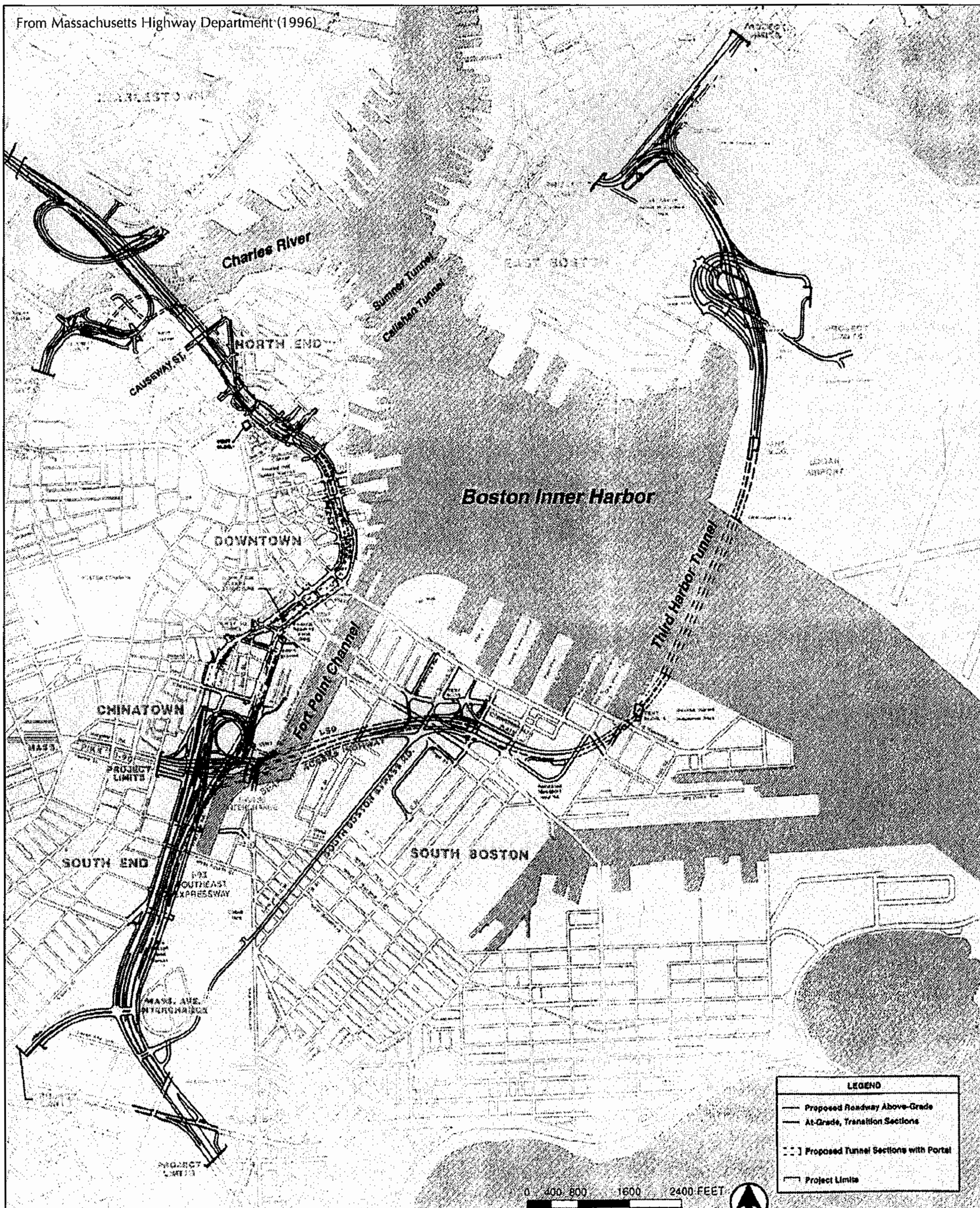



**FIGURE 6-23. Plan of the Interstate 93 Central Artery/Tunnel routes.**

Point Channel, which was isolated using cellular coffer dams in order to keep it dry during construction. Bridge construction used many types, including pre-cast bulb-tree girders, pre-cast and pre-stressed butted-box beams, cast-in-place box beams and steel box beams. The variable geology of the CA/T Project areas had substantial impact on the engineering design and construction of various project elements.

*Sources of Information on Geology of the Project Area.* Although the geology of the Boston area is extremely complex, subsurface conditions along the Central Artery/Tunnel route were generally known from several sources of available data that included:

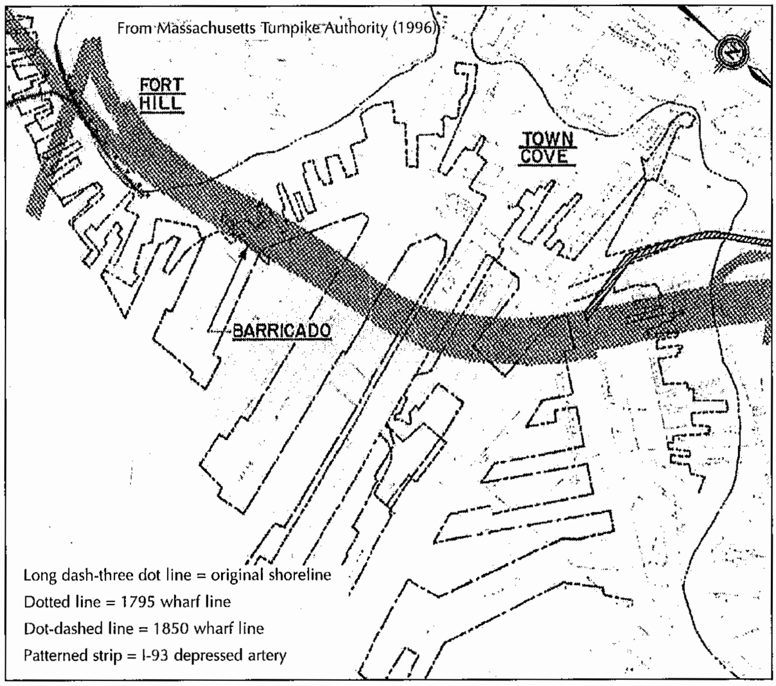



**FIGURE 6-24. Map of the Town Cove area of Boston's inner harbor showing the original shoreline, historic wharves and depressed route of Interstate 93 (view southwest).**

- Historical maps dating back to the seventeenth century that showed the original shoreline of the Shawmut Peninsula, and what was then the highlands associated with the Trimountain. These maps were important because the artery route followed the old shoreline along Atlantic Avenue and Commercial Street from South Station to the Charles River. The original Fort Point Channel ran through the South Station area and had been filled with a succession of wharfs from the late 1700s through 1900 (see Figure 6-24).
- Compilations of test boring records dating back to the early 1900s published in two collections by the Boston Society of Civil Engineers in the late 1960s.
- The record of previous subsurface investigations conducted over the previous thirty years by Boston's geotechnical engineering firms who were selected to work on the new Central Artery.
- The geological data on file with the United States Geological Survey (USGS) as part of its Urban Geology Program (which Clifford A. Kaye had directed).
- Various publications by several non-USGS sources.
- The publication of *The Geology of the City of Boston* by Woodhouse and Barosh (1991), which included a compilation of the existing structures and their foundation types along the artery route.

From an historical point of view, the route of the depressed CA/T from north (Zakim Bridge) to south crosses the former colonial Mill Cove and then enters the original higher Shawmut Peninsula and the adjacent North End. From there, it proceeds across the Town Cove, crosses the southeast portion of the Shawmut Peninsula and then into the South Boston Bay (see Figures 6-24 & 6-25). The Massachusetts Turnpike Connector passes through the east side of the Boston Neck, the South Cove, Fort Point Channel and through South Boston Bay before traversing Boston Harbor, the Bird Island Flats area and up to Noddle's Island. The types of geologic deposits underlying the artery route have been described in general; the description here looks at specific conditions along the exact alignment.

A section along the route of the Central Artery displays a sequence of typical deposits below the low-lying areas that surrounded the original Shawmut Peninsula. Surface fill materials overlie and compress an organic sediment layer that represents estuarine deposits.

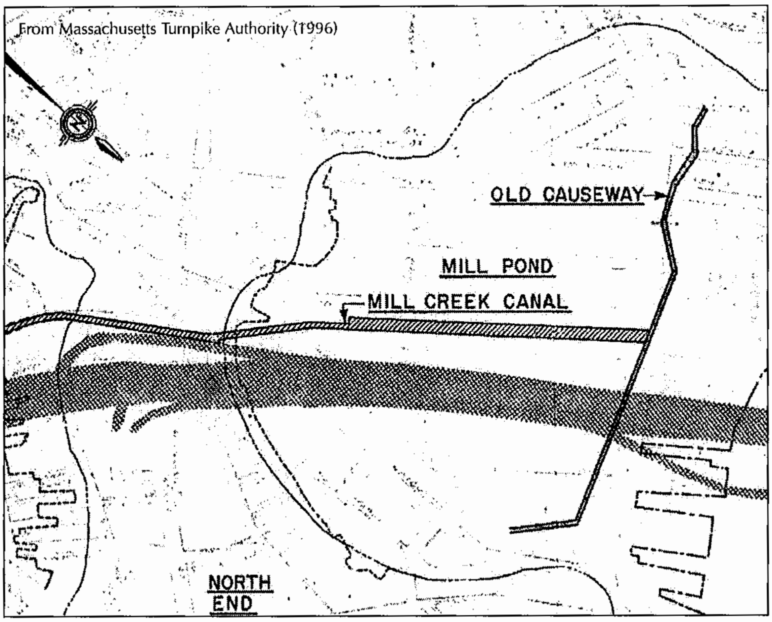



**FIGURE 6-25. Map of the Mill Pond area near Boston's North End, showing the original shoreline and the depressed route of Interstate 93 leading to the Zakim Bridge at the right side of the old Causeway.**

The till has been found to be locally absent or thin (such as under the Thomas P. O'Neill Building at North Station), or to reach considerable thickness in the Fort Hill-South Station area and near Charlestown (see Figures 3-86, & 3-110). In addition to these vertical changes in material, the pinching out of units and their surface relief results in great lateral variation over short distances (see Figures 3-82 & 3-94). This variation, in turn, results in widely different foundation conditions, amounts of water inflow and characteristics of material to be excavated.

A discontinuous outwash sand layer underlies the organic sediment and overlies marine clays known to reach considerable thickness. The clay layer is for the most part a competent bearing stratum but where it is eroded and redeposited, or reworked (such as in the Fort Point Channel and Charles River areas), the reworked clay is softer, less over-consolidated and has much lower strength. Some of the clay encountered in test borings contains coarser material such as sand, gravel and cobbles. Although this mixed clay has a till-like appearance, it is part of a glaciomarine deposit. Foundation engineers learned lessons about this material on earlier projects when piles driven into what was classified till or till-like often did not take up as planned and instead became friction piles. This problem also occurred where the actual till contains a high percentage of clay and behaves plastically. This behavior, for example, was experienced during the construction of the Little Mystic housing project in Charlestown, in the Fenway area of Boston and in Haymarket Square. A second discontinuous outwash deposit below the clay occurs on top of the till.

The lithology of the bedrock of Boston and the bedrock contours in the project area along Atlantic and Commercial avenues are shown on Kaye's maps of 1980 and 1982, respectively (see Figures 3-12, 3-51 & 3-54). The bedrock argillite surface is at an elevation of roughly –30 meters (–100 feet) MSL, in agreement with that found in explorations for the International Place (Fort Hill) office building near South Station. However, the top of bedrock varies considerably along the lengths of the entire CA/T Project. Many more details of this argillite surface are now known along the project area, along with the character and variations of the surficial geology.

*Central Artery.* The new tunnel section of the Central Artery wraps around the northeast side of Boston between South Station and North Station, which serve Amtrak and commuter rail lines. This section is officially the Thomas P. O'Neill, Jr. Tunnel, which extends 2.4 kilometers (1.5 miles) from Kneeland Street northward to Causeway Street. From there, it rises to cross the mouth of the Charles River and expands into a maze of viaducts and ramps over the western edge of Charlestown. Hundreds of test borings were drilled between 1989 and 1997 along this route to add to the data provided by previous explorations for the design of the new highway. Lines of boreholes were designated the West, Center and East Slurry Wall Test Borings and the West and East Tunnel Wall Test Borings. The test borings were spaced 30 to 46 meters (100 to 150 feet) apart. The findings allowed a series of well-controlled geologic profiles (see Figures 6-26 through 6-39) to be drawn both parallel and transverse to the roadway.

The surface of the argillite shows two low bedrock mounds in the south and only local irregularities to the north on the nearly continuous section from near South Station to the Charles River (see Figures 6-26 to 6-35). The irregularity of the bedrock surface is due to stream and some glacial erosion. The degree of erosion is influenced by kaolinized zones, fault zones and the degree of weathering. The surface climbs along a distance of 1 kilometer (0.6 mile) from about elevation –32 meters (–105 feet) MSL at the south side of Kneeland Street, opposite the southern end of the platforms of South Station, to over elevation –20 meters (–65 feet) MSL near the terminal building at Summer Street and then descends back down to –30.5 meters (–100 feet) MSL a short distance of 0.5 kilometers (0.3 miles) to the north at Congress Street. The surface rises again to –24.4 to –18.3 meters (–80 to –60 feet) MSL between Congress and Oliver streets, a distance of 0.6 kilometers (0.37 miles). The surface is at about elevation –36.6 meters (–120 feet) MSL on the north side of Oliver Street, from which it gradually rises to approximately –12 meters (–40 feet) MSL at North Station, with moderate local variable relief of 3 to 6 meters (10 to 20 feet) over a distance of 3.6 kilometers (2.25 miles).

The argillite was known to be locally kaolinized. For CA/T design and construction purposes, argillite samples that could be crumpled by hand and sampled with a split spoon sampler were classified as severely to completely weathered and given the designation $B_1$ on the soil profiles. Its geotechnical properties were generally equivalent to hard clay. The geotechnical engineers recommended that the end-bearing design contact pressures for the slurry walls be reduced in the areas where thick weathered rock was found. The $B_1$ rock was found in many of the borings. South of Essex Street, the $B_1$ rock was generally confined to the top 1.5 meters (5 feet) of the rock. The $B_1$ rock is mostly encountered north of Essex Street and is thickest near Congress and Summer streets, and one of the borings just south of Summer Street penetrated more than 30.2 meters (99 feet) of kaolinized argillite. This area coincides with a fault zone shown on Kaye's 1982 map (see Figure 3-51). The rock is so soft that split spoons for standard penetration tests could be readily driven to depths of 14.6 meters (48 feet) below the surface of the rock. From Congress Street to North Street, the $B_1$ rock is on the order of 6.1 meters (20 feet) thick, except near Congress Street, where it is up to 27.4 meters (90 feet) thick. It is generally less than 3 meters (10 feet) thick between North and Causeway streets. The kaolinized zone was usually confined to the top of the rock, but was also found deeper, where it is associated with major jointing and faulting.

The surfaces of the overlying Pleistocene units have much greater relief, which causes them to vary greatly in thickness and commonly pinch out laterally. The thickness of the till is less than 3 meters (10 feet) at Kneeland Street, over 10.7 meters (35 feet) at the edge of South Station and Summer Street, and reaches 35 meters (115 feet) a little north of Oliver Street (see Figure 6-27), where it constitutes the thick till of the Fort Hill drumlin. Farther north near Milk Street, the till thins to about 3 meters (10 feet). The south and north slopes of the till appear close to that of the original drumlin, which is not "cored" by bedrock. Along the rest of the section toward North Station, the till generally ranges between 1.5 to 7.5 meters (5 to 25 feet) in thickness and is absent locally. Two large clay lenses occur within the southern part of the Fort Hill till (see Figure 3-82) and a thicker 10.8 meter (35 foot) clay and sand lens lies within the till over a slight bedrock low at Valenti Way farther north in the North Station area (see Figure 6-32). These lenses apparently separate the two tills seen in the harbor and are related to the thrusted deposits in Beacon Hill to the west. Similar

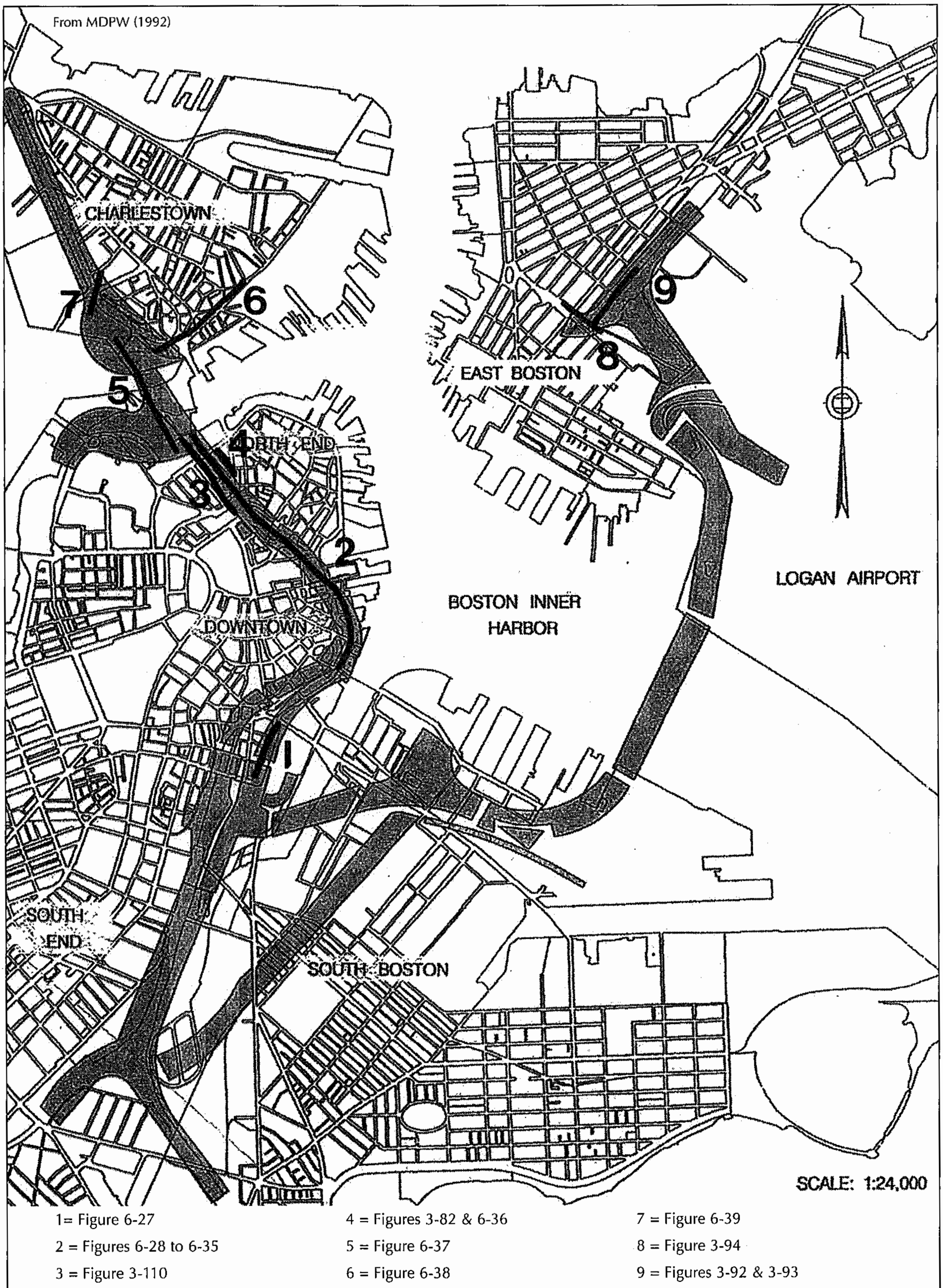



**FIGURE 6-26. Plan of the Central Artery/Tunnel Project showing sites of sections.**

lenses on the other side of Boston at the Feldberg Building of the Beth Israel Hospital on Longwood Avenue were interpreted as local ponding. Of particular interest is a lens of sand and gravel found between the till and bedrock near Congress Street that could represent a glaciation older than that of the lower of the two tills. (Such an occurrence of sand was also found under Tech Square in Kendall Square, Cambridge.)

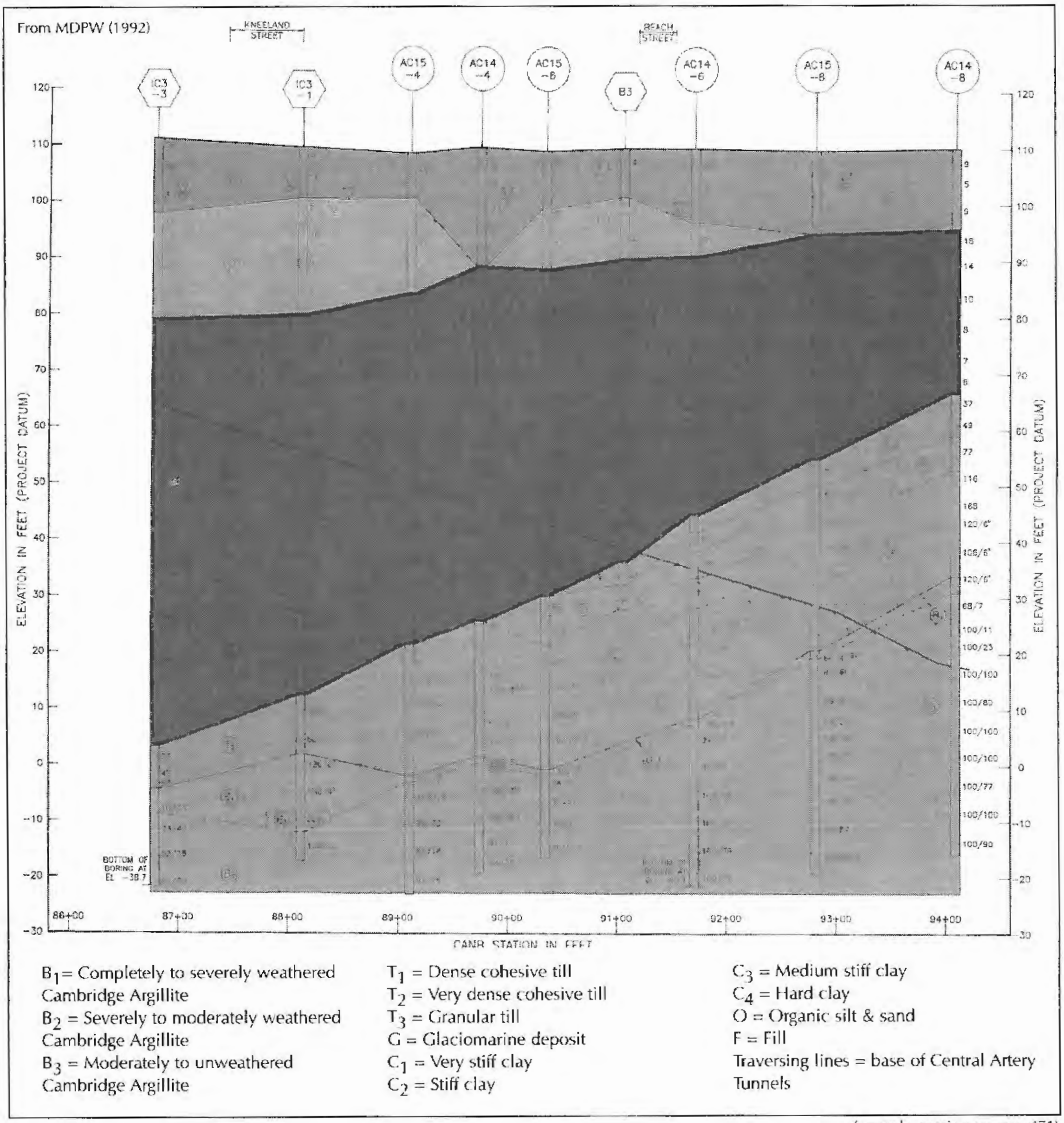
Marine clay flanks the sides of the Fort Hill drumlin and rests directly on the till. At Kneeland Street, the clay is 23 meters (75 feet) thick, and thins to about 4.6 meters (15 feet) at Beach Street or Essex Street, at the south edge of the South Station terminal building, before pinching out a short distance to the north at Summer Street (see Figure 6-27). The Blue Cross-Blue Shield Building at 100 Summer Street did not encounter any clay in the excavation. A shallow and very dense clayey till was encountered close to the surface. The clay wedge on the north flank of the drumlin begins near India Street and thickens northward to 16.8 meters (55 feet) where it underlies the old Town Cove area between North Street and Broad Street (see Figure 6-30). North of State Street, a mound of glaciomarine material rises beneath the clay and expands opposite Quincy Market to a thickness of about 13.7 meters (45 feet) and the clay is reduced to 3 to 4.6 meters (10 to 15 feet) locally (see Figure 6-31). The marine clay again thickens to about 24.4 meters (80 feet) as the glaciomarine material pinches out at the south edge of North Street for a short distance. The glaciomarine deposit again appears and thickens northward at the expense of the clay to about 22.8 meters (75 feet) near Hanover Street as the clay pinches out (see Figure 6-32). Just south of Hanover Street, a lens of sand and gravel nearly 7.6 meters (25 feet) thick occurs in a channel cut into the top of the glaciomarine deposit. The clay again appears at the projection of North Marginal Street and thickens northward to about 9.1 meters (30 feet) where the glaciomarine once more pinches out beneath it near the south edge of North Washington Street (see Figure 6-33).

Organic sediment with a thickness of 6.1 meters (20 feet) is present near Kneeland Street and thins to the north in the area of the South Station terminal building. Organic sediment also overlies the clay in the Town Cove area (see Figure 6-30) between India Street and the south edge of North Street, and reaches a thickness of about 6.1 meters (20 feet). Organic sediment comes in above the clay at Endicott Street in the North End and thickens northward to nearly 15.2 meters (50 feet) at Causeway Street as the clay wedges out between it and the thin till below (see Figures 3-82 & 3-110). The organic sediment thins northward in passing North Station, where the overlying fill increases to over 12.2 meters (40 feet) in thickness.

Fill is found over the entire Central Artery. It is generally in the range of 3 to 6.1 meters (10 to 20 feet) in thickness with 3 to 7.6 meters (10 to 25 feet) in the Town Cove section and 6.1 to 9.1 meters (20 to 30 feet) between Congress and Oliver streets (see Figures 6-26 through 6-36).

The surficial deposits were well expressed by the original colonial topography. The Fort Hill drumlin was formed by thick till, with the spine of the drumlin connected to the North End by a mound of glaciomarine deposit. The general lowlands north of Fort Hill, at the Town Cove and in the Mill Pond areas, were connected by marine clay, with specific low areas corresponding to the presence of organic sediment. The low areas were first used for the colonial town docks at the present-day Dock Square and Long Wharf, and Mill Pond at the Bullfinch Triangle. These areas were subsequently sites of thick filling, with urban expansion following shortly thereafter. The Town Dock area in particular received heterogeneous building material such as granite blocks, wood used for cribbage and debris that caused many construction problems over the centuries (see Figure 6-24).

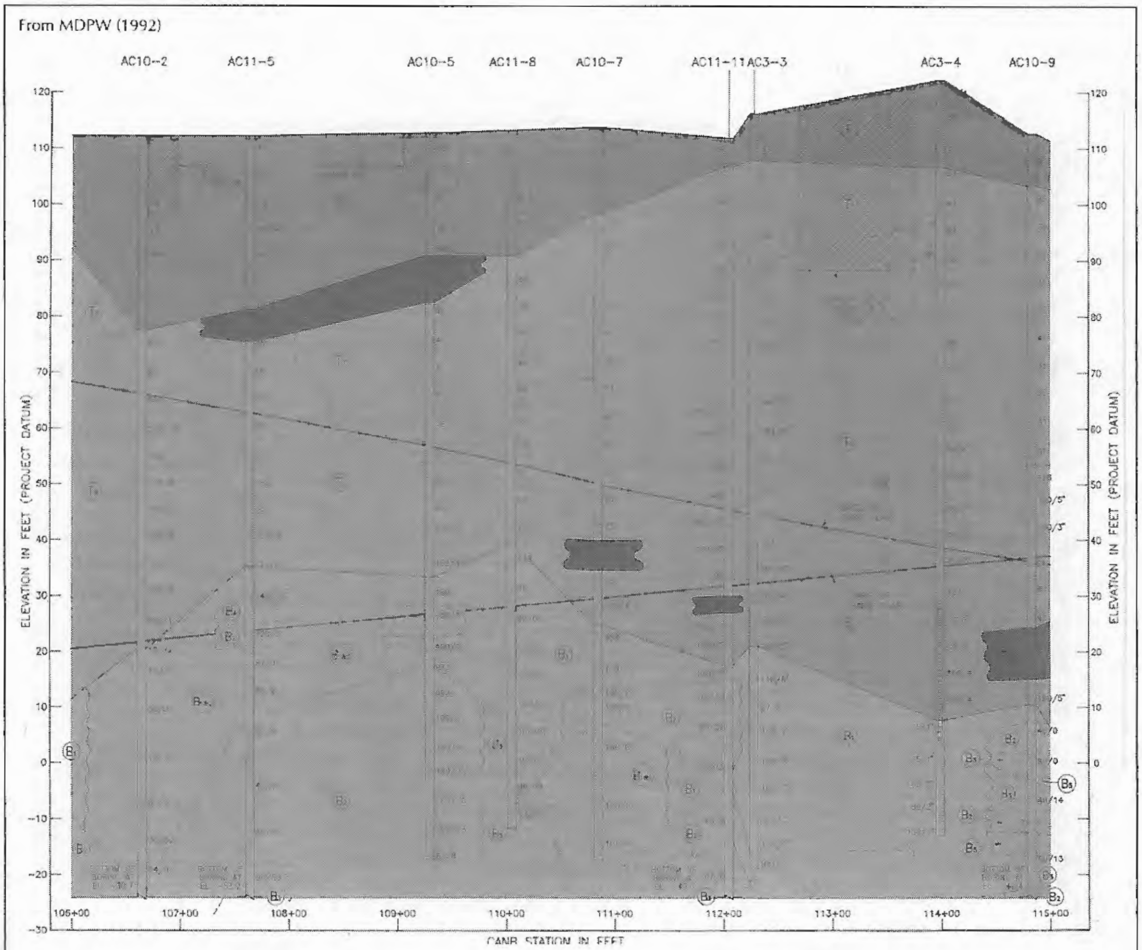
The northbound depressed artery descends from the southern artery entry, which is about 380 meters (1,250 feet) south of Kneeland Street. Proceeding north and downward, the tunnel between Kneeland Street and South Station descends through clay, till, and 4.9 meters (16 feet) into the argillite, which is severely weathered. The roadway joins the




(see color version on page 471)

**FIGURE 6-27. Section along the Central Artery west of South Station (middle slurry wall between stations 87+00 and 94+00) showing the marine clay overlapping the south side of the Fort Hill drumlin (view west).**

southbound tunnel at about Northern Avenue where it re-enters the till south of Congress Street and continues through it past Oliver Street and International Place, following along Atlantic Avenue. Near the old Fort Hill and Northern Avenue, the highway continues through the thick layer of till, which is part of the excavated Fort Hill drumlin. Very hard clay lenses up to 9.1 meters (30 feet) thick are found in the till. A section in the area of Oliver Street, Rowe's Wharf and International Place to Harbor Towers near India Street shows the roadway ascending through the Fort Hill till into a marine clay layer in the area of India Street to State Street. From there, the artery tunnel passes over the Blue Line Tunnel and begins a descent through the clay northward to the Quincy Market area where it passes




$B_1$ = Completely to severely weathered Cambridge Argillite
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G = Glaciomarine deposit
$C_1$ = Very stiff clay
$C_2$ = Stiff clay
$C_3$ = Medium stiff clay
$C_4$ = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

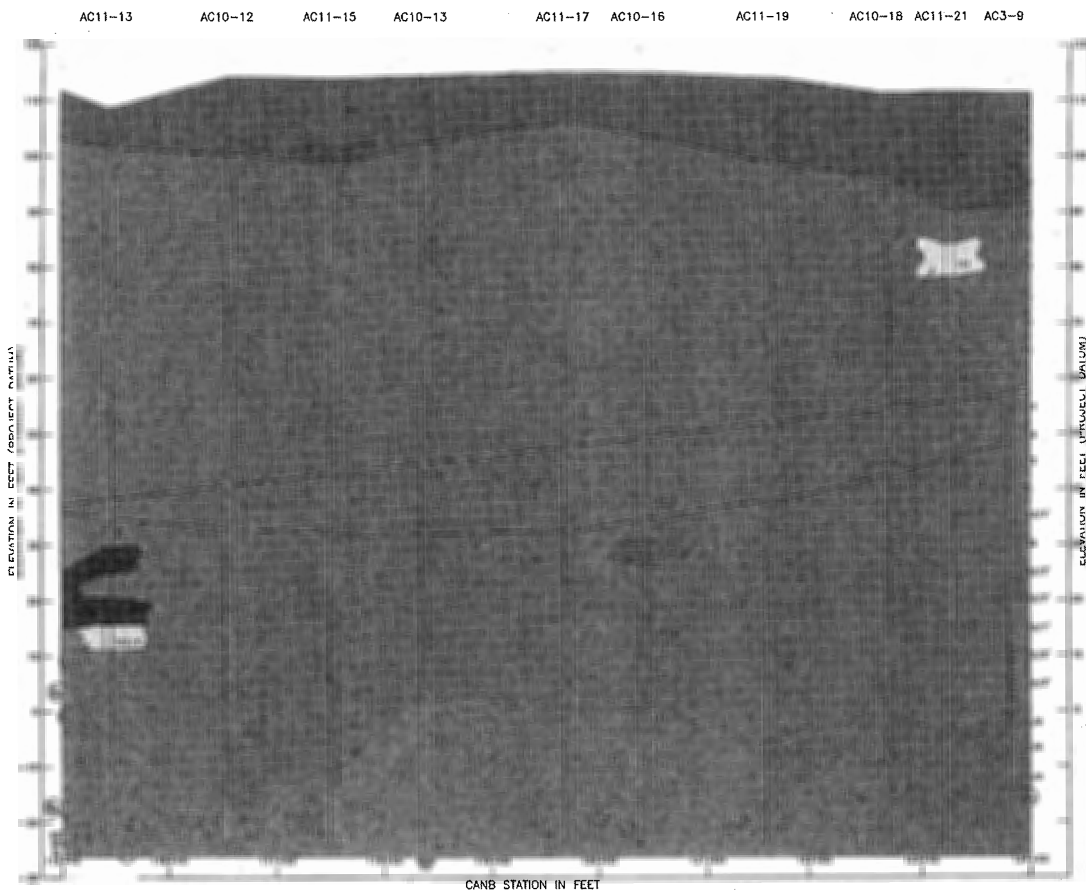
(see color version on page 472)

**FIGURE 6-28. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 106+00 and 115+00 (view west to southwest).**

through a mound of glaciomarine material and back into marine clay. It re-enters the glaciomarine deposit near North Street, levels out for a short distance and begins a long, gradual ascent toward the Charles River as it enters thin till and argillite in passing the entrance to the Callahan Tunnel.

The tunnel invert continues to skim the top of the weathered bedrock and basal till through the North End and much of the old Mill Dam area as it ascends toward the Charles River Crossing. It re-enters the clay near Valenti Way and rises into the organic sediment at Causeway Street. The till near the Charles River Crossing contains a 4.6 meter (15 foot) thick layer of outwash and a hard compacted clay layer about 12.2 meters (40 feet) thick between the till and the bedrock. Water carried by such sand lenses can cause serious problems during construction, but did not cause problems for CA/T Project construction.

From MDPW (1992)

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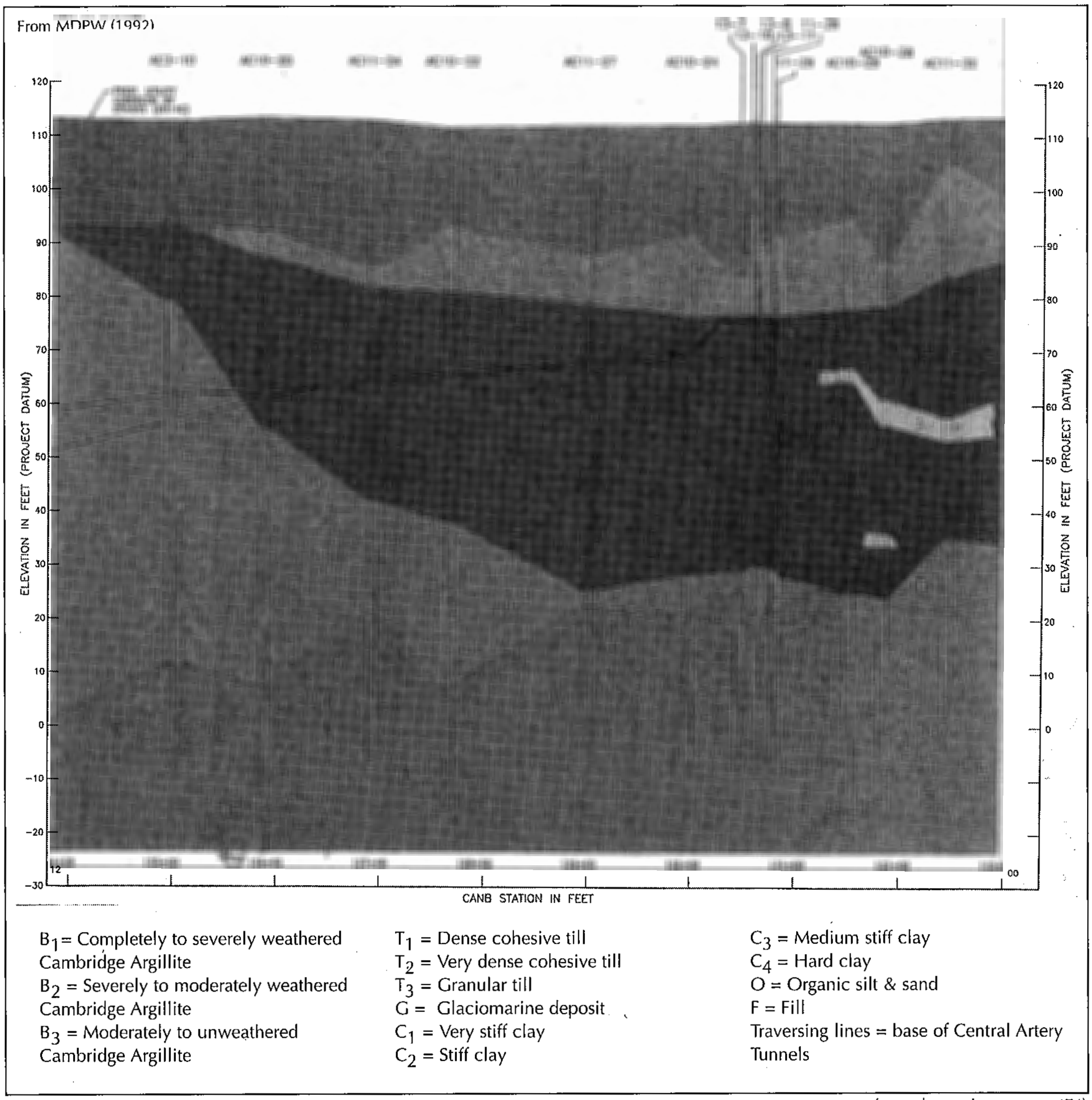
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 473)

**FIGURE 6-29. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 115+00 and 124+00 (view west to southwest).**

*Leverett Circle-Charlestown.* Very extensive drilling was carried out in stages around a broad area of the Charles River from Leverett Circle, North Station and southeastern Charlestown. An analysis of hundreds of these test borings was used to produce preliminary geologic profiles in 1980-1981 (see Figures 6-37, 6-38 & 6-39), and other more detailed profiles in the 1990s. The contours of the top of bedrock in this area were known prior to the final design of the new artery and shown in the early Central Artery working papers. The bedrock surface (see Figure 3-63) shows ridges and valleys that range from a high of elevation –3 meters (–10 feet) MSL near the former Massachusetts Registry of Motor Vehicle headquarters on Nashua Street to an elevation of –33 meters (–110 feet) MSL at the Museum of Science on the other side of the Charles River. The bedrock elevation –12 meters (–40 feet) MSL at the end of the Central Artery is on a narrow northwest-trending ridge that extends



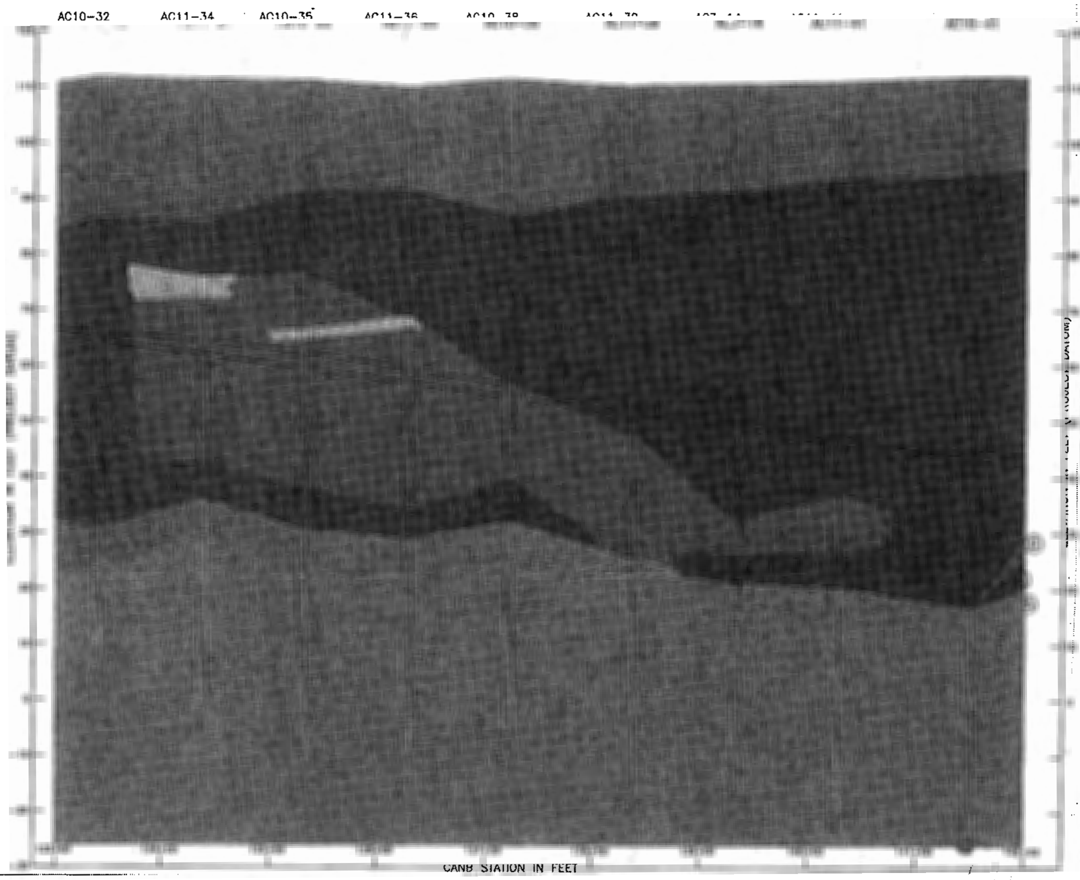

(see color version on page 474)

**FIGURE 6-30. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 124+00 and 133+00 (view west to southwest).**

into Charlestown from the east side of North Station. The ridge dips down slightly to the west and from there rises to elevation –3 meters (–10 feet) MSL into a broad north-trending arch northwest of the station. The south end of the arch is crossed by a northeast-trending swale under the Charles River. Farther to the northwest near Charlestown Neck, the bedrock rises to within 6.1 meters (20 feet) of the surface (Stone & Webster, 1996) and the drumlin at this location is apparently rock-cored. Bedrock consists of the argillite, which is kaolinized in places to a minimum depth of 15.8 meters (52 feet).

The overlying till is thin to absent from North Station northward into the southwest edge of Charlestown and generally ranges from 3 to 9.1 meters (10 to 30 feet) in thickness farther north, although it is absent locally. Within the till, pervious zones of sands up to 6.1 meters (20 feet) thick are found locally and possibly separate the two tills. The till increas-

From MDPW (1992)

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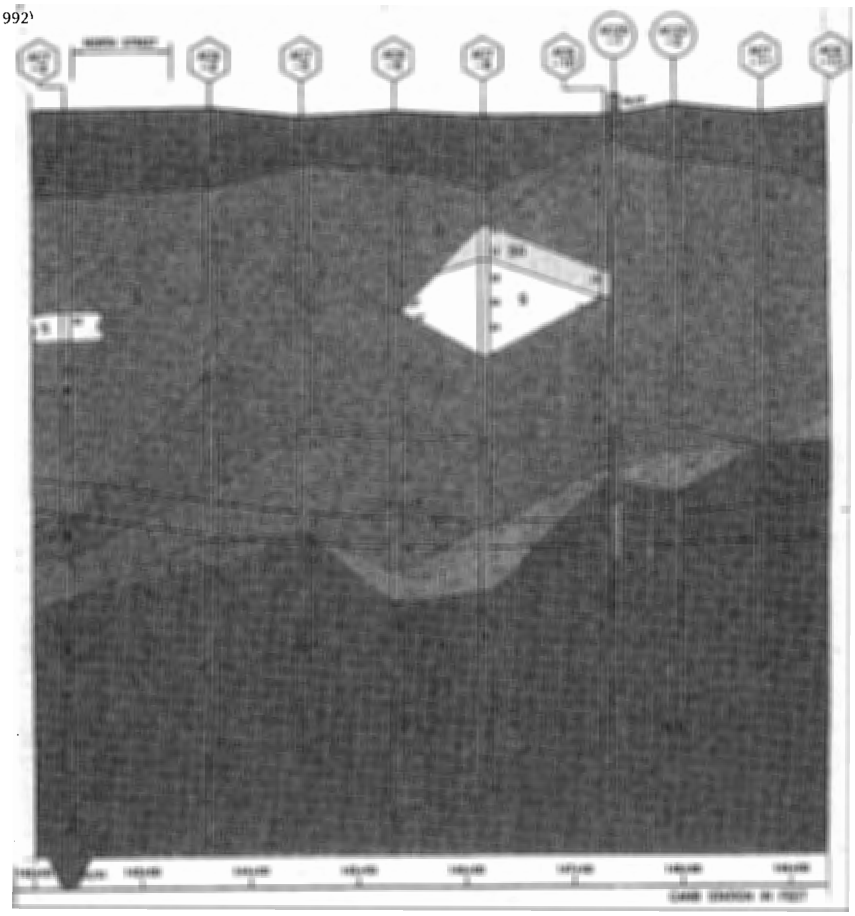
$C_3$ = Medium stiff clay
$C_4$ = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 475)

**FIGURE 6-31. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 133+00 and 142+00 (view west to southwest).**

es northeastward of the highway alignment toward the drumlin complex, which forms most of Charlestown. The till is over 15.2 meters (50 feet) thick northeastward toward the Morton's Hill drumlin at the southern end of the Tobin Bridge. The glaciomarine material was not identified and separated from the till during the early work in this area, principally because the origin of this type of deposit was not known at the time of those earlier explorations. However, the till-like material that was recognized at places above the till is apparently the glaciomarine material. This material was found along the northeast side of the Millers River and in a zone extending northeastward from the Charles River near North Station to the old Charlestown Navy Yard. The additional drilling in the mid-1990s along the highway alignment indicates a considerable amount is present and that much of the earlier till had been eroded. A mound of glaciomarine material, about 5.2 meters (50

From MDPW (1992)



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F = Fill
Traversing lines = base of Central Artery Tunnels

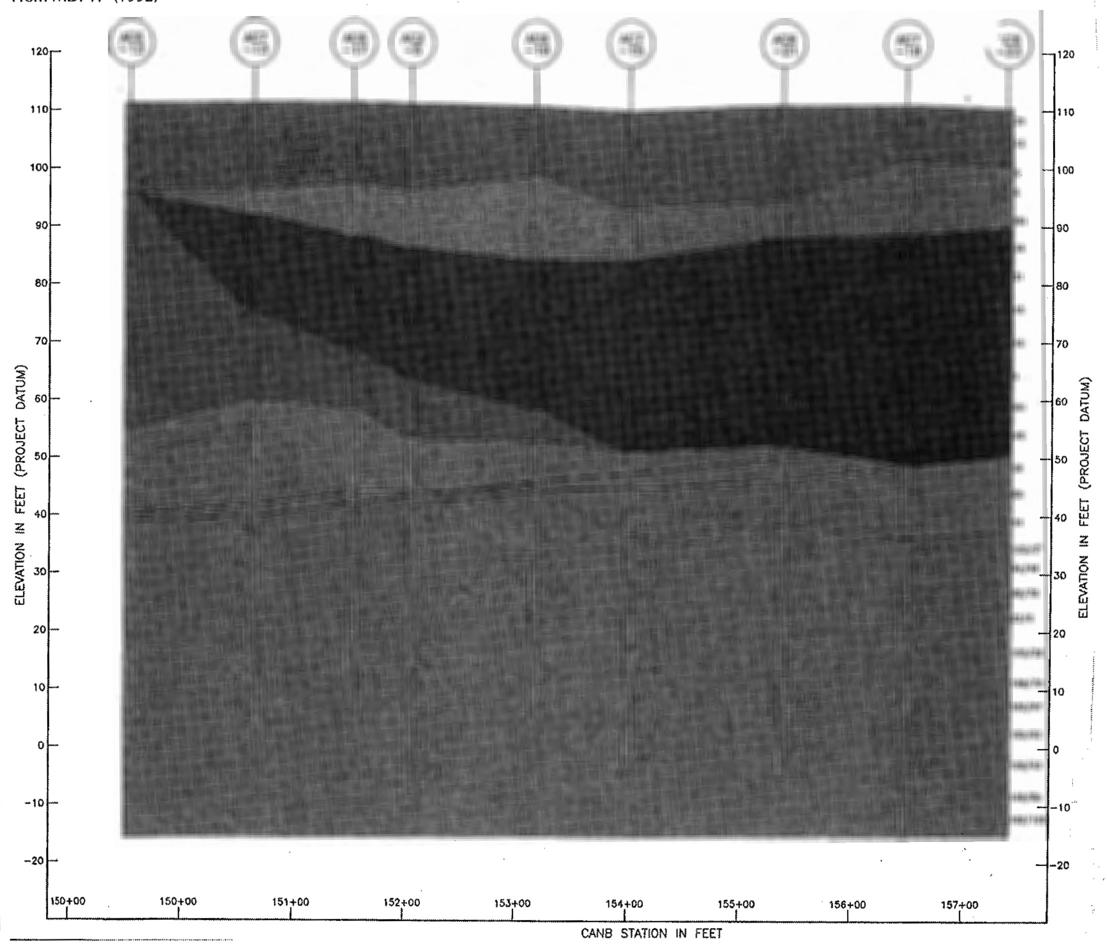
(see color version on page 476)

**FIGURE 6-32. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 142+00 and 150+00 (view west to southwest).**

feet) thick (Stone & Webster, 1996), identified in the Gilmore Bridge-Bunker Hill Community College area, separates basins of marine clay to the north and south (see Figure 6-39). However, the material to the northeast in the drumlin complex is till.

The top of the till and glaciomarine deposit are eroded and cut by several channels. The deepest channel lies beneath the Charles River and close to the underlying swale in the top of the bedrock. Most of the channels are filled by marine clay, but the lower outwash sand and gravel occurs as fill below the clay in many places. This discontinuous layer of pervious sand and gravel is generally less than 3 meters (10 feet) thick, but ranges up to 6.1 meters (20 feet) in an east- to northeast-trending channel cut across the area. This channel likely traces the route of the former Millers River. The overlying marine clay stratum varies in consistency and thickness. The clay is generally found between elevations 1.2 to –15.2 meters (4 to –50 feet) MSL

From MDPW (1992)

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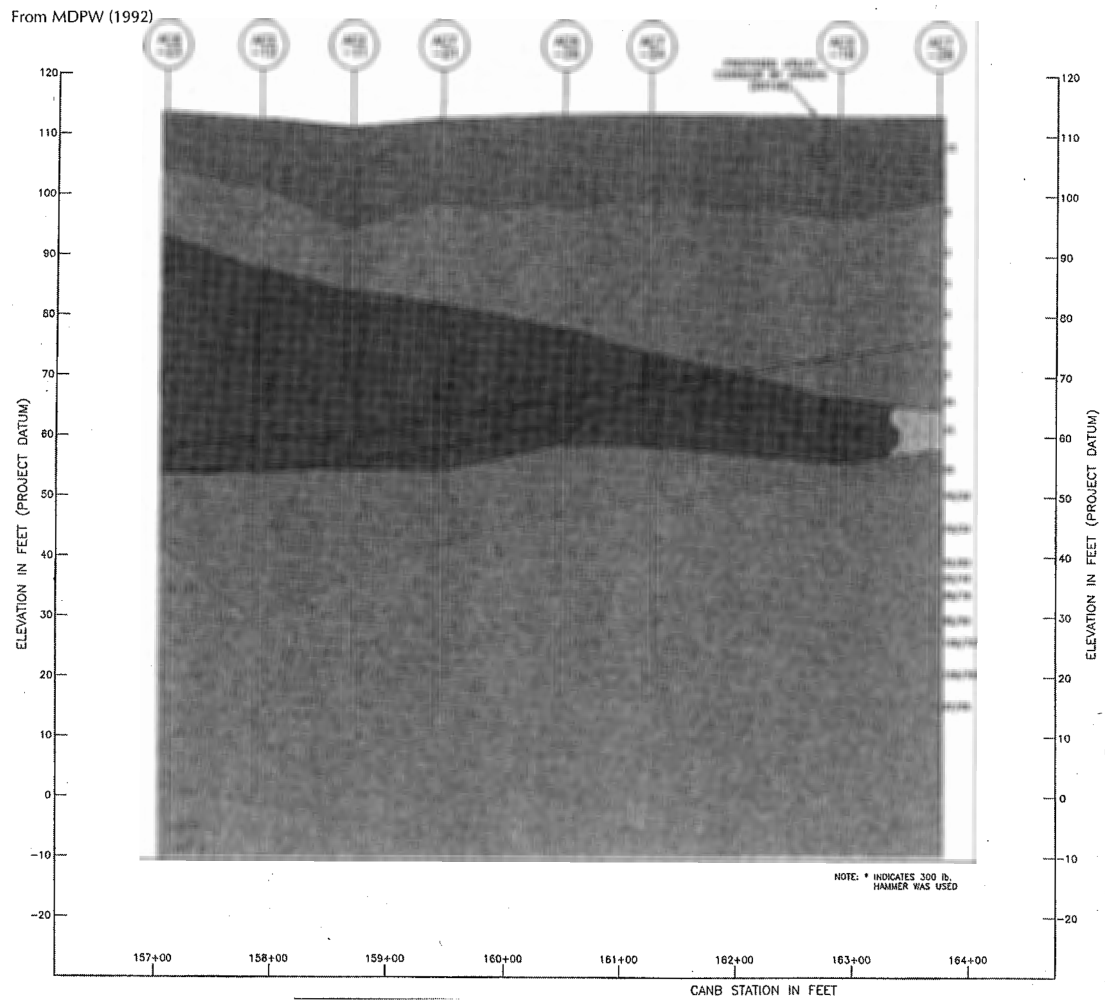
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 477)

**FIGURE 6-33. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 150+00 and 157+00 (view west to southwest).**

and is up to 10.7 meters (35 feet) thick, but more commonly is between 2.7 and 7.6 meters (9 and 25 feet) thick. The clay pinches out due to deposition against the thick glaciomarine material or higher drumlin till and also locally due to later erosion (see Figure 6-37).

The undulating top of the clay, with a few channels, is due to erosion after a drop in sea-level or isostatic uplift. An upper discontinuous, generally 1.5 to 3 meter (5 to 10 foot) layer of sand and gravel outwash, representing the Lexington Outwash (and possibly some alluvium) overlies the clay. It is thickest in the shallow channels and missing over the areas of higher drumlin till. Organic silt deposits blanket the area and usually range from 0.6 to 6.1 meters (2 to 20 feet), being thinner where compressed by the overlying fill and pinching out against the drumlin to the northeast (see Figure 6-38). Some irregularities at the base of

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$C_4$ = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

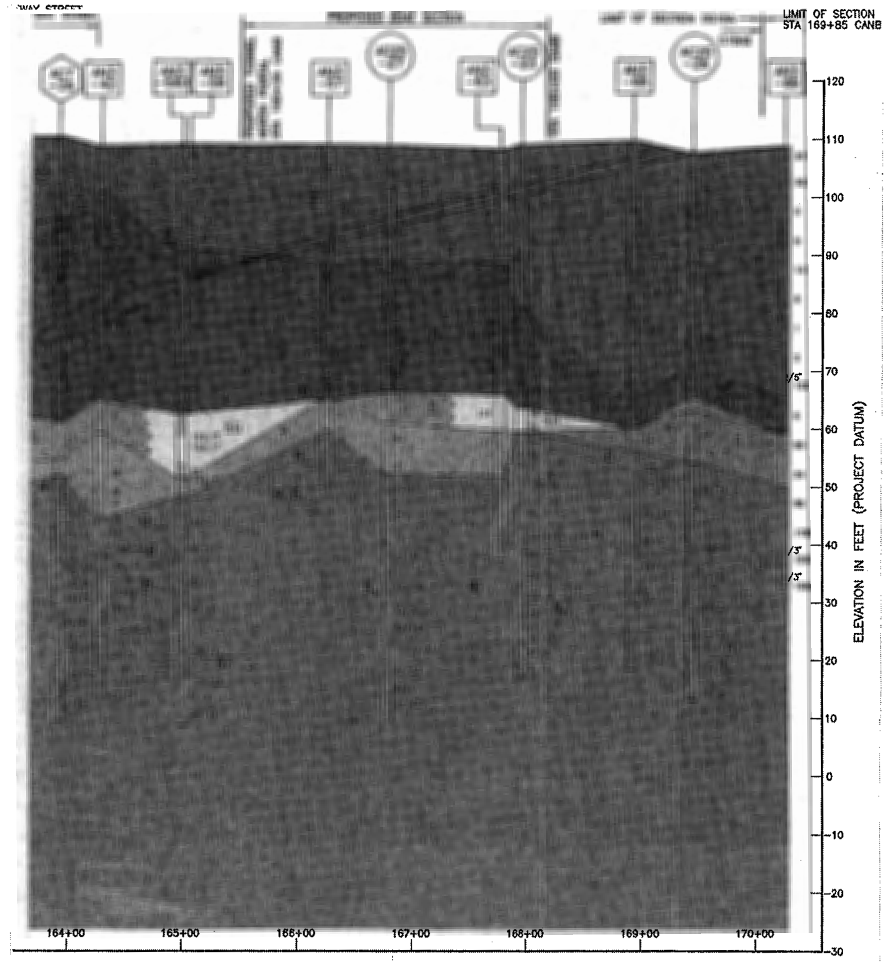
(see color version on page 478)

**FIGURE 6-34. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 157+00 and 164+00 (view west to southwest).**

the silt indicate at least slight erosion before its deposition. The upper limit of the organic silt at that location and elsewhere lies near the 1630 shoreline. Also, younger organic silt is found along the channels of the Charles and Millers rivers.

A channel in the till on the flank of the Morton's Hill drumlin displays the stratigraphic relations well and indicates a long geologic history (see Figure 6-38). It was probably first cut into a gently sloping southwest flank of the drumlin, filled by the Lower Outwash, and then apparently re-cut slightly before the deposition of the marine clay, creating a small surface depression that first received Lexington Outwash and then organic silt after additional erosion. Below the existing remnant of the Millers River are offset

From MDPW (1992)

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|---|---|---|
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| $B_3$ = Moderately to unweathered Cambridge Argillite | $T_3$ = Granular till | O = Organic silt & sand |
| | G = Glaciomarine deposit | F = Fill |
| | $C_1$ = Very stiff clay | Traversing lines = base of Central Artery Tunnels |
| | $C_2$ = Stiff clay | |

(see color version on page 479)

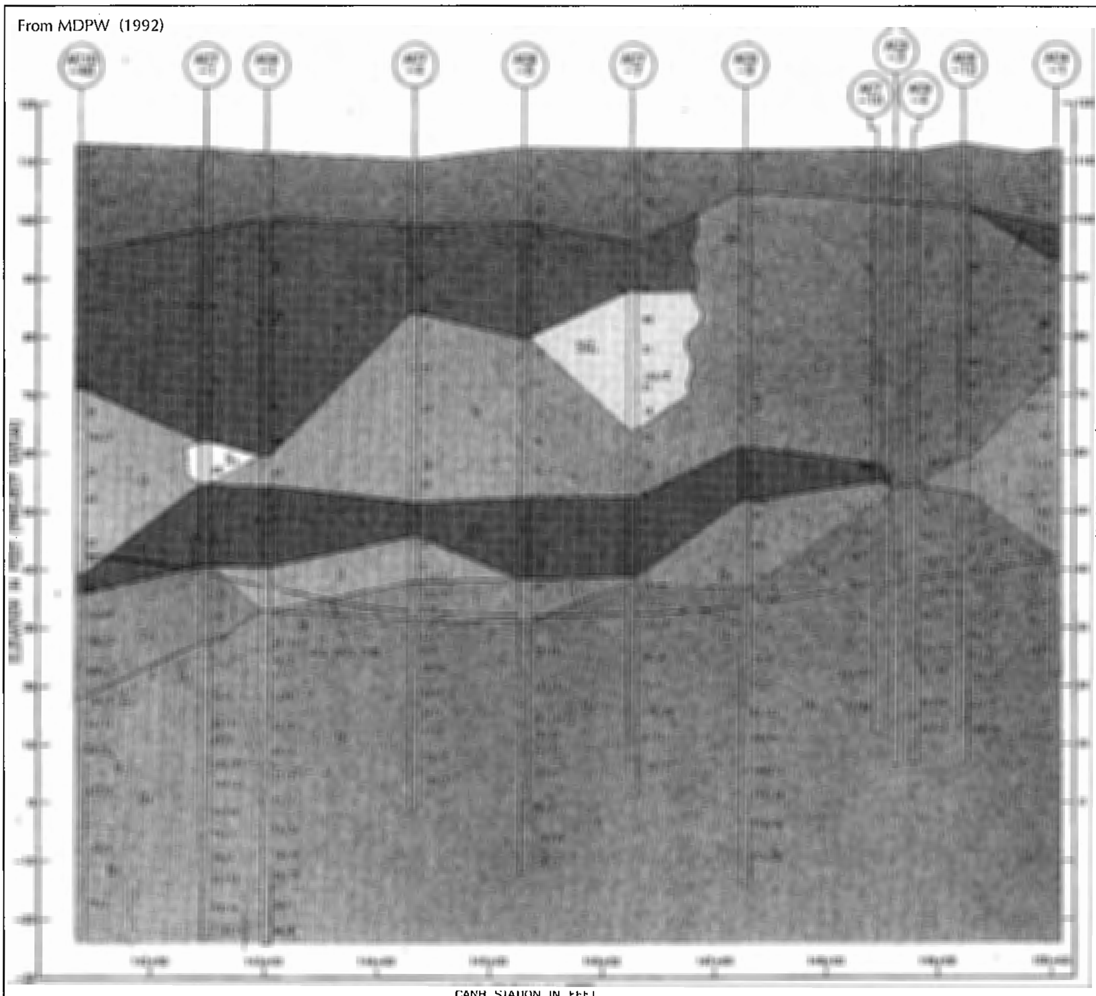
**FIGURE 6-35. Section along the Central Artery Tunnel from Congress Street to Fleet Center near the Charles River, middle slurry wall between Stations 164+00 and 170+00 (view west to southwest).**

channels of the river's predecessors (see Figure 6-38).

Fill covers the entire area and varies in quality and quantity. It is thickest in the original lowlands bordering the lower Charles and Millers rivers, where it ranges from 9.1 to 12.2 meters (30 to 40 feet) in thickness, and thins across buried tops of small drumlins and the large ones of Charlestown to 1.5 to 4.6 meters (5 to 15 feet).

All the structures for the CA/T Project, with the exception of the Central Artery North Area tunnels through Charlestown, are founded on end-bearing piles or drilled shafts into the till or bedrock.

*Interstate 90 (Massachusetts Turnpike) Extension.* A major part of the CA/T Project was the Massachusetts Turnpike extension for 5.6 kilometers (3.5 miles) to Logan International Air-




B₁= Completely to severely weathered Cambridge Argillite
$B_2$ = Severely to moderately weathered Cambridge Argillite
$B_3$ = Moderately to unweathered Cambridge Argillite
$T_1$ = Dense cohesive till
$T_2$ = Very dense cohesive till
$T_3$ = Granular till
G = Glaciomarine deposit
$C_1$ = Very stiff clay
$C_2$ = Stiff clay
$C_3$ = Medium stiff clay
$C_4$ = Hard clay
O = Organic silt & sand
F = Fill
Traversing lines = base of Central Artery Tunnels

(see color version on page 480)

**FIGURE 6-36. Section along the Central Artery Tunnel between North and Cross streets (east slurry wall Stations 142+00 to 150+00) showing the lower outwash sand and the gravel filling channel in the glaciomarine deposit and both covered by marine clay.**

port via the South Boston Seaport Access Highway and the Ted Williams Tunnel (Third Harbor Tunnel) under Boston Harbor (see Figure 6-23). This construction accounted for approximately 45 percent of the nearly $15 billion cost of the CA/T Project. From an historical and geologic perspective, the extension passes through the now-filled South Bay, a portion of the filled Dorchester tidal flats, the filled South Boston tidal flats and what is now a part of the new Seaport in South Boston. It then passed under Boston Harbor, beneath/through Bird Island Flats and on to Noddle's Island in East Boston. The extension of Interstate 90 had to cross under railroad tracks at South Station and under the Fort Point Channel without interrupting the Red Line subway below, and traverse under Boston

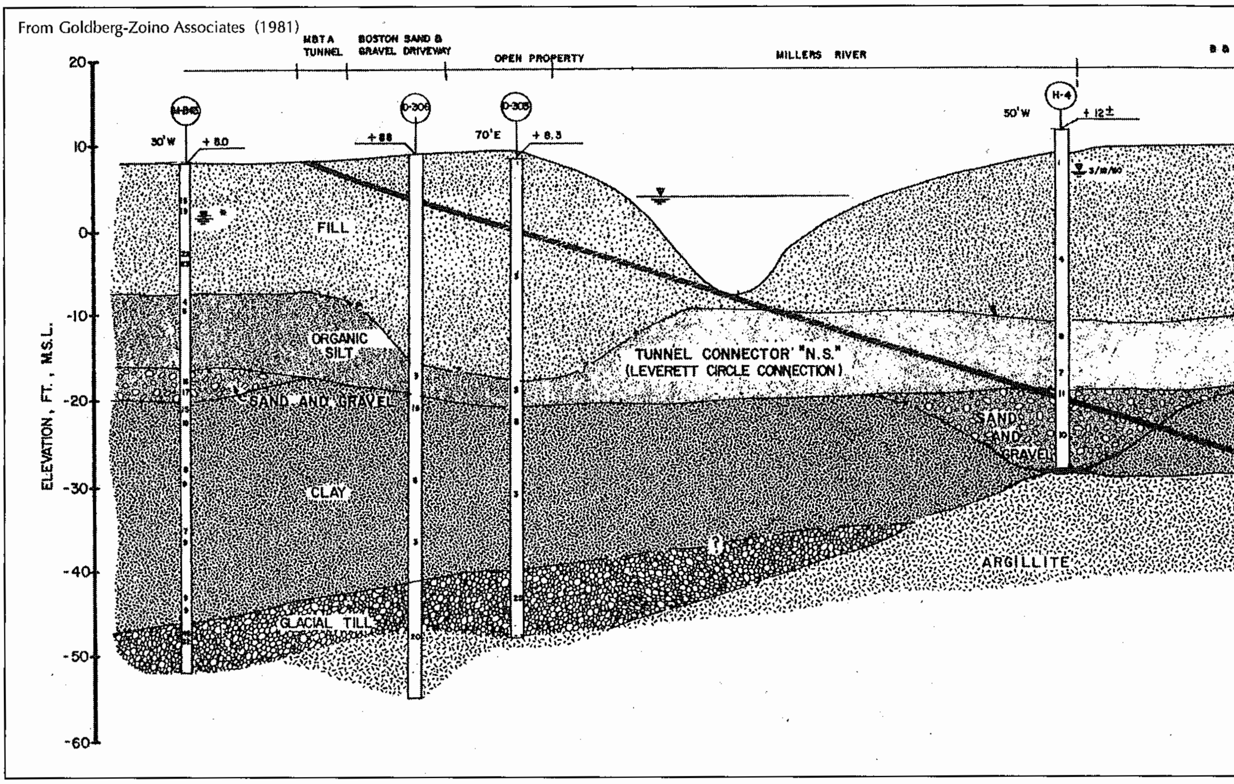
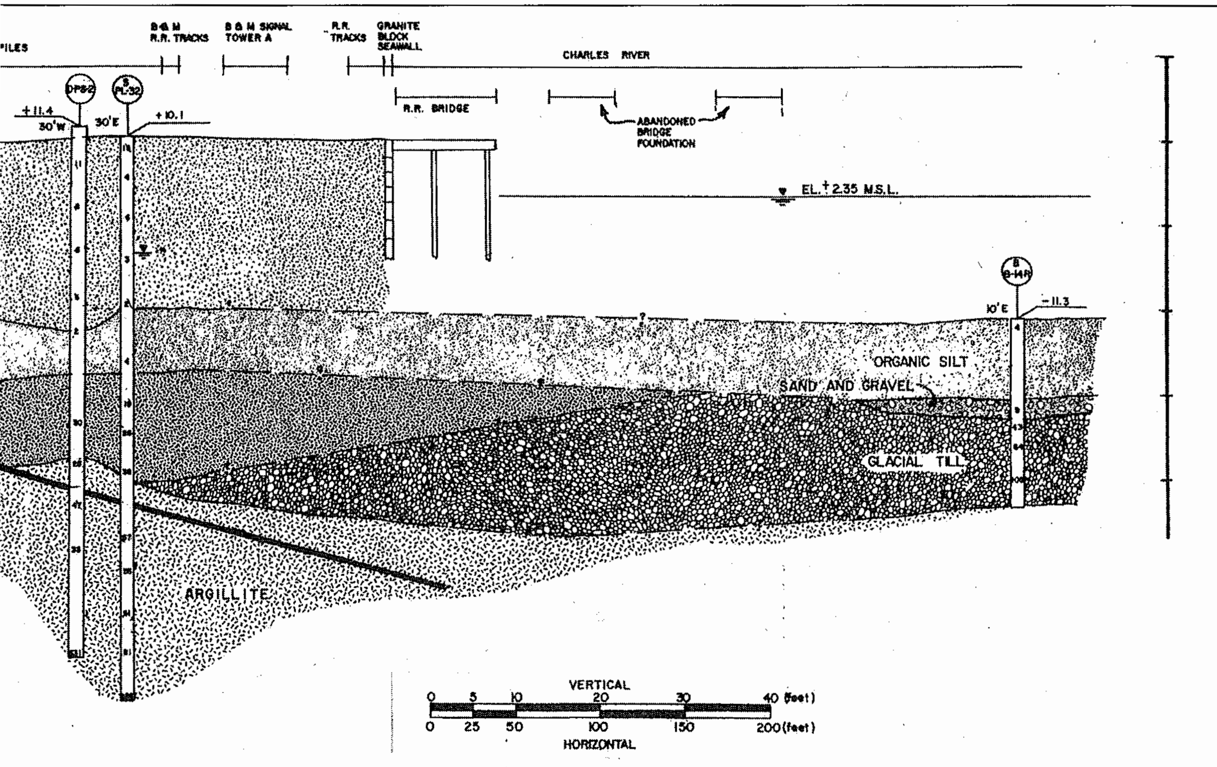



**FIGURE 6-37. Section from south bank of the Charles River just west of the railroad bridge north into Charlestown and across the Millers River remnant to Interstate 93 midway between the Charles River and the Gilmore Bridge, showing marine clay with upper outwash channel fill capped by organic sediment and fill (view east).**

Harbor, with 20 meter (65 foot) deep excavations on both sides for connections with the new 1,250 meter (4,100 foot) long four-lane immersed tube tunnel. Bottom stability issues and the typical in-situ reduction in shear strength of the clay with depth were particular problems for the excavations of unprecedented depths and size required just west of the Fort Point Channel (Lambrechts *et al.*, 1999).

In summary, except for a small area of the southern tip of the Boston Neck, which is clay, a thick layer of fill overlies the peat and organic silt in the former Roxbury tidal flats and South Boston Bay area. Until the 1970s, a grounded barge and pier could be seen west of the Central Artery Expressway at the Massachusetts Avenue exit. This area was filled in during the late 1960s and early 1970s for the construction of the Flower Exchange. Dredged clay and shells from Boston Harbor and Lynn underlie the South Boston Naval Reservation and areas to the south (according to Kaye). The remaining sequence of soil strata is typical of many areas outside the original Shawmut Peninsula. These strata include marine clay, outwash and till overlying deep argillite bedrock. Beneath the railroad yard behind South Station, subsurface conditions consisted of up to 8 meters (26 feet) of fill overlying about 5 meters (16 feet) of organic sediments. This layer in turn is underlain by thick clay on the order of 28 meters (92 feet) thick, but reaches more than 33 meters (110 feet) in some areas. The underlying till is up to 5 meters (16 feet) thick with the bedrock surface at elevation –33 meters (–100 feet) MSL at a depth of more than 43 meters (141 feet).

The extension presented a huge challenge behind South Station in having to advance tunnels through a 610 meter (2,000 foot) by 305 meter (1,000 foot) plot of harbor-side land composed of very soft ground that contains




over two hundred years of miscellaneous landfill, along with archeological artifacts needing to be preserved. In addition, the tunnels cross a waterway and eight highly active railway lines. Three tunnels were designed to cross under the railway using the tunnel jacking method (Lambrechts *et al.*, 1999). The tunnels were advanced through fill, organic silt, outwash sand and marine clay. The use of this technique was the largest and most complex set of tunnels ever installed using the tunnel jacking method. The size of the jacked tunnels was ten times that of any jacked tunnels ever attempted within the United States. Site constraints and available working space were also considerably less than ideal or even what is typically required for tunnel jacking operations.

The first step in the tunneling was to transform the entire tunneling zone from soft ground into solid ground, making it easier to excavate. The ground beneath the tracks was specified to be solidified by grouting, but the contractor selected to freeze the ground instead. The freezing was accomplished with the installation of as many as 2,000 vertical steel pipes drilled into the ground to depths of 21 meters (70 feet) through which a cold brine solution was injected that froze the soil. Three concrete jacking pits were dug out and inside each pit tunnel boxes measuring 24 meters (80 feet) wide and 12 meters (40 feet) high were constructed. Once the soil was hardened for excavation, crews then broke the head end of the concrete pit and began excavating soil in three-foot increments using a road header. The soil was removed from the back of the tunnel box using large buckets that were then lifted to the surface using a crane. Hydraulic jacks, as many as up to fifty at one point during the construction, were used to push the tunnel boxes forward from inside the concrete jacking pits into the frozen soil excavation zone. This process was repeated over and over again, and on average the jacking achieved advances of the tunnel sections through the ground about 0.9 to 1.8 meters (3 to 6 feet) per day with the trains rumbling just 6.1 meters (20 feet) above. Once the jacked sections were permanently placed, the jacking pits were incorporated as part of the highway paths. The application of this technique in construct-

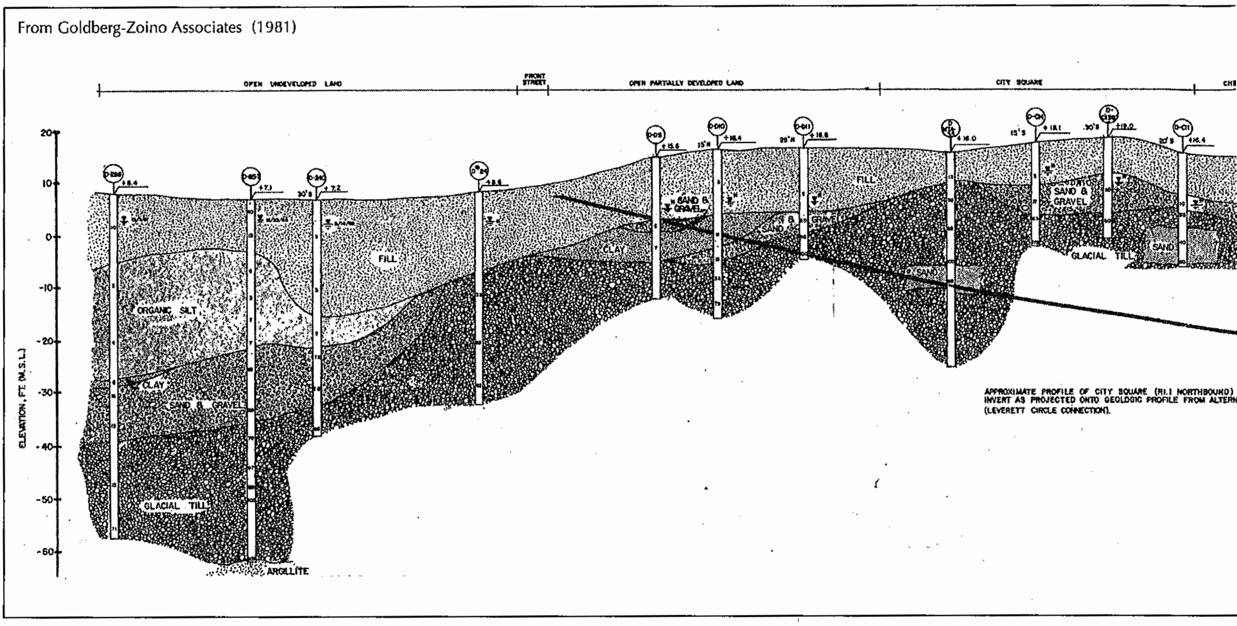
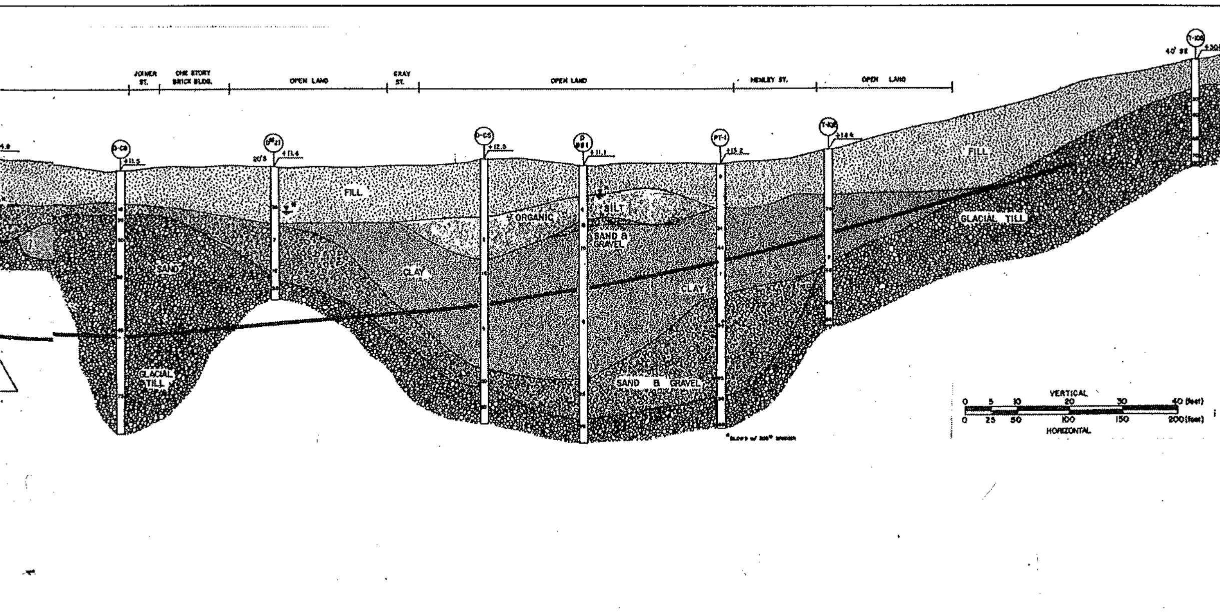



**FIGURE 6-38. Section extending approximately along Route 1 northeastward from the Central Artery nearly to Mount Vernon Street in Charlestown, view northwest showing variety of units from lower outwash, very thin marine clay and organic silt in the south to a channel fill of lower outwash, marine clay, very thin upper outwash and organic silt on the flank of Morton's Hill drumlin.**

ing the tunnels cost approximately $150 million, but saved considerable time. Deep soil mixing was used for tunnel foundations in the area between the Fort Point Channel immersed tube tunnels and the jacked tunnels and along the Fort Point Channel for a major ramp from Interstate 93 Northbound to Interstate 90 Eastbound. The new multi-level interchange between Interstate 90 and Interstate 93 was constructed adjacent to, over and beneath the eight railroad tracks on which there are over four hundred passenger train movements each day in and out of South Station. At Ramp D, 5 meters (16.5 feet) of fill overlies a 6 meter (20 foot) thick layer of organic soils. Clay up to 17 meters (56 feet) thick underlies the organics. About 2 meters (7 feet) of till overlies the bedrock at elevation 3 meters (10 feet) MSL.

*The Casting Basin.* Crossing Boston's Fort Point Channel with a highway tunnel proved problematic. Undertaking an operation similar to constructing the Ted Williams Tunnel (*i.e.,* the use of steel tube tunnel sections each longer than a football field and shipped in by barge) could not be carried out because there was not enough room to float the sections under the three bridges that cross the Fort Point Channel. Therefore, engineers decided to use concrete tunnel sections, which was a first in a U.S. construction project. Concrete tunnel sections were fabricated in such a way that they could be easily moved into place and assembled in the channel. This fabrication was performed within a casting basin — a huge dry dock 305 meters (1,000 feet) long, 91 meters (300 feet) wide and 18.3 meters (60 feet) deep. Over 344,050 cubic meters (450,000 cubic yards) of soil were excavated to form the basin on the South Boston side of the Fort Point Channel. A series of circular cellular cofferdams filled with crushed stone were used to seal off the channel end of the basin.

The cofferdams were founded on concrete drilled shafts that extended deep to the argillite. The tunnel sections, six in total, were built right in the bottom of basin and then completed sections were sealed watertight at either end. The basin was then flooded and all the crushed gravel removed from within the




cofferdams. Steel sheet piles were also removed so that sections could be floated out of the basin and positioned for lowering into a trench that was dredged on the bottom of the channel. The lowering of tunnel sections into position had to be done precisely since the sections had to be lined up and could not be moved once placed. Another problem was the support of such heavy concrete sections because an existing subway tunnel already ran directly under the channel and the extension of Interstate 90 would be just a few feet above it. The solution was achieved by the use of 110 concrete shafts 1.8 meters (6 feet) in diameter that were drilled into the bottom of the channel on either side of the subway tunnel as much as 44.2 meters (145 feet) into the bedrock.

*Logan Airport.* Excavations as deep as 20 meters (65 feet) using the deep soil mixing method for excavation support walls were required in soft marine clay for the construction of the deep cut-and-cover tunnels that lead Interstate 90 from the new Third Harbor Tunnel to Logan Airport. Total width excavated was from 60 to 87 meters (197 to 285 feet).

Considerable exploration was done around Logan Airport for the Ted Williams Tunnel and connections, and for the new approaches to the existing Sumner and Callahan Tunnels from the northwest side of the airport (see Figures 3-92 & 3-94). The work at the northwest side shows the types of variations found. One line of boreholes followed Route 1A from the tunnels past the MBTA Airport Subway Station and another perpendicular line extends from the subway station to the Airport Hilton Hotel adjacent to the airport's Central Parking garage.

The top of the argillite is deep along Route 1A. At the west side of the Airport Subway Station there is a slight mound in the till to just over elevation –38.1 meters (–125 feet) MSL. The mound slopes gently to the northeast before dropping off very abruptly to elevation –54 meters (–178 feet) MSL and the bedrock surface stays low farther to the northeast (see Figure 3-93). The till is stripped off the bedrock except for a few thin remnants. The overlying glaciomarine deposits have a highly variable thickness — 29 to 0 meters (95 to 0 feet) — due to the relief across its upper surface. The relief is apparently from the erosion of channels prior to the deposition of the marine clay. A north-trending channel, which passes east of the subway station and midway between the station and the Hilton Hotel, cuts through the glaciomarine and into the argillite locally. The channel is responsible for the drop off of the bedrock surface east of the subway station. The channel is asymmetric, with the west side having a steep slope that has a relief

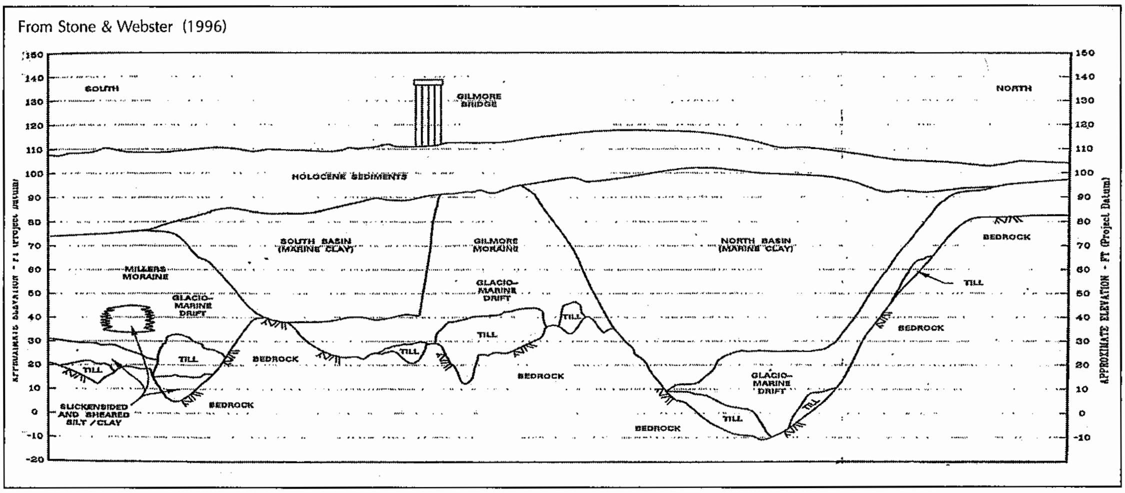



**FIGURE 6-39. North-south section across the Gilmore Bridge and Interstate 93, Charlestown, showing marine clay filled channels cut into the glaciomarine deposit (view west).**

of over 40 meters (130 feet) and with the east slope being gentle. The channel axis slopes to the north. Glaciofluvial sand and gravel up to 15.2 meters (50 feet) thick lie within it. The overlying marine clay ranges in thickness from 36.7 meters (120 feet) over the channel to about 7.6 meters (25 feet) over its western side. In all three surficial deposits are patches of apparently only partially reworked material of the underlying deposit above erosional unconformities. These unconformities are identified as lenses of till in the glaciomarine and sand and gravel deposits, and glaciomarine deposit in the clay. The top of the clay is relatively flat, with overlying marine silt 1.5 to 4.6 meters (5 to 15 feet) thick, capped by lenticular sand up to 3 meters (10 feet) thick that thins to the north. The sand and silt are apparently part of the Lexington Substage Outwash. The underlying silt may be the early, distal part of the outwash that was later overwhelmed by the coarser material as the glacial front moved closer — or, less likely, by the reworked top of the clay that concentrated a silt component. Peat and organic silt up to about 2.4 meters (8 feet) in thickness overlie most of the area under 2.1 to 6.1 meters (7 to 20 feet) of fill.

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