Tunneling Projects in the Boston Area

Tunneling provides an opportunity to hone the geologic knowledge of an area.

DAVID WOODHOUSE

The use of underground space in the Boston area has been very extensive, dating back to the colonial days when wooden water pipes were laid underground. This use became more intensive in the 19th century when pipes for illuminating gas were laid and the first subway in the United States was constructed. Since that time, major underground projects have included the construction of rock tunnels to distribute water from Quabbin Reservoir, sewer interceptors to Deer Island, subaqueous transportation tunnels and subway tunnels (see Table 1).

Tunneling under Boston has been so extensive that only a summary is presented here. Numerous other authors present more detailed studies.[1-18] In addition, many detailed, but unpublished, engineering geological studies have been conducted by the major geotechnical firms in the area.

Subway Tunnels

More than a century has passed since state and local governments in Massachusetts first recognized the need for increasing the speed and capacity of public transportation in the Boston area. The many rapid transit facilities built since that time formed the foundations of today's Red, Orange, Blue and Green rapid transit lines of the Massachusetts Bay Transportation Authority (MBTA) (see Figure 1). This network, now 125 km (77.4 mi) in length, carries an estimated 128 million riders annually. For a city the size of Boston, its rapid transit system is disproportionately large when compared to rapid transit facilities elsewhere in the United States. This reliance on mass transportation is no accident, for Boston has long been a leader in rapid transit development, starting with the first subway in America that opened in Boston in 1897 and remains in daily use.

History. Chapter 478, Acts of 1893, created a three-man Board of Subway Commissioners, subject to the approval of the Boston City Council and appointed by the Mayor.[19] The board was charged by the state legislature to report on the feasibility of building a subway under Boston Common through the deformed till, clay and outwash in order to replace the streetcar traffic on Tremont Street. Work progressed so rapidly that the first section from Park Street to a portal in the Public Garden, near Arlington and Boylston Streets was opened on September 1, 1897. Two additional segments of subway were opened later. The leg under Tremont Street from Boylston Street Station to Pleasant Street (now Broadway) opened

TABLE 1
Major Tunnels in the Boston Metropolitan Area

Name of Tunnel	Purpose	Date Constructed	Length (km)	Lined Diameter (m)	Approx. Depth (m)	Method of Construction	Predominant Lithology
Dorchester Bay Tunnel	Sewer	1880s	3.2	1.0	10.0 - 20.0	Cut-and-cover	Clay/Till
City Tunnel	Water	1947-51	7.7	3.7	70.0 - 137.0	Drill and blast	Argillite, Tillite Sandstone, Diabase, Conglomerates
City Tunnel Extension	Water	1951-56	11.4	3.1	70.0 - 122.0	Drill and blast	Conglomerate Sandstone, Argillite
North Metropolitan Relief Tunnel	Sewer	1950-56	6.3	3.1	85.5	Drill and blast	Argillite
Main Drainage Tunnel	Sewer	1954-59	11.5	3.1 - 3.5	89.0 - 92.5	Drill and blast	Conglomerate, Argillite, Tillites, Sandstone, Shale
Malden Tunnel	Water	1957-58	1.6	3.8	85.5 - 100.0	Drill and blast	Felsite, Argillite, Diabase
Dorchester Tunnel	Water	1968-74	10.2	3.1	30.5 - 61.0	T-BM, Drill and blast	Argillite, Sandstone, Conglomerates, Basalts
Boston Main Drainage Relief Sewer	Sewer	1950	3.8	3.1	70.0 - 80.0	Shield	Clay
Stony Brook Conduit	Sewer	1880s	3.4	5.2 × 4.7	10.0 - 15.0	Open cut	Sand/Gravel Till
MBTA Red Line Extension Northwest Mined Tunnels	Transit	1976-80	2.2	5.8	15.0 - 43.0	Shield (till) Lull fleet	Till, Argillite Sandstone, Diabase
Blue Line Harbor Crossing	Transit	1900-03	2.6	6.2 × 7.0	19.2 - 25.0	Shield compressed air	Clay
Red Line Fort Point Channel	Transit	1915-16	1.0	6.1	18.3 - 23.0	Shield, compressed	Clay, Sand, Gravel
Red Line Subway	Transit	1912	4.0	5.8	7.2	Cut-and-cover	Clay, Sand, Gravel
Orange Line Subway	Transit	1904-06	4.5	Horseshoe/Box	3.9	Cut-and-cover	Clay, Sand, Gravel
Green Line Subway	Transit	1895-1912	5.7	Horseshoe/Box	6.0 - 10.0	Cut cover shield	Clay/Till Fill
Sumner Tunnel	Vehicular	1920s	2.3	Circular	10.0 - 40.0	Shield & compressed	Clay
Callahan Tunnel	Vehicular	1960s	2.3	Circular	10.0 - 40.0	Shield compressed	Clay

on October 1, 1897. On September 3, 1898, operation commenced on the final section from the filled tidal flat area of North Station to Park Street on the edge of Beacon Hill.[20]

Chapter 500, Acts of 1897 amended the original Boston Elevated Railway Act of 1894 that provided for a new transit tunnel under Boston Harbor to East Boston and the Boston segment of a subway to Cambridge. Construction began in 1900 on the first underwater transit tunnel in America. The tunnel was constructed in mainly Pleistocene sediments varying from marine clays under the harbor to the deformed clay and sand around Beacon Hill.[3] The East Boston Tunnel opened for business on December 30, 1904. The tunnel extended from Maverick Square, East Boston, to Court Street Station, near Scollay Square in downtown Boston (now Government Center).

Plans were made to build a subway under Washington Street for the Sullivan-Dudley line. The subway followed the old Shawmut Neck, the original tidal flat area that connected Boston to Roxbury. The tidal flats have long since been filled in. Marine clays underlie the estuarine organic silt and peat that formed the flats. This structure, the Washington Street Tunnel, was opened for public use on November 30, 1908. Removal of high-platform and third-rail equipment from the Tremont Street Subway began at once, and on December 4, 1908, streetcar service fully resumed through all parts of the subway formerly used by the elevated trains.

The need for rapid transit service in the congested Back Bay area led to construction of the Boylston Street Subway through a complex area of clay and fill (see Figure 2).[7] Work began in March 1912 on the two-track tube, which would eventually run from a portal in Governor Square (now Kenmore Square) to a connection with the Tremont Street Subway near the Public Garden Incline. As part of the subway construction, the incline itself would be shifted to the middle of Boylston Street, parallel to its old location. The Boylston Street Subway

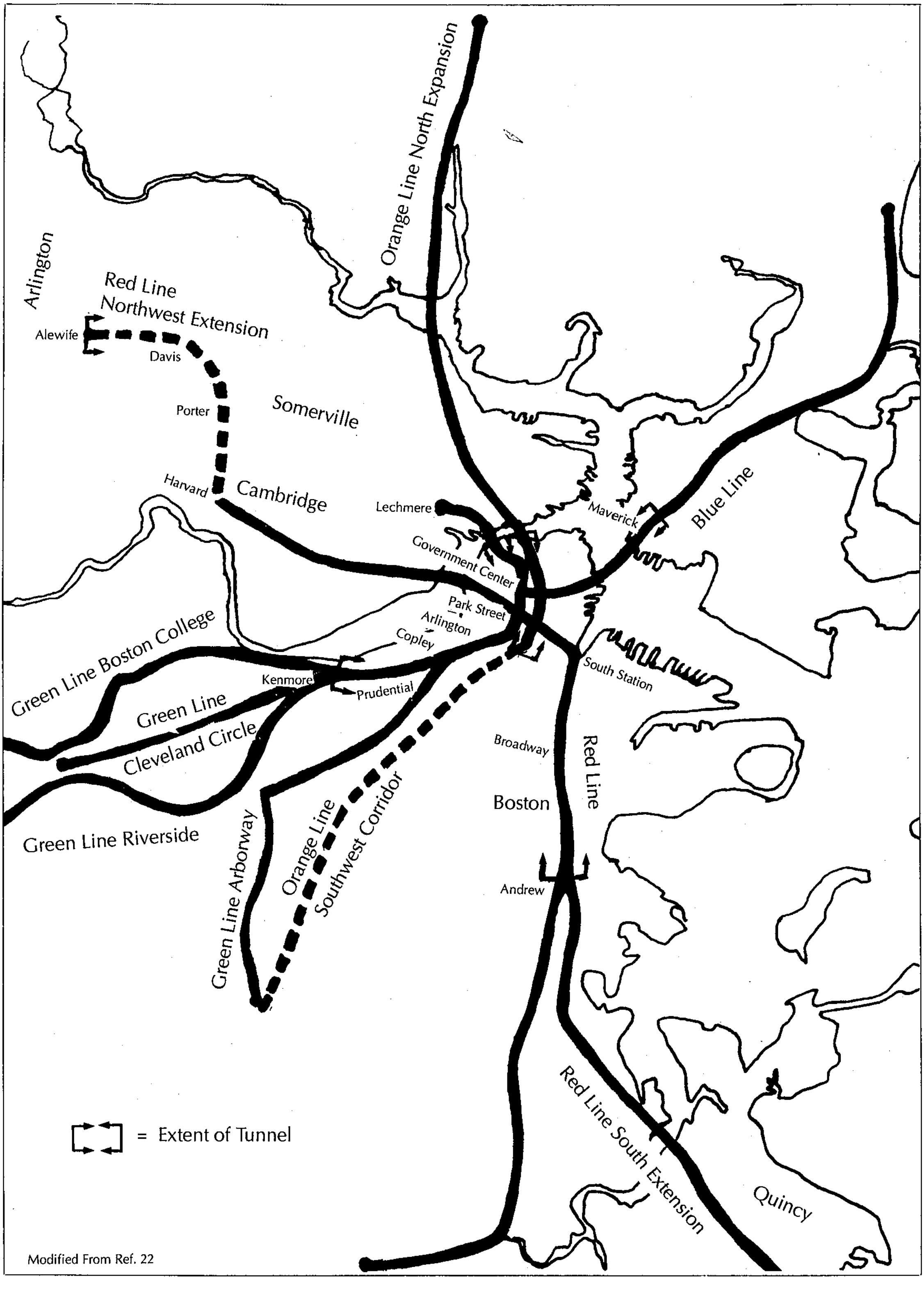
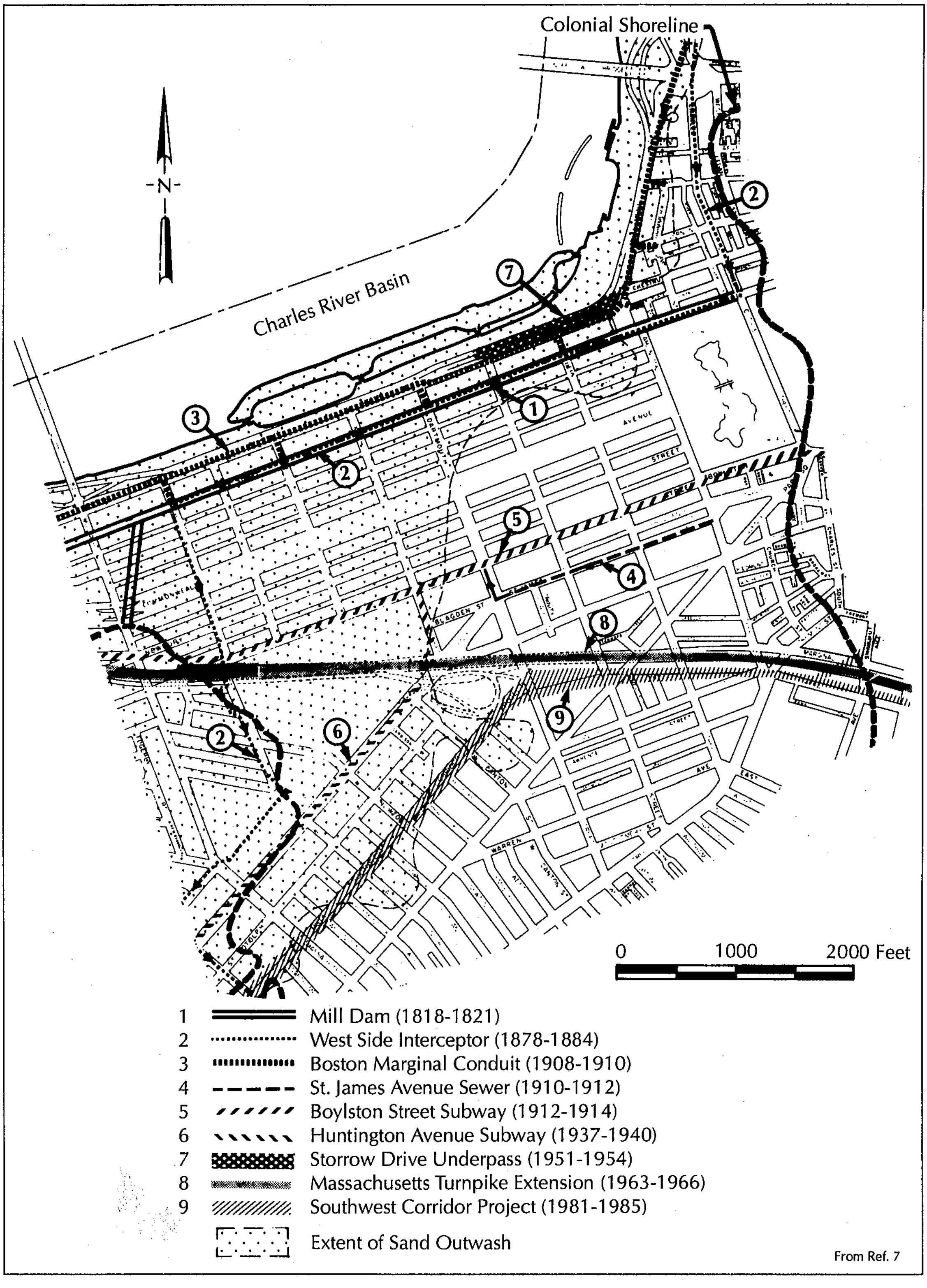


FIGURE 1. Map of the Boston area showing routes of the MBTA's rapid transit system and the extent of tunnels.



From Ref. 7

FIGURE 2. Map of the Back Bay area showing the locations of sewers, drains and major transportation routes.

TABLE 2
Geologic Material Along the Boylston Street Subway

Location	Approximate Station	El. Top of Rail	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 & gravel
Charlesgate East (at Newbury St.)	10+00	-18.9	Sand & gravel; short section of clay
Massachusetts Ave. (at Newbury St.)	19+32	7.5	Sand & gravel fill underlain by silt
Hereford Street	27+15	7.7	Silt over sand & gravel
Gloucester Street	31+55	1.9	Sand & gravel
Fairfield Street	37+15	-4.8	Sand & gravel
Exeter Street	43+75	-6.4	Silt over sand & gravel
Dartmouth Street	49+80	-6.5	Silt over thin peat over thin sand & gravel
Clarendon Street	56+05	-8.8	Silt over thin peat
Berkeley Street	62+25	-13.0	Sand & gravel
Arlington Street	69+10	-14.5	Clay
Hadassah Way	73+35	N -14.0 S -11.5	Fairly hard blue clay (peat between Hadassah Way & Charles Street)
Charles Street	78+00	N -4.2 S -5.0	Blue clay & gravel

Notes: Information was obtained from Boston Transit Commission Plans No. 10219, 10386, 10091, 10418, 11157, 11159, 11161 and 11162 of "Boylston Street Subway." The bottom of subway structure varies from 4 to 5.5 ft. below top of rail. The subway is supported on wood piles from Station 71+82 to Station 76+41.

From Ref. 7

opened on October 3, 1914.

Another extension of an existing subway took place between 1912 and 1916. The East Boston Tunnel, when it originally opened, ran downtown to Court Street Station, a stub-end single-track terminal. Traffic volume through the tunnel increased tremendously over the years, and this single-track turnback became an operational nuisance. The answer was a 2,610-foot extension to Bowdoin Square through the deformed Pleistocene material of Beacon Hill,[21] where an underground station, a loop and a surface incline to Cambridge Street were provided. The loop furnished a quick turnaround for streetcars from East Boston, while the incline permitted cars to travel all the way through from Cambridge to East Boston. The East Boston Tunnel Extension was opened on March 8, 1916.

The Boston Elevated Railway and the Boston Transit Commission shared joint construction responsibility for the Cambridge-Dorchester Tunnel, today part of the MBTA Red Line. Construction began in 1909. The first phase of construction was in an area consisting primarily of outwash sand and clay that extended from Harvard Square, Cambridge, to Park Street in Boston. This line began operation on March 23, 1912. The last tunnel segment, constructed in clay, ran from Broadway Station to Andrew Square, in South Boston and was opened on June 29, 1918.

TABLE 3
Geologic Material Along the Huntington Avenue Subway

Location	Approximate Station	El. Top of Rail	Soil Conditions at Bottom of Subway
Massachusetts Ave.	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 (Mass. 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: Information was obtained from City of Boston Transit Department Plans No. 17947, 17943, 17936, 17933 and 17914 of "Huntington Ave. Subway, Plan & Profile." The bottom of the subway structure varies from 3.5 to 6 ft. below top of rail. Footings, pedestrian passageway (Mass. Ave.) and bottoms of catch basins are deeper.

From Ref. 7

In the late 1930s, the Boston Transit Department began the Huntington Avenue Subway through a variety of material (see Figure 2).[7] 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 car line ran past Northeastern University on Huntington Avenue to Copley Square and then over Boylston Street as far as the block between Arlington and Charles Streets. Here, 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 to the new subway on February 16, 1941 shortened the running time considerably.

Engineering Geology. Most of the old subways were constructed 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 "Neck." The subaqueous East Boston Tunnel under Boston Harbor was constructed using a shield under pressure. The new Red Line Extension was tunneled through both bedrock and soft ground.

The Boylston Street subway crosses Back Bay from the portal at Kenmore Square near Massachusetts Avenue to Charles Street (see Figures 1 and 2, and Table 2). The bottom of the subway varies from approximately el. +0.9 m (+3.0 ft) at Massachusetts Avenue, to its lowest

TABLE 2
Elevations Along the Southwest Corridor Project

Location	Elevation of Bottom of Structure Subway	Elevation of Bottom of Structure Amtrak	Elevation of Bottom of Deepest Excavation
Gainsborough Street	6.0	3.3	3.6
Massachusetts Avenue	6.0	-6.0	-7.5
Blackwood Street	-8.2	-14.4	-23.0*
West Newton Street	-10.4	-16.7	-24.5*
Harcourt Street	-10.4	-16.4	-24.5*
Yarmouth Street	-4.7	-12.4	-14.4 -18.4**
Dartmouth Street	3.6	-4.0	-5.6 -12.4**
Clarendon Street	3.6	-5.0	-6.4 -9.6**
Berkeley Street	1.6	-5.0	-6.4 -8.4**
Chandler Street (to east end)	-2.1	-3.0	-4.4

Notes: Information was obtained from 1981 and 1982 Massachusetts Bay Transportation Authority construction plans for Contracts No. 097-115 and 097-120.
*Removed organic silt to top of clay stratum.
**Lower elevation for trench excavated for track drain pipe.

From Ref. 7

point of el. -5 m (-19.0 ft) between Arlington Street and Hadassah Way thence to el. -3 m (-10.0 ft) at Charles Street.[7] The soft ground conditions and elevations change along the route of the subway (see Table 2).

The structure was supported on a wide variety of soils including the fill, organic silt, and natural sand and gravel outwash. Where peat was encountered, approximately between Hadassah Way and Charles Street (a distance of 140 m [460 ft]), wood piles were driven to support the structure.[7]

During construction, a temporary drawdown of water levels both in the fill and in the sand and gravel stratum would have occurred.[7] The drawdown in the sand stratum is estimated to have reached el. -3 m (-10 ft) where the subway route passed opposite to what is

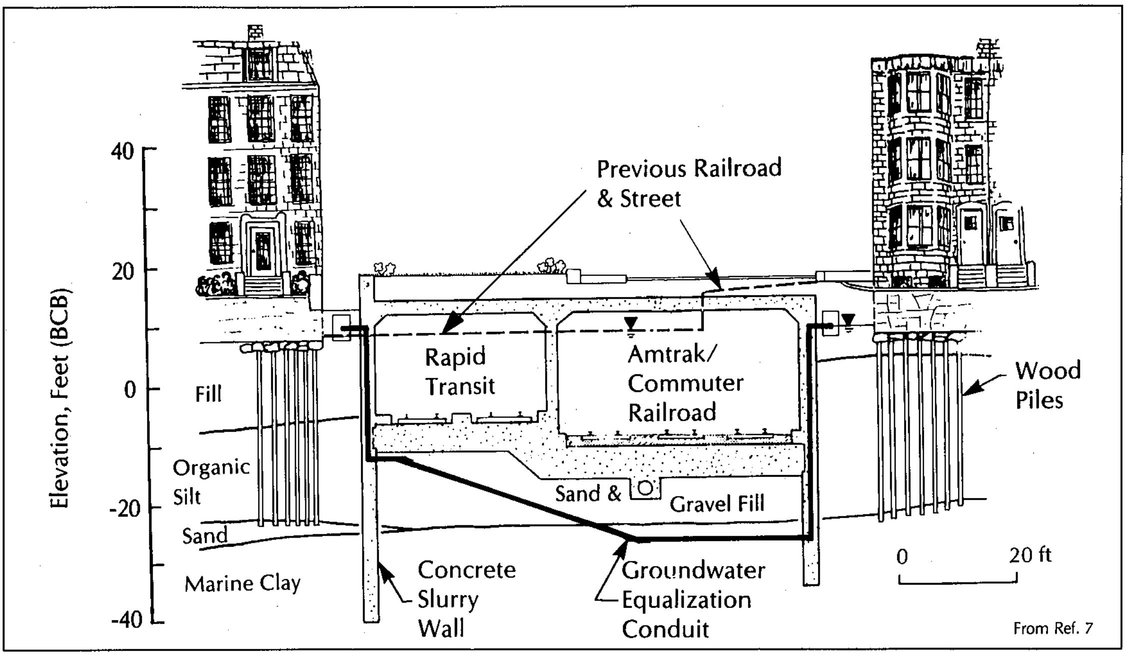


FIGURE 3. Cross-section of the Southwest Corridor tunnel at Follen Street.

now the Prudential Center.

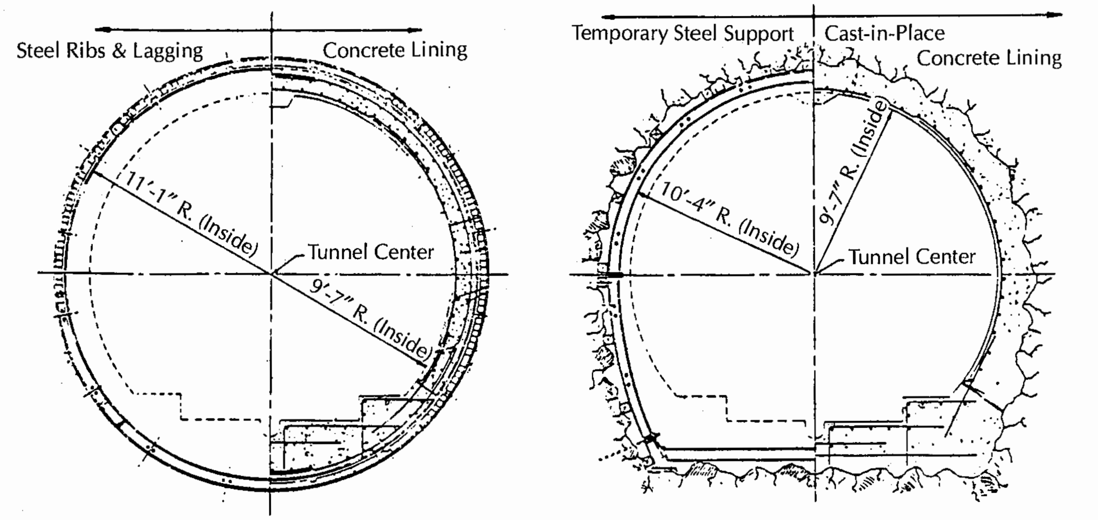
The Huntington Avenue subway, constructed between 1937 and 1940, crosses under Massachusetts Avenue as it enters Back Bay and joins the Boylston Street subway at Exeter Street (see Figure 2 and Table 3). Within this area, the bottom grade of the subway structure varies from -3 m (el. -10 ft) at Massachusetts Avenue down to el. -5.8 m (-19 ft) where the structure passes below the railroad tracks (and under the Massachusetts Turnpike Extension).[7]

Aldrich and Lambrechts noted that:

> "The subway was founded on the outwash stratum that extends from 1.5 to 3.7 m (5 to 12 ft) below the bottom of concrete from Massachusetts Avenue to the Turnpike. North of the Turnpike to Boylston Street, the structure bears on clay and organic soils, without piling. During construction, the outwash stratum was dewatered for the entire length of the subway along Huntington Avenue to grades as low as, or even below, el. -6 m (-20 ft). A very significant drawdown of water level occurred over a wide area, for a period of 2 to 3 years. The level in an observation well at Massachusetts and Commonwealth Avenues, 0.6 km (0.4 mi) away, was reported to have dropped from el. 2.1 m (7 ft) to el. 0 in 1939."[7]

Construction for the Huntington Avenue Subway required extensive and prolonged dewatering to levels below any known construction before or since.[7] In addition, drains installed in the tunnels of both subway lines have undoubtedly collected groundwater that leaked into the structure.

Southwest Corridor. A major expansion of the MBTA took place with the construction of the Red Line Extension and the Southwest Corridor which was constructed between 1981 and 1985. It has two tracks for the relocated MBTA Orange Line subway and three tracks for commuter rail and Amtrak service. Through Back Bay the alignment followed parts of two original railroad embankments that were constructed across the tidal basin in the mid-1830s (see Figure 2). From Massachusetts Avenue to Dartmouth Street, the new concrete structure was below ground in a 915 m (3,000 ft) long cut-and-cover tunnel that required excavations as deep as 11.6 m (38 ft). East of Dartmouth Street, the structure extended about 3 m (10 ft) below former grade. Depths of excavations and other data are summarized in Table 4.



Soft Ground Tunnel
Concrete Lining With Steel Ribs & Lagging

Rock Tunnel
Concrete Lining With Steel Ribs

FIGURE 4. Typical tunnel sections.

Aldrich and Lambrechts summarized the engineering geology as follows (see also Figure 3):

> "Reinforced concrete slurry walls were used for lateral support of the sides for about 640 m (2,100 ft) of the tunnel excavation. The concrete walls were 1 m (3 ft) thick and penetrated 2.4 to 4.6 m (8 to 15 ft) into the clay stratum. They were used as the tunnel's permanent outside walls. Although water leakage did occur through some of the vertical joints between wall panels, there was no appreciable lowering of groundwater levels in adjacent areas.
>
> "In other deep excavation areas where

TABLE 5
Engineering Properties of the Cambridge Argillite

	Unit Weight (kg/m³; pcf)***				Unconfined Compression f_c (N/m²; psi)***				Tangent Modulus E_{t50} (N/m²; psi)***			
Location & Rock Type	**Low**	**Average**	**High**	**No. Tests**	**Low**	**Average**	**High**	**No. Tests**	**Low**	**Average**	**High**	**No. Tests**
Dorchester Tunnel Argillite	2691.0	2747.0	2810.0	15	34,480	103,430	236,840	15	39,990	62,740	84,120	15
	168.0	171.5	175.4		5,000	15,001	34,350		5,800	9,100	12,200	
MBTA Red Line Extension	2538.0	2747.0	2844.0	52	41,990	131,420	255,120	50	20,690	47,580	63,430	50
Argillite	158.4	171.5	177.5		6,090	19,060	37,000		3,000	6,900	9,200	
MBTA Red Line Extension	2606.0	2738.0	2861.0	12	12,620	67,570	166,860	10	14,480	24,130	31,030	10
Melaphyric Dike Rocks*	162.7	170.9	178.6		1,830	9,800	24,200		2,100	3,500	4,500	
MBTA Red Line Extension	2518.0	2739.0	2884.0	6	29,650	103,620	250,980	6	29,650	59,300	74,470	6
Tuff/Trachyte**	157.2	171.0	180.0		4,300	15,030	36,400		4,300	8,600	10,800	

Notes: * Rock types include diabase, andesite, basalt & altered varieties of these rocks.
** Rock previously identified as dark grey to black tuff; believed to be black trachyte appearing as irregular sill-like intrusion in Porter Square exploration shaft.
*** Metric units are shown above English units on the table grid.

From Ref. 4

TABLE 6
Engineering Properties of Materials in Boston

Stratum	Consolodation Condition	Effective Friction Angle	Total Unit Weight (pcf)	Allowable Bearing Pressure (tsf)
Fill				
Sands distributed along entire project	Loose to medium dense	28-33	110-120	1.0
Sands & Gravels				
Glacial outwash deposits; sands, gravelly sands, silty sands	Medium dense to very dense	32-36	110-125	1.0-2.5
Marine Clay				
Silty Clay	Over-consolidated	24	110-120	2.0-4.0
Till				
Glacially deposited mixture of sand, gravel, cobbles, boulders, silt, clay	Dense to very dense	36	125-140	3.0-5.0
Cambridge Argillite				
Bedrock (slightly indurated)	Medium hard to hard with locally weathered & broken layers	45	165-170	10.0-20.0

From Ref. 16

adjacent structures were further 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 in adjacent areas as much as 3.7 m (12 ft).

"Where concrete slurry walls were used, the tunnel was supported on a thick concrete invert slab bearing on compacted sand and gravel fill that was used to replace unsuitable organic soils. East of this portion of the tunnel, the structure was supported on precast-prestressed concrete piles driven through the clay to end bearing on glacial till or bedrock.

"In order to allow groundwater movement across the corridor structure, a groundwater equalization underdrain system was installed. This system consisted of longitudinal drains placed 0.6 to 1.2 m (2 to 4 ft) below the pre-construction groundwater level on either side of the structure. Where slurry walls formed the tunnel walls, 20 cm (8 inch) diameter header pipes surrounded by crushed stone were connected to 20 cm (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."[7]

Red Line Extension. The 5.0 km (3.1 mi) Northwest Extension of the MBTA Red Line beyond Harvard (see Figure 1) consists of two deep tunnel sections and a cut-and-cover section. The first section, which is 1,342 m (4,400 ft) long, connects the new cut-and-cover Harvard Square Station to the deep rock Porter Square Station. Porter Square Station is, in turn, linked to the cut-and-cover Davis Square Station by the second deep tunnel section, which is 884 m (2,900 ft) long.[16] 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.

The deep tunnels are twin-bore excavated and 6.7 m (22 ft) in diameter, with the construction access shafts now serving as ventilation and emergency egress shafts at intervals along the alignment. A variety of excavation and support techniques were utilized during the construction of the shafts and tunnels.

Based on the expected subsurface conditions, the minimum support requirements specified for lengths of the tunnels are as follows (see Figure 4):

- Length of tunnel with circular steel ribs and wood lagging for soft ground and mixed-face conditions was 1,479 m (4,850 ft).
- Length of rock tunnels with steel sets specified was 1,085 m (3,560 ft).
- Length of rock tunnels with rock bolt support or support at contractor's option was 1,866 m (6,120 ft).

Engineering properties of the soil and bedrock are summarized in Tables 5 and 6.[3,16]

The primary rock type along the tunnel alignment is the Cambridge Argillite with lesser amounts of intrusive rocks that penetrate the country rock (see Table 5). The argillite, though non-uniform in appearance, does not show any significant variation from a geotechnical standpoint, except where it has faulted or sheared (especially where groundwater has been introduced).

Bedding characteristics in the argillite along the Red Line Extension show extreme variability,[16] although the bedding generally dips gently to moderately (20° to 45°) to the south, representing the northern limb of the Charles River Syncline. The bedrock varies from a massive dark-to medium-gray, fine-grained type to an argillite that exhibits rhythmic bands of light gray layers alternating with medium-to-dark-gray layers. The coarser grained and generally lighter colored layers have well developed bedding structures. These structures include graded sequences, cross bedding and ripple marks. Bedding plane joints are usually spaced 30 to 50 cm (12 to 20 in) apart and their presence or absence does not normally affect the stability of the tunnel opening. The exception exists when nearby faulting, or proximity to the top of the rock, results in the extreme jointing developed parallel to the bedding surfaces. The joint spacing in these cases is usually 10 to 25 cm (4 to 10 in).

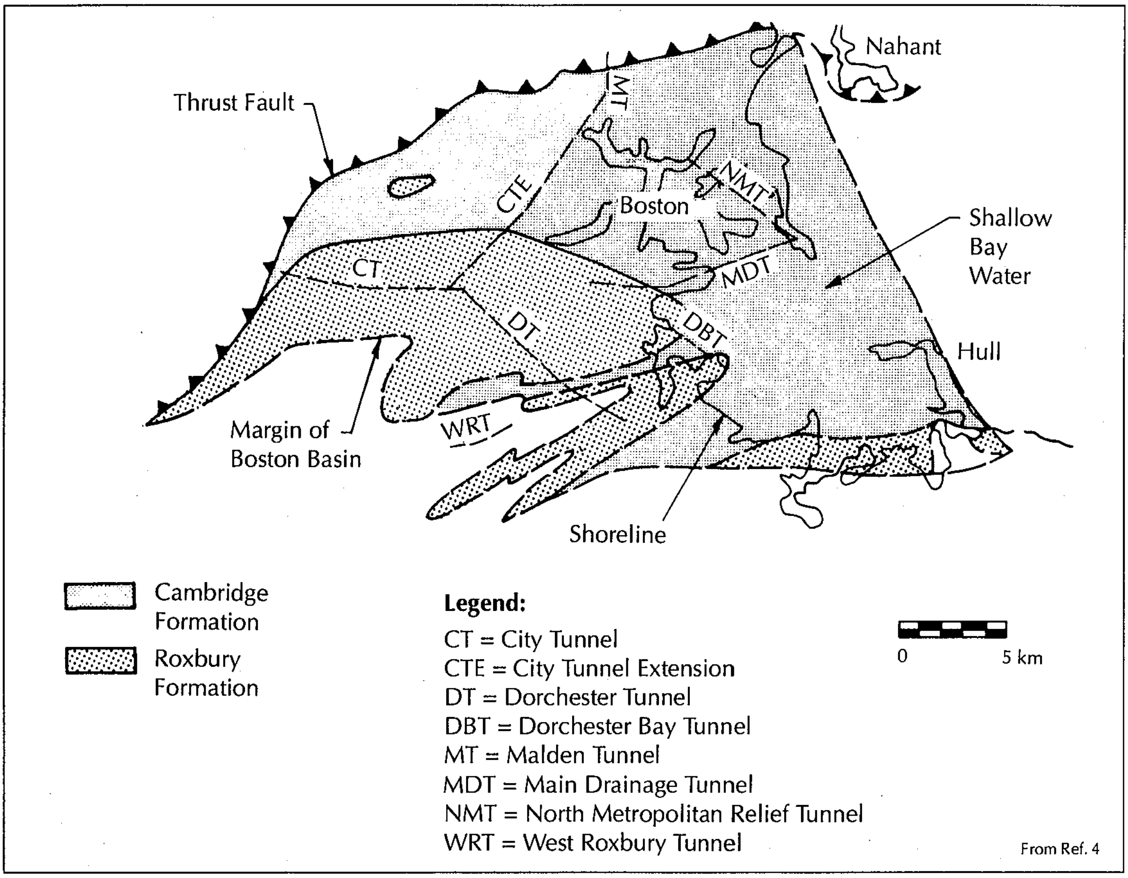
The orientation of the alignment is obliquely down- or up-dip in the tangent sections, depending on the direction the heading is being driven. On the curved section from Porter Square Station to Davis Square Station, the alignment swings around almost parallel to the strike to the beds.[16] This gradual change results in a varying response by the bedrock to the tunneling activity that translates into a differently shaped tunnel opening.[4]

The major joint set along the alignment, other than bedding plane joints, generally strike north-northeast, with nearly vertical dips. Jointing parallel to bedding is commonly developed and strikes nearly east-west with gentle to moderate dips, either north or south. A strong set of joints is developed nearly parallel to shear zones, which are usually oriented more east-north-east. These joints tend to die out with increasing distance from the shear zone and have not contributed to major support problems, because most have been oriented nearly normal to the tunnel alignment. Locally, overbreak is experienced parallel to the alignment.[16]

The occurrence of mafic to felsic igneous intrusive bodies along the alignment is not uncommon and the characteristics of each occurrence are unique. They vary in composition, texture, orientation and contact relationships with the country rock. Shear or fault zones without associated clay gouge have not had much effect on the construction aspect of the tunnel other than the variable fracturing effect on the rock. Where gouge is present, however, the stability is affected because of the reduction of the frictional forces that bind blocks of rock together around the opening. The integrity of the tunnel opening is further affected when these zones are nearly parallel to the alignment.[16]

Water Supply & Drainage Tunnels

Bedrock Geology. Water supply and drainage



From Ref. 4

FIGURE 5. Generalized geologic map of the Boston Basin showing water supply tunnels.

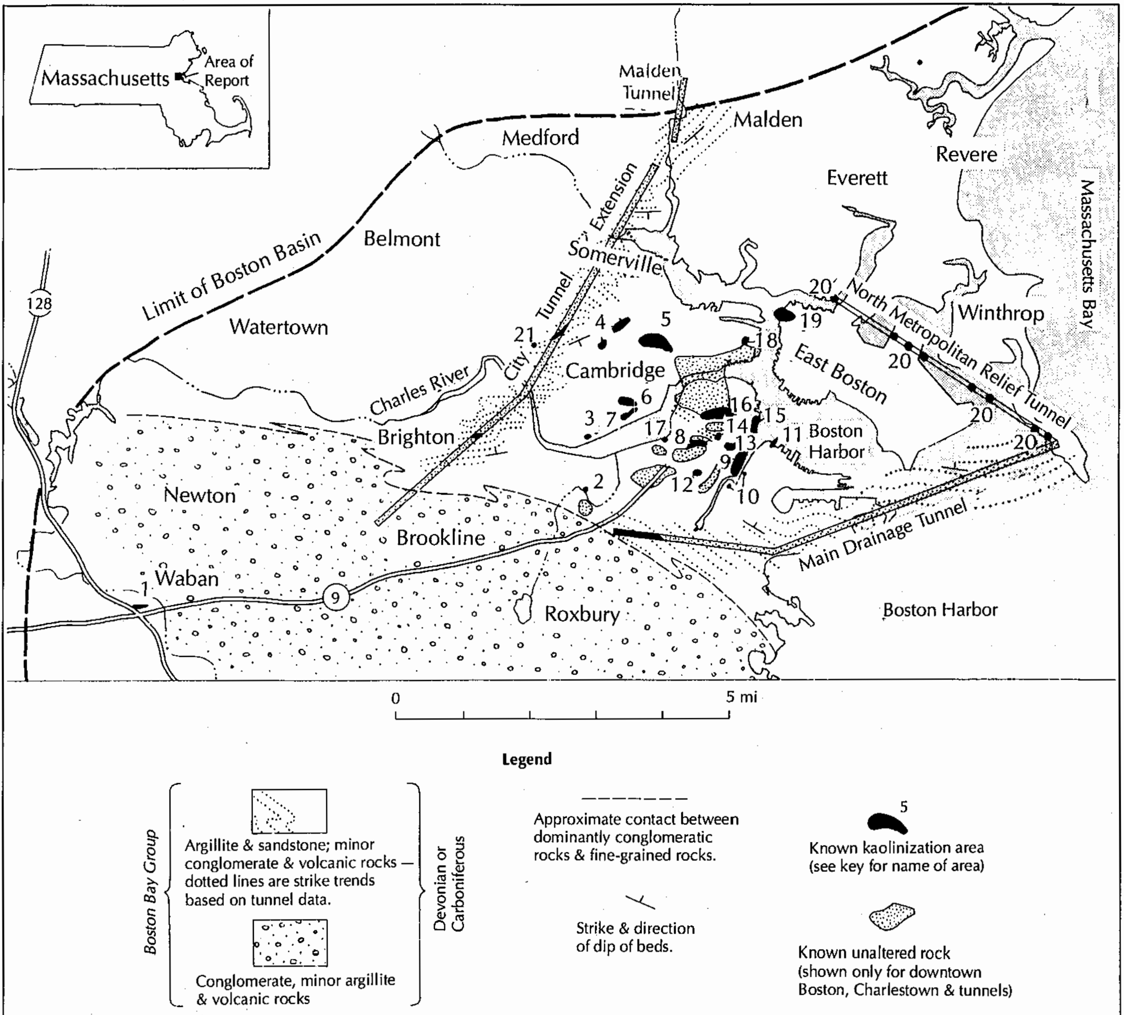
tunnels have been constructed in the region at various times (see Table 1). These tunnels were constructed largely in sedimentary rock (chiefly conglomerate and argillite, but with lesser amounts of sandstone, arkose, shale, melaphyre and diabase). Altered rock was also found in the tunnels.

The tendency of altered rocks to be restricted to certain beds is clearly expressed in the reports by Rahm, and Billings and Tierney, on the tunnels under Boston constructed by the Metropolitan District Commission (see Figures 5 and 6, and the first seven tunnels listed in Table 1).[12,11] In both tunnels studied — the City Tunnel Extension and the Main Drainage Tunnel — soft rock was found, but in both it was limited to certain beds or groups of beds. However, because tunnel observations are limited by the height of the tunnel (about 4 m [13 ft] for the Boston tunnels), the possibility exists that if viewed on a larger scale, the alteration would be seen to cut across planes of stratification.[1]

In the western 1.31 km (4,300 ft) of the Main Drainage Tunnel (see Figures 5 and 6), altered argillite (called "shale" in the tunnel reports) and sandstone are interbedded with massive conglomerate and arkose, some of which appears from the description to be altered. Three diabase dikes and sills are shown on Rahm's map as cutting the soft rocks.[12]

Billings and Tierney found "shale" in two places in the City Tunnel Extension (see Figures 5 and 6).[11] A section about 13 m (40 ft) thick of soft kaolinized argillite, interbedded with thin quartzite beds, purple argillite, sandstone and conglomerate, was found in the tunnel south of the Charles River at a depth of about 69 m (225 ft) below the top of the bedrock surface.

The North Metropolitan Relief Tunnel was completed before a geologist had an opportunity to map it. The geology of this tunnel is based on a study of the cores of exploratory



Note: Occurrences of kaolinization are in these areas as follows:

1. Intersection of Routes 128 & 9
2. Fenway, in front of Sears Roebuck store
3. Memorial Drive
4. Inner Belt route
5. Boston & Maine freight yards
6. Broad Canal
7. Green Building, MIT
8. Boston Common
9. South Station Postal Annex
10. Gillette Safety Razor plant
11. Pier 2
12. Castle Square
13. Former site of Stone & Webster Building, & the New England Telephone & Telegraph Building
14. West side of Washington Street at intersection of Water Street
15. Atlantic Avenue
16. Government Center
17. Beacon & Clarendon Streets
18. Charlestown Navy Yard
19. East Boston
20. Borings for North Metropolitan Relief Tunnel
21. Memorial Hall, Harvard University

From Ref. 1

FIGURE 6. Map of the Boston area showing the areas of known kaolinization, the bedrock tunnels and the generalized geology of the Boston Bay Group.

borings and on a very rapid survey of the finished and partly-lined bore by Billings.[1] Eight borings were made in badly altered rock, but altered rock was not noticed by Billings in the tunnel, and in all likelihood it was covered by the concrete lining. There are about 40 separate lined sections, and most if not all of these sections may have been built to support altered rock: 24 percent of the tunnel was lined. Unlike the other tunnels, there was an abundance of altered rock in this tunnel and this material was distributed fairly evenly throughout the length of the bore. The length of the lined sections suggests that altered strata ranged from as little as 3 to 30 m (10 to 100 ft) or more in thickness. Between these lined sections are hard argillite and sandstone. Similar rock alterations did not occur in the contiguous western end of the Main Drainage Tunnel.[12]

The deepest recorded occurrence of alteration beneath the surface of bedrock was reported by Billings and Tierney from the City Tunnel Extension under Cambridge.[11] At this point, their profile shows about 91 m (300 ft) of rock overburden.[11] The altered rock obviously extends below the tunnel level to greater depth. No borings yield unequivocal evidence of having reached the base, or maximum depth, of a particular kaolinized zone.

There is one indirect line of evidence that alteration dies out at relatively moderate depths. The distribution of altered rock is much more restricted in the Main Drainage Tunnel and the City Tunnel Extension than it is under the Boston Peninsula and adjoining Cambridge (see Figures 5 and 6). The average altitude of the rock surface in the altered zones is about -30 m (-100 ft), whereas the altitude of the tunnels ranges from -88 to -116 m (-290 to -380 ft). However, because the tunnels do not pass under the highly altered zone of Boston and Cambridge, it cannot be demonstrated that the sparseness of alteration in the tunnels bears on the depth of alteration. In addition, altered rock is abundant at an altitude of -85 (-280 ft) in the North Metropolitan Relief Tunnel.

Engineering Geology. The construction of four bedrock tunnels in the greater Boston area between 1948 and 1960, and under the supervision of the Construction Division of the Metropolitan District Commission (MDC), has greatly added to the geologic knowledge of the area. These four tunnels, totaling slightly more than 32 km (20 mi) in length, are the City Tunnel, the City Tunnel Extension, the Main Drainage Tunnel, and the Malden Tunnel (see Figures 5 and 6). The inner diameter of these tunnels when the concrete lining was emplaced was 3 to 3.7 m (10 to 12 ft).

City Tunnel. The main part of the City Tunnel extends from Riverside, some 8 km (5 mi) northeast of Wellesley, to the Chestnut Hill Reservoir, and is 7,700 m (25,260 ft) long. A branch tunnel 1,043 m (3,422 ft) long extends southeasterly from the east end of the main tunnel to the Chestnut Hill Pumping Station. Seventy-four faults were mapped in the course of explorations.[13] Most of these faults strike northeast and dip steeply to the northwest or southeast. Twenty-nine of the faults have gouge or breccia, or both, ranging in thickness from a smear to 3.4 m (11 ft), but averaging 1 m (3 ft).[8]

No support was needed in the approximately 2,134 m (7,000 ft) of andesites found, nor in the approximately 457 m (1,500 ft) of sandstone exposed in the western part of the City Tunnel.[2,13] Two short sections of sandstone in the Extension required support either because of "excessive splitting parallel to the bedding or to closely spaced joints."[11]

Along 16 faults, the fault-trace separation ranged from several centimeters to 3 m (few in. to 10 ft), averaging 1 m (3 ft); along 6 faults it exceeded 3.7 m (12 ft), the height of the tunnel. Along 52 faults, precise data were not available, but in 36 cases the fault-trace separation was certainly only several centimeters to a meter or less (few in. or ft). Breccia and gouge along 16 of the 52 faults suggest the possibility of greater movement.

Only 16 feet, or 0.0005 percent of the entire tunnel, is supported by structural steel (no bolts were used). The support is just west of a fault and probably indirectly related to it. Seventy-four faults in the City Tunnel did not necessitate support, with one possible exception.[8]

City Tunnel Extension. In the City Tunnel Extension, which is 11,436 m (37,511 ft) long and goes from Chestnut Hill Reservoir to Malden, Billings and Tierney measured 220 faults, exclusive of those along the contacts of dikes or along bedding planes.[11] These 220 faults are in four rather ill-defined groups:

- a prominent group striking northeast and dipping northwest;
- an equally prominent group striking northwest and dipping northeast;
- a minor group striking northeast and dipping southeast; and,
- a very subordinate group striking northwest and dipping southwest.

The faults range in observed length from 1 m or so (few ft) to a maximum of 82 m (271 ft). The true lengths are always greater than the observed lengths, since the faults have invariably disappeared into the walls or roof of the tunnel.[8] Most of the faults are sharp, tight fractures, at the greatest only several centimeters (few in.) wide. Only a dozen of the faults exceeded a foot in width and the maximum width was 1 m (3 ft). In at least 8 instances several faults were close enough to form fault zones from 1.5 to 59 m (5 to 194 ft) wide. Twenty-one of the faults contained gouge or breccia or both that ranged in thickness from a smear to 1 m (3 ft). Of the 220 faults, 114 were characterized by foliated (slaty) rock several centimeters to 0.3 m (few in. to a foot) thick.[8]

The fault-trace separation was measured on the tunnel walls. Along 84 percent of the faults, the fault-trace separation was only a meter or so (few ft). Along the other 16 percent, it exceeded 3.7 m (12 ft), the height of the tunnel, but was probably only for an extent of several meters (a few tens of ft) at the most. The net slip along the faults was of the same order of magnitude as the fault-trace separation.

Structural steel support with very few bolts was used in 634 linear m (2,103 ft) — 5.6 percent — of the tunnel. Seventy six percent of the support was necessitated by weak shales and argillites, or by badly fractured dikes. Twenty-four percent, equal to 152 m (498 ft) of the support was related to faults. Of this, 29 m (94 ft) was necessitated by faults striking across the tunnel and dipping 25° north-northeast. Associated closely-spaced joints were also a factor. Support in the other 123 m (404 ft) was necessitated by steep shears striking nearly parallel to the tunnel, although in a few cases dikes were a contributing factor. But there were many faults, including some striking parallel to the tunnel, that did not necessitate support. Only 12 of the 220 faults that were recorded were present in areas of support.

Main Drainage Tunnel. The Main Drainage Tunnel, at 1,093 m (3,586 ft) long, extends in a generally easterly direction from near Wentworth Institute in Boston to Deer Island in Boston Harbor. Two short sections of sandstone required support, either because of excessive splitting parallel to the bedding or the joints were too closely spaced.

Rahm mapped 158 faults in the Main Drainage Tunnel.[12] The most abundant had an average strike of N 30° east and dipped 60° northwest. The width ranges from a centimeter to 0.3 m (fraction of an in. to a ft). Gouge was noted along 45 of the faults with thicknesses ranging from a smear to as much as 0.3 m (1 ft). Fault breccia, recorded along 5 of the faults, ranged from a couple of centimeters to 0.3 m (in. to a ft) in thickness. Veins of quartz or calcite, or both, are associated with eight of the faults, generally ranging in thickness from 2 to 9 cm (1 to 6 in), but one is 30 cm (12 in) thick and another is 60 cm (24 in) thick. Rahm states that in the 63 faults for which sufficient data are available, the stratigraphic throw ranges are from 2 cm to 8.5 m (1 in. to 28 ft), with a mean of 0.8 m (2.5 ft) and a median of 1 m (3 ft). The net slip was probably the same order of magnitude as the stratigraphic throw.[12]

Sixty-seven of the faults occur on land between Shaft A at the west end and Shaft B at the edge of the harbor. Seventy-seven percent of this section was supported by structural steel, chiefly because of inherently weak shales and argillites. Forty-six of these faults were in areas supported by structural steel, but this support was related to the lithology, rather than to the faults.[8,12]

Ninety-one of the faults are beneath the harbor — that is, between Shaft B and Shaft C on Deer Island. Only eleven percent of this section was supported by structural steel. This support was associated with diabase dikes or jointed argillite. Some roof bolts were used to stabilize gently dipping strata. None of the faults necessitated support.[12]

In the 915 m (3,000 ft) of conglomerate cut by the Main Drainage Tunnel,[12] about 12 percent required steel supports, since there was apparently badly altered rock and rock that was faulted and cut by a diabase dike.[2]

Malden Tunnel. The Malden Tunnel, at 1,605 m (5,266 ft) long, extends in a north-south direction through Malden near Malden Square.[10] It crosses the Northern Boundary Fault of the Boston Basin. The Northern Boundary Fault is a large fault that dips northwest, and along which the Lynn Volcanics have been thrust southeasterly over argillite. The stratigraphic throw exceeds 3,000 m (10,000 ft) and the net slip is probably at least 4,570 m (15,000 ft).[10] It is a much larger fault than any of those discussed above. Gouge, breccia, silicification and other features are absent. On the other hand, the argillite for 540 m (1,771 ft) south of the fault and the Lynn Volcanics for 262 m (861 ft) north of the fault were sufficiently jointed to necessitate using structural steel.[10]

Dorchester Tunnel. The Dorchester Tunnel is a high-pressure (200 psi) water supply tunnel that was constructed and operated by the MDC for water delivery to the southern Greater Boston area (see Figure 5). It is the most recent MDC water supply tunnel, having been constructed between 1968 and 1974. The Dorchester Tunnel extends southeastward for about 10.5 km (6.5 mi.) from the Chestnut Hill Reservoir area to Dorchester Lower Mills on the Neponset River estuary. The central construction shaft (Shaft 7C) now serves as an intermediate access point used primarily for water distribution to surface mains. The tunnel is circular in cross-section, and is lined with 0.3 m (1 ft) or more of concrete to provide a 3 m (10 ft) internal diameter. Invert (floor) elevations range from approximately 30 m (100 ft) below sea level at the shaft at Chestnut Hill to 61 m (200 ft) below sea level at the central construction shaft and 64 m (210 ft) below sea level at the shaft at Dorchester Lower Mills. The tunnel was excavated entirely in bedrock. Excavation was by traditional drill-blast methods except for about 1,220 m (4,000 ft) near the main construction shaft, where a mole was used.[17]

The tunnel was mapped by Richardson and travels mostly through the rock of the Boston Basin — mostly through conglomerate, pebbly mudstone and argillite.[15] In addition, the tunnel passes through the Mattapan volcanic rock, principally in the core of the Mattapan anticline and also immediately southeast of the Mount Hope fault.

The central construction shaft was excavated in the argillite of the Roslindale Syncline, and the use of the mole was started in this unit at about 91 m (300 ft) southeast of this shaft. When the mole reached the Mount Hope fault and passed into the Mattapan volcanic rock, it was unable to excavate those rocks satisfactorily, and it was removed from the tunnel. Traditional drill-blast excavation was substituted to complete the tunnel to the shaft at Dorchester Lower Mills.[17] About 884 m (2,900 ft) of volcanic rocks were pierced by the Dorchester Tunnel, of which 46 m (150 ft) required the installation of steel supports due to localized jointing.[15]

The Dorchester Tunnel pierced the entire width of the conglomerate that crops out in Brookline, Jamaica Plain and Roxbury. About 13 percent of the 6,310 m (20,700 ft) of conglomerate traversed by the tunnel required steel support because of soft-rock alteration, which seems to be concentrated along a very wide fault zone.[15,17] Another two percent of supported rock was the result of close jointing, faulting and the effects of a thick diabase dike and interbedded argillite.

Shortly after the tunnel was placed in service in November 1974, the basements of some homes in the area became flooded. Tests made by the owners and the MDC subsequently confirmed that the flooding was the result of water flowing under pressure from the Dorchester Tunnel. Inspection of the tunnel indicated that the lining was significantly cracked, with major water flow occurring between Stations 510 and 523.

MDC engineers and their consultant generally agreed that the internal water pressure in the tunnel was transmitted through the liner and caused compression of the rock.[17,18]

Following investigations, plans and specifications were prepared for pressure grouting to repair the cracked lining. Pressure grouting was performed from within the tunnel. A neat, type III Portland cement grout was used, with a maximum injection pressure of 400 psi. Following the grouting of the primary stage holes, secondary stage grouting was undertaken at split spacing. Results of water pressure tests, grout take and core borings were used to evaluate the effectiveness of the grouting.[18] After the grouting was completed, a test section of the tunnel lining was instrumented to measure the behavior of the tunnel and adjacent rock during pressure testing. Instrumentation included diametric convergence meters, strain gages, extensometers and piezometers. Over a period of six weeks, the tunnel was water tested under service pressures. In addition to the instrumentation readings, observation well measurements were made to observe the effect of water flow from the tunnel on groundwater levels in the area. Finally, the tunnel was drained, inspected and placed back into service.

Trans-Harbor Highway Tunnels

Two major subaqueous highway tunnels connect downtown Boston with the communities northeast of the harbor, exiting in East Boston (formerly Noddle Island). These tunnels were constructed in two phases. The first tunnel, the Sumner Tunnel, was constructed in the 1920s by conventional shield method, with the muck being removed by hand. To alleviate traffic to Logan Airport in East Boston, a second tunnel, the Callahan Tunnel, was constructed in the 1960s, also using the shield method.

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

REFERENCES

1. Kaye, C.A., "Kaolinization of Bedrock of the Boston, Massachusetts, Area," U.S. Geological Survey Professional Paper 575-L, 1967, pp. C165-C172.

2. Kaye, C.A., "Engineering Geologic Framework of the Boston Basin," in Hatheway, A.W., ed., *Engineering Geology in New England*, American Society of Civil Engineers, Annual Meeting, Boston, Preprint 3602, 1979, pp. 1-17.

3. Kaye, C.A., "Bedrock and Quaternary Geology of the Boston Area, Massachusetts," *Geological Society of America, Reviews in Engineering Geology*, Vol. V, 1982, pp. 25-40.

4. Hatheway, A.W., & Paris, W.C., Jr., "Geologic Conditions and Considerations for Underground Construction in Rock, Boston, Massachusetts," in Hatheway, A.W., ed., *Engineering Geology in New England*, American Society of Civil Engineers, Annual Meeting, Boston, Preprint 3602, 1979, 20 pp.

5. Hatheway, A.W., "Hardrock Geologic Mapping for Underground Construction in the Boston Basin," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, Univ. Massachusetts Graduate School, 1982, pp. 236-246.

6. Aldrich, H.P., Jr., "Back Bay Boston, Part 1," *Journal of the Boston Society of Civil Engineers*, V. 57, N. 1, 1970, pp. 1-33.

7. Aldrich, H.P., Jr., & Lambrechts, J.R., "Back Bay Boston, Part II: Groundwater Levels," Boston Society of Civil Engineers, *Civil Engineering Practice*, V. 1, N. 2, 1986, pp. 31-64.

8. Billings, M.P., "The Significance of Faults in Tunnels," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, University of Massachusetts Graduate School, 1967, pp. 267-272.

9. Billings, M.P., "Failure of the Concrete Lining in the Dorchester Tunnel (Discussion)," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, Univ. of Massachusetts Graduate School, 1982, p. 229.

10. Billings, M.P., & Rahm, D.A., "Geology of the Malden Tunnel, Massachusetts," *Journal of the Boston Society of Civil Engineers*, V. 54, 1966, pp. 116-141.

11. Billings, M.P., & Tierney, F.L., "Geology of the City Tunnel Extension, Greater Boston, Massachusetts," *Journal of the Boston Society of Civil Engineers*, V. 57, 1964, pp. 111-154.

12. Rahm, D.A., "Geology of the Main Drainage Tunnel, Boston, Massachusetts," *Journal of the Boston Society of Civil Engineers*, V. 49, 1962, pp. 319-368.

13. Tierney, F.L., Billings, M.P., & Cassidy, M., "Geology of the City Tunnel, Greater Boston, Massachusetts," *Journal of the Boston Society of Civil Engineers*, V. 55, 1968, pp. 60-96.

14. Aldrich, H.P., & Dugan, J.P., "Investigation of a Cracked Pressure Tunnel Lining in Rock," Transportation Research Board, 58th Annual Meeting,

Washington, D.C., 1979, Abstracts.

15. Richardson, S.M., "Geology of the Dorchester Tunnel, Greater Boston, Massachusetts," *Journal of the Boston Society of Civil Engineers Section/ASCE*, V. 63, 1977, pp. 247-269.

16. Cullen, T.R., Young, L.W., Jr., & Keville, F.M., "Tunneling Through the Cambridge Argillite," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, Univ. of Massachusetts Graduate School, 1982, pp. 197-211.

17. Ashenden, D.D., "Geologic Factors Affecting Failure of the Dorchester Tunnel, Boston," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, Univ. of Massachusetts Graduate School, 1982, pp. 213-219.

18. Dugan, J.P., Jr., "Pressure Grouting to Repair the Dorchester Water Tunnel, Boston," in Farquhar, O.C., ed., *Economic Geology in Massachusetts*, Univ. of Massachusetts Graduate School, 1982, pp. 221-228.

19. MBTA, *The Boston Rapid Transit System: A History of Progressive Growth*, date unknown.

20. Whitehill, W.M., *Boston: A Topographical History*, 2 ed., Belknap Press of Harvard University, 1973, 249 pp.

21. Kaye, C.A., "Beacon Hill End Moraine, Boston — New Explanation of an Important Urban Feature," in Coates, D.R., ed., *Urban Geomorphology*, Geological Society of America Special Paper 174, 1976, pp. 7-20.

22. Keville, F.M., & Pizzo, C.D., "Community Participation in Public Works Projects," Boston Society of Civil Engineers, *Civil Engineering Practice*, V. 1, N. 1, 1986, pp. 23-42.