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GEOLOGY OF THE DORCHESTER TUNNEL, GREATER BOSTON, MASSACHUSETTS

By
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Abstract

The Dorchester Tunnel extends 6.33 miles southeasterly from shaft 7B at the Chestnut Hill Reservoir in Brighton to a newly constructed shaft (7D) in Dorchester Lower Mills. The tunnel was constructed as a major water supply for the southern part of Greater Boston to complement the City Tunnel Extension to the north. It is entirely in bedrock, and is the first modern tunnel to be driven south of the axis of the Central Anticline in the Boston area, providing a previously unattainable geologic section through sediments in the southern half of the Boston Basin and into the volcanics of the Mattapan Formation. Approximately 3300 feet of the tunnel (less than 10%) was supported by structural steel ribs. Most of the excavation was performed by conventional blasting methods, but nearly 3800 feet of the tunnelling was performed by a full-face rotary drilling machine ("Mole"), used here for the first time in New England.

Introduction

Investigations of the bedrock geology in the Boston Basin have been carried on in a series of tunnels built under the supervision of the Engineering Division of the Metropolitan District Commission during the last thirty years (Rahm, 1962; Billings and Tierney, 1964; Billings and Rahm, 1966; Tierney, Billings, and Cassidy, 1968; Billings, 1975). Except for the Dorchester Bay Tunnel (Fig. 1; Clarke, 1888), these tunnels are in areas north of the axis of the Central Anticline.

The Dorchester Tunnel offered an opportunity to study in detail the stratigraphy and structure south of the Central Anticline. Various sedimentary and igneous rocks were crossed in the tunnel: conglomerate, sandstone, arkose, argillite, felsite, and melaphyre. Locally the rocks were extensively altered and fractured. These varying conditions were major factors influencing the method of excavation and the amount of support.

Of special interest in the construction of the Dorchester Tunnel has been

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the experimental use of a full-face rotary drilling machine, or "Mole", and of a rotary raise drilling machine. A short discussion of these excavation tools, as well as a consideration of some physical properties of the rock in the Dorchester Tunnel has been included here because of its significance for engineers. Shotcrete was used in an experimental way for structural support for 300 feet in the headings either side of shaft 7C, but was deemed inadequate for most of the tunnel.

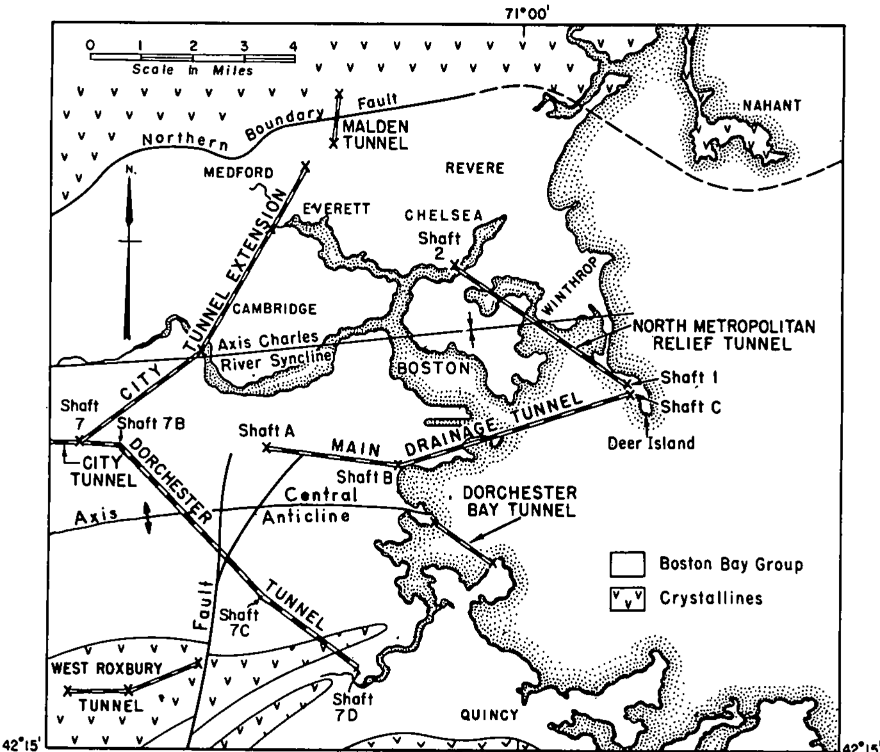

Figure 1: Index map, showing the location of bedrock tunnels in the eastern part of the Boston Basin.

Preliminary geologic maps and sections along the tunnel line were prepared in 1964 by Dr. Marland P. Billings of Harvard University, and were based on data from his own surface studies and from examination of 48 bedrock cores. Dr. Billings also mapped the headings extending 300 feet on either side of shaft 7C during construction and paid several visits to the excavation site during tunnel construction. I performed the remainder of the mapping between January 1970 and March 1973, and produced the final geological report on the Dorchester Tunnel for the MDC.

Location, Size, and Construction

The Dorchester Tunnel, built under the direction of the Construction Division (now the Construction Engineering Division) of the Metropolitan District Commission, Commonwealth of Massachusetts as contract C-338, is a water supply tunnel extending 33,437 feet (6.33 miles) from shaft 7B in Chestnut Hill to a newly constructed shaft (7D) in Dorchester Lower Mills (see figure 2). Shaft 7B, constructed as part of the City Tunnel excavation

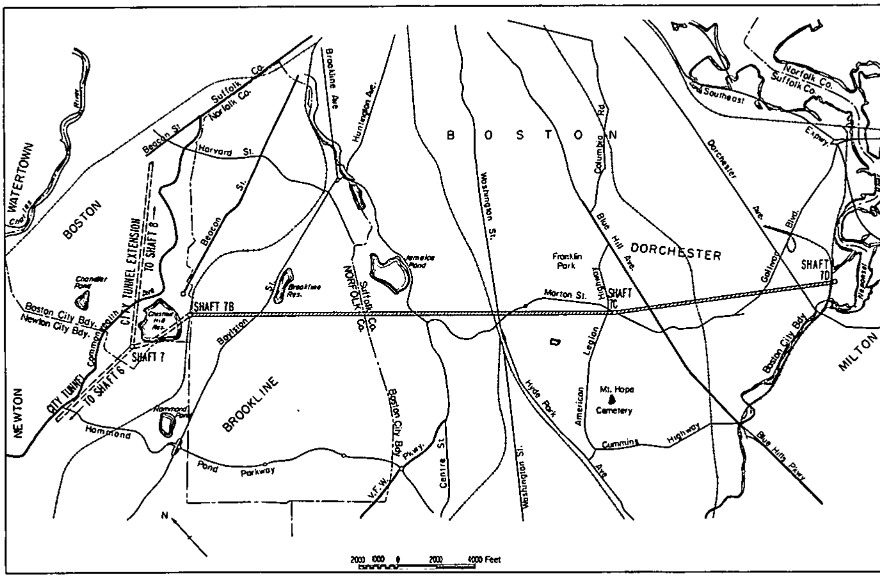

Figure 2: Detailed index map, showing the location of the Dorchester Tunnel.

completed in 1951, is located at the Chestnut Hill pumping station on the eastern end of the Chestnut Hill Reservoir in Brighton, a few hundred feet from the Brookline town line. Shaft 7D, built as part of the present contract, is located at the end of Bearse Avenue in Dorchester Lower Mills, a few hundred feet from the Neponset River. An intermediate shaft, 7C, is located on the grounds of the Mattapan State Hospital at the intersection of Morton Street and the American Legion Highway in Mattapan, and served as the working shaft during construction. From the plug at the end of City Tunnel construction, 150 feet S.82°E. of shaft 7B, the tunnel line extends 21,849 feet (4.14 miles) S.44°58'36"E. to shaft 7C, and thence 11,383 feet (2.16 miles) S.55°21'07"E. to shaft 7D. Excavation along this line was continued an additional 116 feet southeast of 7D to allow for future connections. During construction, all locations in the tunnel were referenced to the center line of shaft 5 (sta. 0+00) in Weston. Center lines of shafts 7B, C, and D are thus at stations 286+81, 506+92, and 621+64 respectively. All locations referred to in this paper are referenced to the same system. Colloquially, the headings northwest and southeast from shaft 7C were known respectively during construction as the Brookline and Dorchester (or Neponset) headings, and those designations are retained here.

The tunnel invert slopes downward from elevation -100.0 feet at shaft 7B to an elevation of -195.0 at station 440+94 and then on a slightly decreased slope to -210.0 at shaft 7D. The finished invert level at shaft 7C is -200.0. All elevations are taken relative to Boston City Base, which is 5.65 feet below the U.S. Geological Survey Base (mean sea level).

The tunnel was excavated to a nominal diameter of 12'2", though deviations toward a larger diameter were common in most sections of the tunnel. The tunnel was lined with concrete to a finish diameter of 10'0".

Geological Setting

The general geology of the Boston Basin has been described by LaForge (1932) and most recently by Billings (1976a). The bedrock consists of a thick sequence of intermontaine basin deposits, varying in lithologic character from a coarse pebble- or cobble-conglomerate to a fine-grained argillite, known collectively as the Boston Bay Group. The exposed thickness of these sediments in the tunnel is nearly 9000 feet. The group is subdivided into two formations: an upper, thinly laminated argillaceous unit called the Cambridge Formation (3500 feet thick here), and a lower unit, called the Roxbury Formation, composed of conglomerate, argillite, sandstone, and melaphyre (5500 feet thick here). The Roxbury Formation is further subdivided into three members which are, from top to bottom in the stratigraphic column, the Squantum, Dorchester, and Brookline Members. These members are best distinguished by particle size and sorting characteristics. The Brookline Member consists primarily of fairly well-sorted arkosic conglomerates in which the average clasts are well-rounded, locally spherical, but generally somewhat elongated in one direction. Clasts vary in diameter from 1 inch to 6 inches or more, with individual cobbles more than a foot across. The Brookline Member contains beds, some hundreds of feet thick, of sandstone and argillite. The Dorchester Member is characterized by conglomerates interbedded liberally with arkosic sandstones, grading locally into finely laminated argillites. The Squantum Member contains conglomerate and a rock that has been variously described as a tillite or a tilloid (Sayles, 1914, 1929; Dott, 1961; Lindsay *et al.,* 1970; Rehmer and Hepburn, 1974, 1975; Baker and Dott, 1975; Stuart, 1975). The tillite (tilloid) is characterized by its relatively high proportion of matrix to clasts, poor sorting within single beds, and angular clasts.

The basement rocks on which the Boston Bay Group have been laid down are different from place to place around the Basin, and may be either a plutonic rock or different volcanic rocks, ranging from very light-colored to reddish or brown felsites to dark green extrusives known locally as melaphyres. Any of these volcanics can and do appear as heterogeneous breccias or agglomerates, and the melaphyres are commonly amygdaloidal. In the southern portion of the Basin transsected by the Dorchester Tunnel, the volcanics are referred to collectively as the Mattapan volcanics, whereas those in the north are called the Lynn volcanics.

Dating of the Boston Bay Group is tentatively upper Paleozoic, no more refined dating being possible because of the rarity of fossils. Two poorly preserved cylindrical casts and molds of tree trunks or roots, described by Burr and Burke (1899), are presently in the collections at Harvard University, and may be either *Calixylon* or *Cordaites,* genera which span geological time from late Devonian to the Permian (Rahm, 1962).

Sedimentation of the Boston Bay Group was a continuous event, though the sources of sediments (as evidenced by the rock types of the clasts) were multiple and constantly changing, and the rates of sedimentation were locally quite variable. Billings and Tierney (1964) have shown that the various sediments of the Boston Bay Group are not purely sequential in a time-stratigraphic sense, but are facies of one another, representing different configurations of the sedimentary environment, varying distances from their source areas, and various degrees of reworking of primary sediments. The sedimentary environment presently envisioned is one of a large intermontaine basin, deeper in the north than in the south, and fed primarily by streams flowing from mountains in the south.

In all probability, the volcanic clasts that appear so commonly in the Roxbury Formation are derived from the Mattapan volcanics. Some vulcanism continued well after the Boston Bay Group began to accumulate, however; exposures of volcanic rocks high in the stratigraphic column have been noted in several localities (Billings and Tierney, 1964; Billings, personal communication). Although some of the melaphyres in the Roxbury Formation are intrusive, others are extrusive (flows, tuffs, and breccias) and may have been the source of some of the clasts in the Roxbury.

The Dorchester Tunnel crosses a series of major and lesser folds and faults which have distorted the stratigraphic record as just presented. The principal folds are: the Central Anticline (axis near sta. 350+00), the Roslindale Syncline (axis near sta. 547+00), the Mattapan Anticline (axis near sta. 576+00), and the Lower Falls Anticline (axis near sta. 614+00). The most important faults are the Mount Hope Fault, near sta. 547+00, and the transverse Stony Brook Fault Zone.

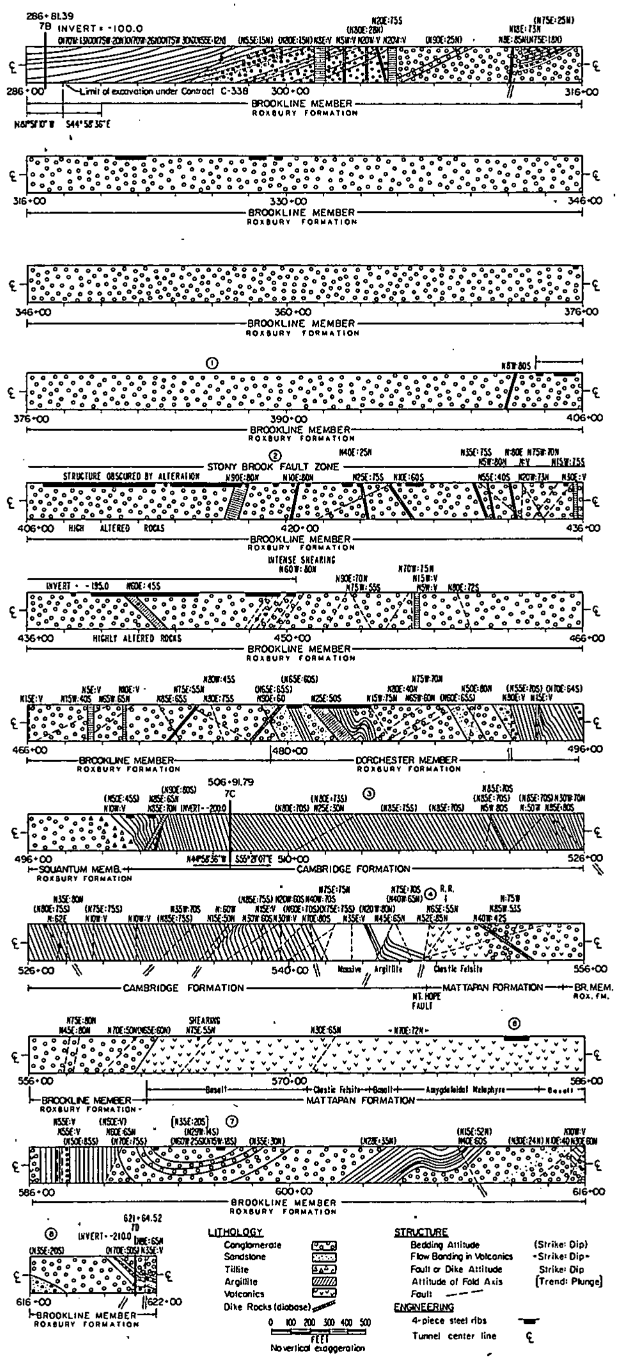

Figure 3: (Caption on facing page)

Stratigraphy and Lithology

The Dorchester Tunnel, which trends southeasterly across the axis of the Central Anticline in Brookline and then across a series of smaller folds and high-angle faults in Mattapan and Dorchester, provides extensive exposures of each of the rock units discussed in the previous section. Because earlier bedrock tunnels were constructed to the north of the Central Anticline, these exposures provide the first continuous view of the stratigraphic record in the southern half of the Boston Basin. From a study of the rocks in the Dorchester Tunnel, then, we may hope to improve our understanding of the sedimentary environment in this portion of the basin, and of the relationship between the Boston Bay Group and the underlying Mattapan volcanics.

In this section, I will present a generalized description of the rock units as they appear in the tunnel and will discuss their relationships to each other and to the stratigraphic sequence in the Boston area. A more detailed presentation of the rock units appears in an appendix. Discussion of the lithology and stratigraphy will proceed from the northwest (shaft 7B) to the southeast (shaft 7D), as shown in figure 3.

Sta. 288+43 to 479+04: Roxbury Formation; Brookline Member. This is part of the main body of the Brookline Member in the Boston Basin, occupying the core of the Central Anticline. Inasmuch as the Central Anticline plunges east, older units of the Brookline Member lie southwest of the tunnel. The minor quantities of argillite and sandstone in the northwest part of the tunnel are lake deposits. These were exposed in the City Tunnel Extension (Billings and Tierney, 1964), and persist to roughly sta. 296+00, where they gradually give way to coarser sandstones and conglomerates. Occasional sandstone beds are present to sta. 309+00, and then briefly again where minor faulting at sta. 312+50 drops them to the tunnel. From there to sta. 479+04 the only rocks exposed (other than occasional diabase dikes) are massive conglomerates in which bedding was never observed.

Sta. 479+04 to 495+75: Roxbury Formation; Dorchester Member. The relative abundance of sandstones and argillites in this section of the tunnel, taken together with their position above the Brookline Member, is sufficient to designate these rocks as Dorchester Member. Throughout the section,

Figure 3: (Facing page):Geological section along the line of the Dorchester Tunnel, facing northeast, based on observations made at the tunnel center line. No vertical exaggeration. Structure attitudes are indicated above the section at the points where they were measured on the center line. The sense of movement on faults, where known, is indicated by double arrows below the section. In most cases the offset on faults is small, and thus not shown at the scale of this drawing. Dikes narrower than 4 feet are not shown. Tunnel invert elevations are given in feet relative to the Boston City Base. Circled numbers refer to structural features discussed in the text.

feldspathic sandstones, argillites, and pebble conglomerates are intimately interbedded, and individual beds often display graded bedding, ripple marks, or other sedimentary indicators of tops. The appearance of well-defined beds is in distinct contrast to the rocks of the chaotic, poorly-bedded Brookline Member beneath. The contact between Brookline and Dorchester, therefore, has been arbitrarily placed where distinct bedding first appears, at sta. 479+04. The contact between the Dorchester Member and the Squantum Member is taken to be at the top of a white, kaolinitic layer of argillite at sta. 495+75. The thickness of the Dorchester Member in this tunnel is thus about 1250 feet, which is comparable to values in other tunnels.

Sta. 495+75 to 501+40: Roxbury Formation; Squantum Member. The base of the section, roughly to sta. 500+00, consists of unbedded sandy conglomerate; the upper portion consists of a light greenish tillite (tilloid(?); recall the discussion earlier). The lithologic character of the tillite is similar to that described by Rahm (1962) in the Main Drainage Tunnel, and by Sayles (1914) at the type locality for the Squantum Member. Stratigraphic position above the Dorchester Member in the present section makes the assignment of these rocks to the Squantum Member unambiguous. The conglomerates in the lower part of this section are included because the contact between them and the underlying argillite at sta. 495+75 is a fairly sharp bedding plane; the transition between the conglomerate and the tillite is gradual.

Sta. 501+40 to 547+52: Cambridge Formation. The rocks are argillite, of the type recognized elsewhere in the Boston Basin as Cambridge, and appear directly over the Squantum Member in the stratigraphic sequence observed in this tunnel. The contact between the Roxbury Formation and the Cambridge Formation is conformable and sharp.

Sta. 547+52 to 550+60: Mattapan Formation. The contact between the Cambridge Formation and the Mattapan Formation at sta. 547+52 is along a tight high-angle fault (the Mount Hope Fault), which will be described later in this paper. The rocks in this portion of the tunnel are pyroclastic felsites and minor basalts, and have evidently been thrown far up section. Their exposures in the tunnel correlate well with surface outcrops of the Mattapan Formation at its type locality.

The contact between the volcanics in this section and the conglomerates at sta. 550+60 (as well as similar contacts at sta. 562+30 and 586+18) was thought by LaForge (1932) to be an angular unconformity, implying that a hiatus existed between the end of Mattapan vulcanism and the beginning of Boston Bay Group sedimentation. I find no evidence for such an unconformable contact. Where Mattapan volcanics appear adjacent to conglomerates in this tunnel, the contact is invariably gradational. A large proportion of the clasts in the conglomerates of the Boston Basin are volcanic (Mattapan-type) rocks and, judging from their coarseness, have been derived from rather steep, nearby slopes. With the discovery of confused, transitional contacts rather than an unconformity between the volcanic rocks and conglomerates, therefore, it is reasonable to presume that vulcanism and sedimentation proceeded simultaneously for some time.

Sta. 550+60 to 562+30: Roxbury Formation; Brookline Member. There is some question about the placement of these rocks in stratigraphic sequence. By the argument just presented, it should be evident that some conglomerates may occur in the main body of the Mattapan Formation, far below the base of the Roxbury Formation. The rocks in this portion of the tunnel might be an exposure of such a unit and, if so, should be labelled as conglomerates in the Mattapan Formation. I have chosen not to do so for two major reasons.

First, although the proportion of volcanic clasts in these conglomerates is higher than in the "average" exposures of Roxbury conglomerate, the lithologic similarities, particularly with regard to granitic clasts and the arkosic matrix, are striking. This conglomerate, therefore, cannot be far below the Mattapan - Roxbury contact, if at all.

More important, however, these conglomerates lie on the northwest limb of the Mattapan Anticline, which has been well-documented on the surface, and they are probably stratigraphically equivalent to the conglomerates and sandstones in the vicinity of sta. 586+00, on the southeast limb. Thus, again, it is most likely that these conglomerates are not in an isolated bed within the Mattapan Formation, but are at the base of the Roxbury Formation.

This interpretation is admittedly open to argument but, in my opinion, is most consistent with the general geology. It also has the distinction of minimizing the uncomfortably large calculated separation on the Mount Hope Fault (see Structure).

Sta. 562+30 to 586+18: Mattapan Formation. This portion of the tunnel is in the type locality for the Mattapan Formation and contains extensive exposures of basaltic rocks, some of which are amygdaloidal.

Sta. 586+18 to 622+80: Roxbury Formation; Brookline Member. These conglomerates and argillites, similar to those described previously, lie between two anticlines of the Mattapan volcanics (fig. 1), one immediately to the northwest in the tunnel and a second to the southwest which, because of its northeasterly plunge, does not reach the tunnel. Since these conglomerates are only about 1200 feet thick and are at the base of the Roxbury Formation (Billings, personal communication), they belong to the Brookline Member.

Sedimentation

The evolutionary picture of the depositional history of the Boston Basin which can be deduced from the Dorchester Tunnel is essentially that described by Billings and Tierney (1964, p.149). Sedimentation apparently took place in a large intermontaine lake, shallower in the south than in the north, and with a gradually fluctuating water level. The shore line facies is the Dorchester Member, as evidenced by the many reversals of sedimentary lithology and by such features as ripple marks. Conglomerates were laid down by streams feeding the lake from the south. The apparent lack of bedding in most of the exposed Brookline Member conglomerates suggests that these sediments were multiply reworked after their initial deposition. The Cambridge argillite represents the deep water facies, and was primarily deposited in the lake in the northern half of the basin.

Structure

From northwest to southeast, the following major structural features are crossed by the Dorchester Tunnel:

1) Central Anticline, shaft 7B (286+81) to 501+40
2) Stony Brook Fault Zone, 403+50 to 450+50 and 480+00 to 484+55
3) Roslindale Syncline, 501+40 to 547+52
4) Mount Hope Fault, 547+52
5) Unnamed syncline, 547+52 to 562+30
6) Mattapan Anticline, 562+30 to 586+18
7) Unnamed syncline, 586+18 to 615+40
8) Lower Falls Anticline, 615+40 to 622+00

These features, as numbered, are shown on figure 3.

Folds

The north boundary of the Central Anticline lies several miles northwest of shaft 7B; the southeast boundary is arbitrarily placed at the base of the Cambridge argillite, at station 501+40. In the Dorchester Tunnel the attitude of the northern limb is shown very well near shaft 7B; the average dip is 20°N. The attitude of the southern limb is well shown between stations 479+04 and 501+40; the average strike is N.60E.; the average dip is 60°S. Assuming concentric folding, the axial plane of the Central Anticline thus dips 70°NW.

The section of the tunnel between stations 313+80 and 479+04 was disappointing in that bedding was never observed. The geology is well-exposed at the surface, however, and shows that the Central Anticline is a broad open fold that plunges 12°E. The tunnel should cross the axis near sta. 386+00.

The Roslindale Syncline extends between stations 501+40 and 547+52. Only the northwest limb is preserved. The southeast limb has been cut out by the Mount Hope Fault. For 4200 feet, as far as sta. 544+00, the attitude of the bedding is very constant; the strike ranges from N.60E. to N.90E., averaging N.77E.; the dip ranges from 70° to 80°SE., averaging 73°SE.

Between sta. 544+00 and the Mount Hope Fault (sta. 547+52) the average strike of the bedding is N.30W., the average dip 70°NE. The synclinal axis, near the Mount Hope Fault, plunges 65°NE.

An unnamed syncline lies between stations 547+52 and 562+30. The Mattapan volcanics (felsites on the northwest, basalts on the southeast) are on the limbs of the syncline; the Brookline Member occupies its core (recall earlier discussion of this area, however). The southeast limb dips 60°NW., but the dip of the northwest limb is unknown.

The Mattapan Anticline extends between stations 562+30 and 586+18. The core is occupied by basalts, felsites, and melaphyres of the Mattapan Formation. The northwestern contact with the Roxbury Formation dips 60°NW., whereas the southeastern contact is vertical. The axial plane dips 75°NW. The surface geology (Billings, personal communication) shows that this band of the Mattapan Formation pinches out to the northeast, indicating a northeasterly plunge.

An unnamed syncline extends between stations 586+18 and 615+50. The core is occupied by conglomerates and argillites of the Brookline Member. The axis is near sta. 594+00. The north limb, which dips 80°S., is cut by a fault at sta. 590+50. The dip of the south limb ranges from 24° to 54°NW., and averages 35°NW. This syncline plunges 20°SW; this is very exceptional for the Boston Basin, since most of the folds plunge NE. The presence of this southwesterly plunging syncline has been known from surface data for many years (Billings, personal communication).

The Lower Falls Anticline occupies the southeast end of the tunnel. Its northwest limb is the same as the southeast limb of the unnamed syncline to the northwest. The axis is near sta. 615+50. The axial plane dips 74°NW. Billings (1976a,b), on the basis of good surface exposures, says that this anticline plunges 18° in a direction N.67°E.

Faults

In all, 67 faults or probable faults with measurable or inferred displacements greater than one or two inches were recorded in the Dorchester Tunnel. Of these, the average fault was a single fracture or a very narrow fracture zone, measuring no more than two or three inches across. Most of these were occupied by gouge or loose breccia, which showed a tendency to wash out with normal ground water flow after several weeks of exposure in the open tunnel. These narrow, tight faults comprise all but about 5% of the faults (exclusive of the Stony Brook Fault Zone) observed in the tunnel. The remainder of the faults in the tunnel are zones of intense shearing, each no more than 15 feet wide, containing large amounts of breccia and usually discharging a moderate flow of ground water.

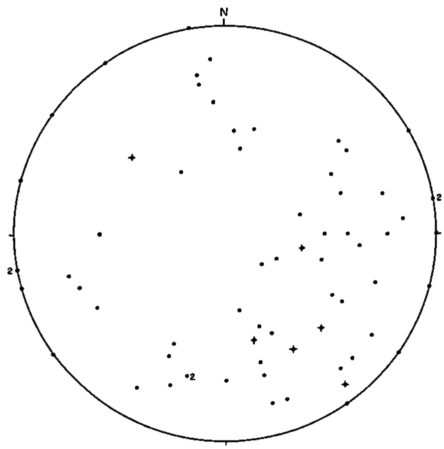

Figure 4: Poles of perpendiculars to 67 major faults or probable faults, projected on an equal area net from the lower hemisphere. Multiple observations with the same attitude are indicated by numerals. Crosses indicate faults with measured or inferred offsets greater than 20 feet.

The attitudes of these 67 faults are shown in figure 4, a point diagram of poles to the fault planes, projected onto the lower hemisphere of an equal area net. For a planar feature, such as a joint, a fault, or a dike contact, each point on the diagram represents the projection of a perpendicular to the planar feature to a horizontal plane. Simultaneous projection of planar features onto a single diagram allows us to assess their "average" attitude in the tunnel. Examination of the diagram in figure 4 shows that the attitudes of faults other than the Stony Brook Fault Zone vary quite a bit. If we consider only the 8 faults with large (greater than about 20 feet) of vertical separation, we observe that their average attitude is more rigidly defined, giving a strike of about N.30E. and a dip close to 60°NW. This fault attitude is the same as the general, or "regional", fault attitude as observed in other tunnels in the Boston Basin. (For comparison, see point diagrams reproduced in Rahm (1962, p. 356), Billings and Tierney (1964, p. 142), Billings and Rahm (1966, p. 130), and Tierney, Billings, and Cassidy (1968, p. 79).)

A few of the faults deserve individual discussion here because of their very large inferred stratigraphic separation. One such is the nearly vertical fault at sta. 547+52, called the Mount Hope Fault by Billings. The attitude of the fault is N.52E.:85N. The stratigraphic throw can be estimated by noting that the southeast side of the fault is in the upper Mattapan Formation, while the northwest side is in the middle to upper Cambridge Formation (see *Stratigraphy and Lithology)*. In order to bring the two stratigraphic units adjacent to one another, it would be necessary to have a vertical displacement at least equal to the entire thickness of the Roxbury Formation, plus a large portion of the Cambridge Formation. This total thickness can be estimated roughly by adding together the true thicknesses of each of the rock units to the northwest of sta. 547+52 (that is, up dip across the exposure of Boston Bay Group rocks in the tunnel). The figure thus derived is around 12,000 feet, but may be in error by as much as 10% either way. Billings (1976a,b) estimates a stratigraphic throw of approximately 10,000 feet.

Physically, the Mount Hope Fault is a tight, single fault, no more than two or three inches across. Brecciation in the wall rocks is negligible. There is only a minor amount of quartz mineralization in the fracture.

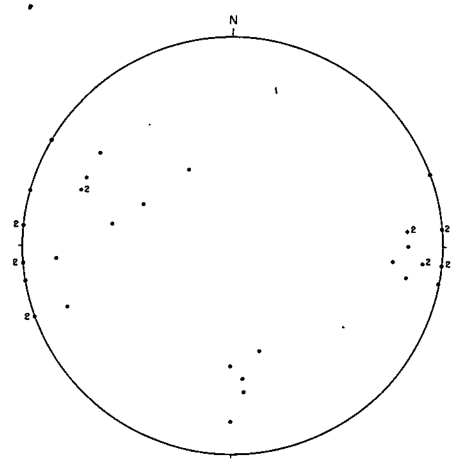

Figure 5: Poles of perpendiculars to 37 diabase dikes, projected on an equal area net from the lower hemisphere. Multiple observations are indicated by numerals.

Billings (1929) and LaForge (1932) assumed that the contact of the Mattapan volcanics and the Roxbury conglomerate in the vicinity of sta. 562+30 was a major fault, called the Sally Rock Fault by Billings. He assumed, by analogy with other observed faults in the basin, that it was vertical. Exposures in the tunnel, however, showed that the contact is sedimentary, striking N.65E. and dipping 60°NW. It is clear that there is no Sally Rock Fault. On the basis of my observations, Billings (1976a,b) no longer shows a Sally Rock Fault.

At sta. 565+00, however, there is a large fault zone, 20 feet wide, striking N.75E. and dipping 55°NW. There is no difference in lithology on the two sides of the fault, and there are no features on which to measure either sense or magnitude of movement.

The third major single fault worthy of extra mention here is the one that crosses the tunnel at sta. 590+50. It strikes N.60E., dips 60°NW. Argillites at the base of the Brookline Member are thrust over conglomerates higher in the stratigraphy. At present no data are available to calculate the stratigraphic throw.

Southwest of the southeast end of the tunnel, Billings (1929) shows a large fault, the Neponset Fault, on the northwest limb of the Lower Falls Anticline — the anticline near sta. 616+00. Billings (1976a, figures 1 and 3) shows this fault extending across the Dorchester Tunnel, but in the text mentions the possibility that the fault may die out before reaching the tunnel. A vertical fault with a strike N.10W. has been mapped in the tunnel at sta. 615+26, on the northwest limb of the Lower Falls Anticline, but this cannot be the Neponset Fault, which has a northeast strike. On the basis of this observation, Billings (1976b) has since terminated the Neponset Fault southwest of Dorchester Lower Mills.

In addition to the major single faults in the tunnel, there are several extensive sections of the tunnel dominated by shear zones on the order of hundreds of feet wide. The bulk of these shear zones lie between stations 403+50 and 450+50, and between stations 480+00 and 484+55, and are collectively referred to as the Stony Brook Fault Zone. On a large geologic scale, the Stony Brook Fault Zone may be observed (Billings, 1976a,b) to

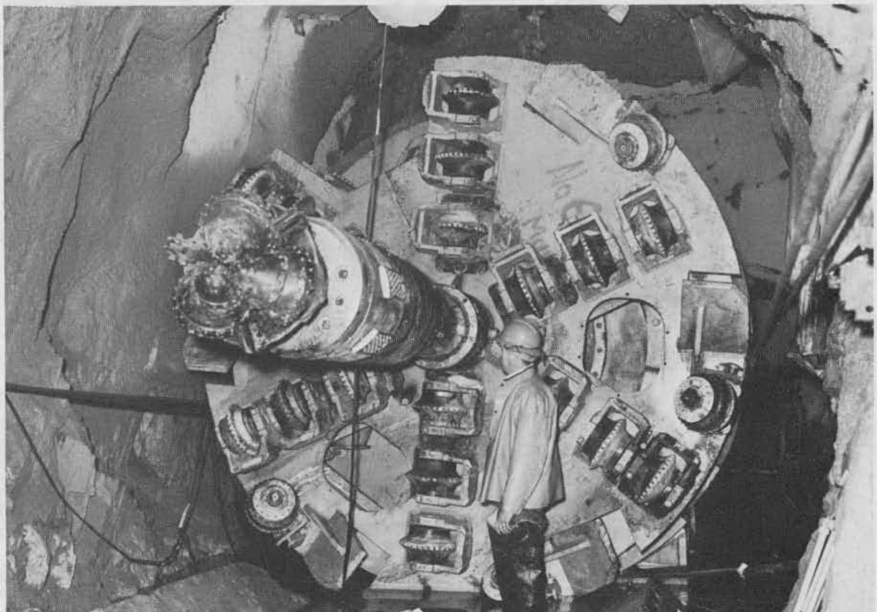

Figure 6: Rotating face and cutter heads of the Mole, with the pilot bit partially extended.

Figure 7: View southeasterly from shaft 7C into the Mole-driven section of the tunnel. The rock is Cambridge argillite.

strike N.10E. across the Boston Basin, cutting the nose of the Central Anticline and downdropping the western end of it approximately 2100 feet relative to the eastern end. The dip is nearly vertical. The fault zone dies out a few miles north of the Dorchester Tunnel, and hence has not been crossed in other tunnels in the Boston area.

The fault zone appears to have two distinct branches, one followed fairly closely on the surface by the main line of Conrail (Jamaica Plain) and Hyde Park Avenue (Hyde Park), and the other lying roughly along the Arborway in Jamaica Plain. It constitutes an easily erodable zone on the surface, where it occupies a broad, poorly defined topographic valley. Core borings along the tunnel line in this area indicate that the bedrock surface lies beneath 125 to 175 feet of glacial deposits, in contrast to areas away from the fault zone, where the surficial cover is from 0 to 25 feet thick.

In the tunnel, the Stony Brook Fault Zone appears in most places not as a series of distinct fractures on which attitudes and displacements can be measured, but as a series of areas characterized by advanced alteration, flowing ground water, and occasional diabasic intrusives. The total width of the fault zone is 4700 feet, of which 2725 feet or 58% of the zone is fractured badly enough to necessitate steel support.

Dikes

Attitudes of the dikes in the tunnel were measured wherever possible, and have resulted in the point diagram shown in figure 5. Three average dike attitudes emerge from this diagram. The first of these, about N.90E.:65°N., represents about 15% of all the dikes in the tunnel. The second, at N.10W.: Vertical, represents nearly 50% of the dikes. The remaining 35% lie in a poorly defined set about N.20E.:70°S. There are no cross-cutting relationships in the tunnel to indicate relative ages of the three sets of intrusions. The median width of 4 feet, calculated from measurements in this tunnel, is typical of dikes in the Boston Basin, as measured in other tunnels.

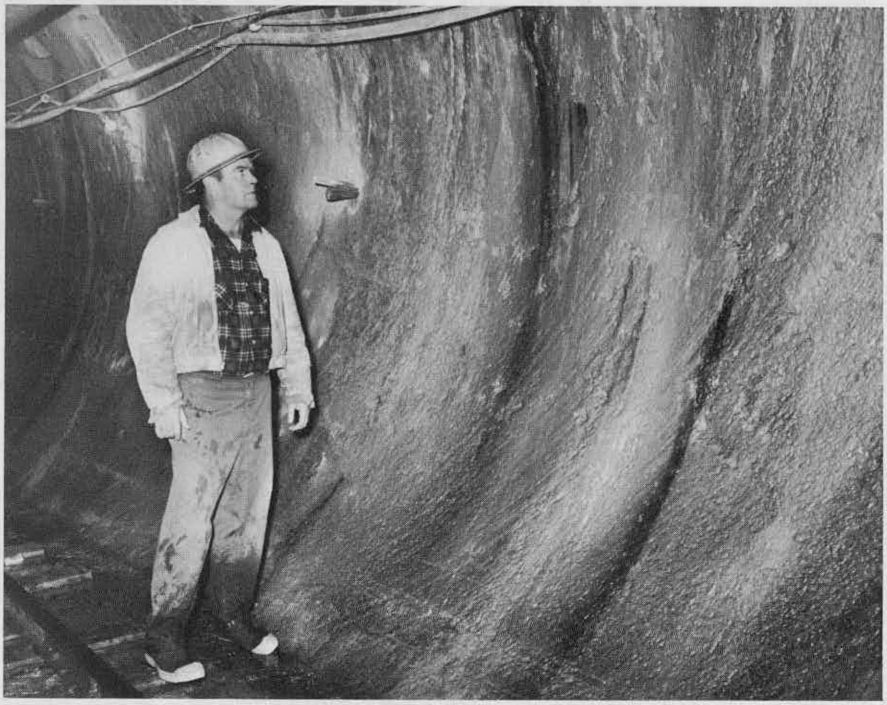

Figure 8: Southwest wall of the Mole-driven tunnel at sta. 510+50, showing bedding in the Cambridge argillite.

Engineering Aspects of the Geology

The Mole

Excavation in the southeast, or Dorchester heading, between stations 511+10 and 548+87, was performed by an Alkirk Hard-Rock Tunneller, model T-7, manufactured by the Lawrence Company, and referred to conversationally as the "Mole". Use of the Mole was experimental in this tunnel, since the contractor had no previous experience with the machine and there was no precedent for its use in the Boston area. Several problems were encountered with the machine during excavation, most of them mechanical or related to human inexperience rather than problems related to the rock.

The problem which ultimately made it necessary to remove the Mole from the tunnel, however, was purely related to the geology. Almost all of the excavation completed by the Mole was in Cambridge argillite, a relatively soft sedimentary unit with well-defined bedding planes. In such rocks the Mole was capable of over 300 feet of progress per week in a 12 foot diameter tunnel. Beyond sta. 547+52, however, excavation was in felsites in the Mattapan volcanics, which are characterized here by a lack of bedding or other planar features (other than widely spaced joints), and extremely high compressive strength. Total progress made in these rocks, with several changes in cutting heads, was only 135 feet in the several weeks before the decision was made to remove the Mole.

It is obvious from the experience gained in the Dorchester Tunnel that the Mole in its present state of development is unsuited for drilling in rocks as hard as the felsites in the Mattapan Formation. There are undoubtedly large portions of the Roxbury Formation which, because of the high proportion of large volcanic cobbles, cannot be drilled by the present Mole as well, though no experience was gained with Roxbury conglomerates in this tunnel.

The Raise Drill

Another innovation in tunnelling technique, a rotary raise drill, was used in construction of shaft 7D. The shaft was sunk by conventional drilling techniques to an elevation of -42.6 feet, from which point a 10 inch pilot hole was bored along the shaft center line from the surface to the tunnel. Figure 9 shows the raise drill itself, which was attached to a rotating shaft through the pilot hole and pulled to the surface. Rock debris was removed to the surface by standard mucking procedures at the invert during the raising operation. In this manner the shaft was bored to a diameter of 6 feet at a rate of 20-40 feet per day.

Steel Support

Support for loose or weakened rock in the tunnel was provided almost exclusively by four-piece steel ribs, each weighing 746 lbs., four feet apart. These were supplemented by steel spacers and wood blocking. In the Brookline heading, 696 ribs were used; the Neponset heading required only 50. A total of 3343 feet, or 9.88% of the tunnel was supported in this fashion. Few rock bolts were used or necessary.

Figure 9: Raise drill being lifted into position at shaft 7D.

Eighty percent of the total support (2725 feet) was needed in the Stony Brook Fault Zone. By way of comparison, the preliminary estimates of steel support necessary for the tunnel were for 7700 feet, of which over 4650 feet was anticipated in the Stony Brook Fault Zone and over 1000 feet in the Dorchester Member of the Roxbury Formation, which needed full support in the Main Drainage Tunnel (Rahm, 1962).

The 618 feet of steel support placed in sections of the tunnel outside of the Stony Brook Fault Zone were primarily necessitated by local jointing. Of the steel support required in the Neponset heading, virtually all falls into this category and, further, the jointing can probably be said to be genetically related to the folding observed or inferred in the heading. The only steel section for which this is not true is the short piece between 561+60 and 561+70, which was required because of faulting. In the Brookline heading, steel support sections not related to the Stony Brook Fault Zone were again related to locally intersecting joint sets, except in the two short sections between 502+45 and 502+85 and between 501+25 and 501+65. These last sections were required partly because of cleavage associated with minor drag folds, and partly because of the soft, kaolinitic character of the basal layers of the Cambridge Formation.

Shotcrete

Early in the construction the contractor was interested in the possibility that shotcrete might be utilized for support in some places instead of structural steel. The headings extending for 300 feet northwest and southeast of shaft 7C were lined with shotcrete. The rock in the immediate vicinity of 7C, however, is argillite, which tends to fracture smoothly and to expose a minimal surface area. For this reason, and because argillite is a rather impermeable rock, the shotcrete failed to make a satisfactory bond with the tunnel walls and was judged to be structurally inadequate. The experiment was not continued into other rock units, but it is reasonable to predict that shotcrete would have been more successful on the extensive exposures of conglomerate.

Acknowledgements

Mapping of the geological features in the Dorchester Tunnel was performed during construction between the spring of 1970 and the late summer of 1972, with the periodic advice and encouragement of Dr. Marland P. Billings of Harvard University. Dr. Billings, whose contributions to New England and Boston Basin geology are well known in the geological profession, first interested me in the mapping venture and has been of immeasurable assistance in the interpretation of the observations. I appreciate the generous and continuous support given to this study by the Metropolitan District Commission, and in particular by Mr. Francis T. Bergin, Chief Engineer for the Construction Division (now the Construction Engineering Division). The assistance of many MDC engineers, notably Mr. Tadeus Medowski and Mr. John Buckley, has been invaluable. The photographs appearing in these pages were taken by Mr. Thomas Reilly, photographer for the MDC. Mr. John H. Peck made several suggestions for substantial improvements on an earlier draft of this manuscript.

Appendix

Lithology by Stations

Descriptions of the general lithology of the Boston Basin have been presented adequately in several previous papers, particularly those dealing with the geology of other MDC tunnels. Except for descriptions of the Mattapan volcanics, exposed to date only in this tunnel and in surface outcrops, the reader is directed to previous literature for physical and chemical descriptions of the rock units referred to in this paper. This appendix is a brief log of the rocks encountered in the Dorchester Tunnel, and an indication of their extents of exposure. The true thickness of a rock unit is always less than its exposed or apparent thickness, unless the measured section is perpendicular to bedding planes. Where possible, true thicknesses for each rock unit described here have been calculated trigonometrically.

Sta. 288+31 to 288+75: The rock in the extreme northwest end of the tunnel is finely-laminated argillite, four feet thick. Above this, in the City Tunnel Extension, 602 feet of strata, mostly argillite but including a little conglomerate, was exposed (Tierney *et al.,* 1968).

Sta. 288+75 to 313+80: This portion of the tunnel consists of interbedded sandy argillites and conglomerates, varying in their relative abundance throughout the section. In the northwest section, to around sta. 297+30, argillite predominates to the virtual exclusion of conglomerate. From 297+30 on, however, the percentage of conglomerate in the section increases, with beds of argillite or sandstone becoming less frequent and narrower in outcrop to sta. 313+80, from which point no further argillite appears. Thickness of rocks in this section is about 900 feet.

Sta. 313+80 to 403+50: The entire section consists of unaltered, unbedded conglomerate. Based on surface exposure, the axis of the Central Anticline should be at about sta. 386+00. Because the tunnel is diagonal to the structure, though, the reversal of apparent dips should be near sta. 337+00.

Sta. 403+50 to 450+50: Rocks in this portion of the tunnel are conglomerates, but are generally very highly altered by water passing through extensive fracture zones (the Stony Brook Fault Zone). Virtually all of the rock supported by structural steel in this portion of the tunnel is altered in some degree. The pattern of alteration is a relatively simple one. Conglomerates farthest from the water-filled fractures are well-indurated; pebbles in them are usually unaltered and rigidly cemented to the surrounding matrix. Closer to fracture zones the pebbles are unaltered, but show an increased tendency to break free of matrix, leaving a smooth hole. Whether this is due to partial dissolution of the pebbles or of the matrix is uncertain. Further into the zone of alteration, pebbles (specifically the granitic ones) are kaolinized — that is, the feldspars are altered to clay, appear white or pale yellow, and are punky to the touch. More intense alteration is signalled by a general darkening of the clays, from a pale yellow to a deep yellow-brown, as the iron-bearing minerals in the conglomerate are oxidized. Kaolinization intensifies as the fracture zone is approached, proceeding through matrix as well as pebbles. In the areas of most intense alteration, no trace of the original pebbles is left, and water flowing through fractures easily washes alteration products from between the few remaining blocks of matrix, making them much less structurally competent. Depending on the intensity of the fracturing and the amount of water flowing through the rocks, it was possible in some cases to predict the advent of "bad ground" as early as forty or fifty feet before it was encountered, by observing this alteration pattern.

Sta. 450+50 to 479+04: Unaltered conglomerate, similar to that on the northwest side of the Stony Brook Fault Zone, and again displaying no bedding, comprises the entire section. As in the preceding sections, no direct measurement of thickness is possible.

The thickness of the strata between stations 313+80 and 479+04 cannot be determined from any data in the tunnel, due to the lack of bedding. Fortunately, however, geological data from the surface may be utilized, although a detailed analysis would be too long to present here. The thickness of the conglomerates between stations 337+00 (the probable location of the axis of the Central Anticline) and 479+04 is 3600 feet; this is the upper part of the Brookline Member. Estimating on the basis of surface outcrops to the southwest of the tunnel line, approximately

1700 feet of rock lies between the base of this upper part and the base of the Boston Bay Group. Thus, in this area, the Brookline Member is 5300 feet thick.

Sta. 479+04 to 480+40: The rock varies in character from a coarse, pinkish feldspathic sandstone to a sandy pebble conglomerate, the two types being intermixed as lenses or as discrete beds from 1 to 3 feet thick. Sandstones are locally laminated on a scale of an inch or less. The thickness of these rocks is 110 feet.

Sta. 480+40 to 480+90: The section is dominated by a purplish-gray slaty argillite, sandy in spots, and with ¼ to ½ inch laminations. Its thickness is about 40 feet.

Sta. 480+90 to 481+90: The rock is the same in character as that between 479+04 and 480+40, with the feldspathic sandstone predominating. Graded sequences approximately 10 feet thick indicate tops to the southeast. The thickness of the rock in this section is 85 feet.

Sta. 481+90 to 482+80: The section is dominated by dark, unweathered diabase, containing irregular areas of dark gray sandstone or coarse argillite. The diabase may either be interpreted as a single intrusive containing large blocks of unoriented wallrock, or as a swarm of contemporaneous dikes following irregular fractures in the country rock. The thickness of these rocks is 65 feet.

Sta. 482+80 to 484+55: The rocks in this section consist of finely laminated pinkish purple argillites, some spotted with white flecks of kaolinite lying concordantly with the bedding. Thickness is not directly measurable, due to folding, but is probably no more than 65 feet.

Sta. 484+55 to 489+20: The rocks are unaltered arkosic conglomerate, unbedded. Calcite veins are fairly common. Thickness of the rocks is about 375 feet.

Sta. 489+20 to 490+20: The section contains interbedded pebble- or cobble-conglomerates and coarse sandstone. The purplish gray sandstone is predominant, occurring in beds up to a foot thick. Thickness of the section is about 86 feet.

Sta. 490+20 to 491+60: The rock in this section is all unbedded conglomerate. Its thickness is about 70 feet.

Sta. 491+60 to 492+30: Rocks in the section are interbedded coarse sandstone and pebble conglomerate, with the sandstone predominating. Some conglomerate bodies are isolated lenses, about two feet across. Thickness of the rocks is approximately 50 feet.

Sta. 492+30 to 495+75: The section is comprised of argillitic rocks, largely dark reddish brown to purple and finely laminated. The southeasternmost ten feet of exposure, however, is cream-colored, contains quite a bit of kaolinite, and has no visible laminations. Oscillation ripple marks appear in the section at 493+60. The thickness of the rocks in this section is 310 feet.

Sta. 495+75 to 501+40: Sandy, arkosic conglomerate extends southeastward to approximately sta. 500+00, where there is a gradual change over a distance of about fifteen feet to a light greenish tillite characterized by an increased proportion of matrix to clasts and an increased angularity of clasts. This unit is 520 feet thick, including 120 feet of tillite.

Sta. 501+40 to 547+52: The entire section consists of light to medium gray argillite, laminated on the average in ¼ inch thick layers. Slaty cleavage is rare, though there is some hint of an unmeasurable cleavage in some areas. (Since this portion of the tunnel was excavated by the Mole, it was always extremely difficult to measure fracture attitudes. See figure 8.) Portions of the section, especially those in which the rocks have been fractured heavily, contain swarms of calcite veins, vuggy in places and containing overgrowths of pyrite. Near the southeastern end of the section, from sta. 541+75 on, the argillite is massive, showing no signs of bedding for distances of two or three hundred feet at a time. The thickness of rocks in this section is difficult to assess directly, since the section is heavily faulted and the magnitudes of the throws on the faults are not known. A reasonable estimate, however, is about 4000 feet.

Sta. 547+52 to 550+50: The rocks in this section are pyroclastic felsites, varying in color from cream or buff colored to bright red to yellowish-green to a dark gray green. Common to all of the rocks are the abundance of irregular, sub-angular clasts and a large amount of siliceous, irregularly-shaped bodies, generally lighter in color than the surrounding rock. If the contact with the conglomerate to the south is vertical, this felsite is 300 feet thick.

Sta. 550+60 to 554+80: The section consists of dark gray-green conglomerate, dominated by reddish andesite pebbles and occasional large granitic cobbles, rather than by the more heterogeneous mixture of quartzite, volcanic, and granitic pebbles found in most conglomerates of the Boston Bay Group. Dark gray-green clastic volcanics also occur. There is no distinct bedding, and clear distinctions between the conglomerate and the clastic volcanics are nearly impossible at times, since one is apparently the matrix of the other locally. These rocks have been interpreted earlier in this paper to lie on the north limb of a syncline; if they are vertical and the synclinal axis is at sta. 556+00, they are 540 feet thick.

Sta. 554+80 to 562+30: Rocks in this portion of the tunnel are conglomerates similar to those common in sections in the northwestern end of the tunnel. Granitic and volcanic pebbles predominate in a matrix which is arkosic and sandy. No bedding is observable. The contact with the underlying Mattapan Formation to the south dips 60°N, and these rocks occupy the southern limb of the syncline. The thickness in this section is thus about 540 feet.

Sta. 562+30 to 571+00: Dark green basaltic rocks comprise the entire section. There is no evidence at any point in the section for flow banding, chill features, color or compositional changes to indicate the mode of emplacement or the number of events represented in the exposure. Locally, calcite veins fill fractures in the rock.

Sta. 571+00 to 574+35: Rocks in the section are felsites, varying in color from northwest to southeast from cream-colored to reddish brown to grayish white to deep red-brown. The general lithologic character is similar to rocks between sta. 547+35 and 550+60.,

Sta. 574+35 to 575+85: Rock in this section is a dark green basalt with occasional clasts of a lighter volcanic in it. No bedding or flow banding was seen.

Sta. 575+85 to 583+50: Rocks in this section are purplish-red to green amygdaloidal melaphyre, with amygdules measuring from ¼ to ¾ inch across. Most amygdules are filled entirely with quartz, some of which is stained red with iron oxides, though some of the larger amygdules also contain calcite and some authigenic plagioclase. Abundance varies considerably, with some portions of the rock being nearly barren and others so amygdaloidal that adjacent amygdules join to form a continuous sheet. Observing the concentrations of amygdules, it is possible to discern individual rock units dipping generally northwest and having approximate thicknesses of 10 feet or less. Such units are hardly measurable and, though they might possibly be individual flows, they are not well enough defined to identify easily. Surface outcrops of similar rocks in the Boston Basin occur along the shore in parts of Hull, and are virtually identical in terms of texture and general petrology.

Sta. 583+50 to 586+18: Rocks in this section are basaltic, showing no flow banding or other indications of mode of emplacement, and containing no amygdules. The thickness of the rocks from sta. 562+30 to here is uncertain because of folding, but may be as much as 2000 feet.

Sta. 586+18 to 590+50: The entire section with the exception of about 30 feet of dark grayish-green conglomerate centered around sta. 587+95 consists of finely laminated dark to medium gray argillite. Thickness of the rocks is about 430 feet.

Sta. 590+50 to 603+90: Rocks in the section are predominantly conglomerates of the type appearing in abundance elsewhere in this tunnel, but locally containing beds of coarse arkosic sandstone from one to three feet thick. Thickness of the rocks in this section, taking into account uncertainties due to folding, is about 500 feet.

Sta. 603+90 to 609+60: Rocks in the section are all dark gray argillite. Thickness is about 175 feet, corrected for folding.

Sta. 609+60 to 615+20: With the exception of some interbedded sandstones near sta. 613+00, the section consists of conglomerate. The thickness is about 180 feet.

Sta. 615+20 to 615+50: This section contains finely laminated light gray argillite. It is about 20 feet thick, and bounded on both sides by faults.

Sta. 615+50 to 621+00: With the exception of roughly 40 feet of mixed coarse sandstone and conglomerate and the northwest end of the section, the section consists of conglomerate. Thickness is about 300 feet.

Sta. 621+00 to 622+80: Rocks in this section consist of conglomerate, sandstone, and argillite, interbedded and faulted so that exposures in the tunnel and in shaft 7D show each rock type for only thirty feet or so at a time.

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