GEOLOGY OF THE MALDEN TUNNEL, MASSACHUSETTS

By Marland P. Billings* and David A. Rahm**

The Malden Tunnel, trending approximately N. 8° E. in the vicinity of Malden Square, is slightly less than a mile long and lies about 275 feet below mean low sea level. It is the southernmost section of the Spot Pond Brook Flood Control Project. The internal diameter of the concrete lining is 12½ feet.

The entire tunnel is in bedrock. The northern part is in various kinds of felsites belonging to the Lynn Volcanics, whereas the southern part is in the argillite of the Cambridge Formation. Dikes and, to a lesser extent, sills of mafic igneous rock (diabase and altered diabase) constitute a small percentage of the rock.

Most of the Cambridge Argillite here strikes northeast and dips southeast, as it is on the north limb of the Charles River syncline. But the northernmost 400 feet of the Cambridge Argillite dips northwest because it is overturned. The structure of the Lynn Volcanics is less clear, but available evidence indicates it is gently dipping.

The tunnel was of special interest because it crosses the Northern Boundary Fault of the Boston Basin, about which there has been considerable speculation for many decades. The Lynn Volcanics have been thrust southward over the Cambridge Argillite. In the tunnel the thrust fault dips 55° N., but data from a bore hole indicates that below the tunnel the dip is nearly horizontal.

The various types of fractures (joints, faults, and shears), as well as dikes, are diversely oriented.

Fifty-two per cent of the tunnel was supported by structural steel, practically all of it in rocks directly north or south of the Northern Boundary Fault. Moreover, the flow of water into the tunnel was excessive. Both of these facts are due to the unusually large amount of fracturing of the rocks because of the fault.

Introduction

Location, Size, and Construction

The Malden Tunnel is part of the Spot Pond Brook Flood Control Project in Stoneham, Melrose, and Malden in eastern Massachusetts (Fig. 1). The building of this project is under the supervision of the Construction Division, Metropolitan District Commission. Section

* Professor of Geology, Harvard University, Cambridge, Mass.
** Associate Professor, Washington State University, Pullman, Wash.

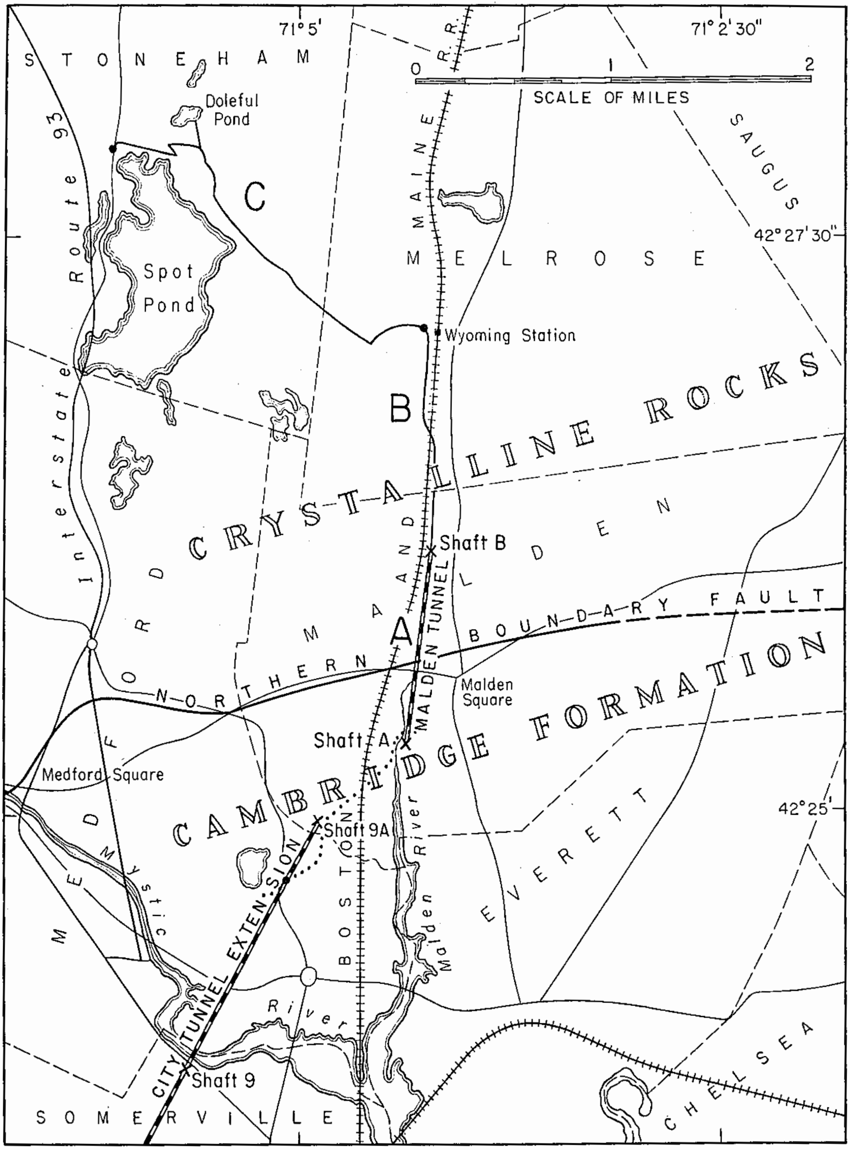

Fig. 1.—Location Map

Spot Pond Brook Flood Control Project consists of three parts: Part A, Malden Tunnel, completed; Part B, trenches and culverts, completed; Part C, trenches, culverts, and tunnels, in planning stage.

Dotted line between Malden Tunnel and City Tunnel Extension is presumed trace, at tunnel level, of a cross-bedded siltstone of use in correlating stratigraphy in two tunnels.

C, still in the planning stage, will probably consist of open trenches, culverts, and tunnels. Section B, already in operation, consists of open trenches and culverts. Section A is the Malden Tunnel, already in operation. The tunnel trends N. 8° 17′ 52″ E. This tunnel is 5265.7 feet long. The invert (bottom of the tunnel) ranges in altitude from minus 280 feet at the southern end to minus 270 feet at the northern end; altitudes are relative to Boston City Base, that is, mean low sea level. The land surface ranges from six feet to 57 feet above base. The internal diameter of the concrete lining is 12.5 feet. Two vertical shafts go from the surface to the tunnel level. The southerly shaft, known as Shaft A or Malden River Shaft, is on the Malden River 2400 feet southwest of Malden Square. The northerly shaft, known as Shaft B or Winter Street Shaft, is 3400 feet north-northwest of Malden Square.

The tunnel is entirely in bedrock. The total thickness of the cover, bedrock and unconsolidated material, ranges from 280 to 330 feet. Of this, 28.5 to 211.0 feet is unconsolidated material. The bedrock cover ranges in thickness from a minimuum of 75 feet to a maximum of 249 feet.

The contractor was the Coker Construction Company of Des Moines, Iowa. The work was done in 1957 and 1958. Shaft A was the construction shaft.

Geological Investigations

Although several trips were made to the tunnel while it was being driven, detailed mapping, deferred until the walls were washed down, occupied four days in February, 1958. The mapping was done on a scale of one inch to 20 feet. The drafting of a folio on this scale, consisting of a map and section of the west wall, was completed in September, 1961. Copies of this folio have been deposited with the Metropolitan District Commission and the Department of Geological Sciences of Harvard University.

In the summer of 1956 the senior author, at the request of F. Lyle Tierney, then geologist for the Construction Division, Metropolitan District Commission, examined the samples of bedrock obtained in the boring program. The logs made at that time have proved of value in the present study.

Geological Setting

The most extensive account of the geology of the Boston area is by LaForge (1932). Recent papers based on data obtained from tunnels are by Rahm (1962) and Billings and Tierney (1964).

The rocks in the Boston area are of two kinds, the relatively young unconsolidated surficial deposits and the much older bedrock (LaForge, 1932, Pl. I and II).

The surficial deposits in the Boston area range in thickness from zero, where bedrock is exposed, to hundreds of feet. They consist largely of glacial deposits such as till, gravel, sand, silt, and clay, as well as peat, river deposits, and beach sands. These unconsolidated rocks are Quaternary and their age does not exceed a few tens of thousands of years.

The bedrock in the Boston area belongs to three groups: (1) "crystalline rocks," (2) Boston Bay group, and (3) dike rocks.

The "crystalline rocks," ranging in age from Precambian to Middle Paleozoic, consist of a complex series of metamorphic, granitic, and volcanic rocks. Further detailed description is here unnecessary, because none of this series, except the Lynn Volcanics, is involved in the Malden Tunnel.

The Boston Bay Group, of Upper Paleozoic age, has traditionally been divided into a lower unit, the Roxbury Conglomerate, and an upper unit, the Cambridge Argillite. However, a recent paper (Billings and Tierney, 1964, p. 148-149) has shown that the Roxbury and Cambridge are sedimentary facies of each other. Only the Cambridge Argillite is involved in the Malden Tunnel.

Mafic dike rocks, many of them diabase or altered diabase, cut the older rocks. Some are considered to be as young as Triassic.

For many decades it has been presumed that the Boston Basin is bounded on the north by a major fault separating the Cambridge Argillite on the south from the "crystalline rocks" to the north. Billings (1929) and LaForge (1932) show this fault as a thrust dipping 45° north.

The major rock units shown in Fig. 8, which covers only part of the Boston Basin, are the Roxbury Conglomerate in the southwest corner, the Cambridge Argillite in the central portion, and the "crystalline rocks" in the northern part.

Presentation of Data

The basic data are presented here in a geological map, a structure section, tables, and so-called point diagrams.

Fig. 2 is the geological map of the tunnel on a scale of 1 inch = 210 feet. Since this map has been reduced 10 times from the original folio, much generalization has been necessary and only repre-

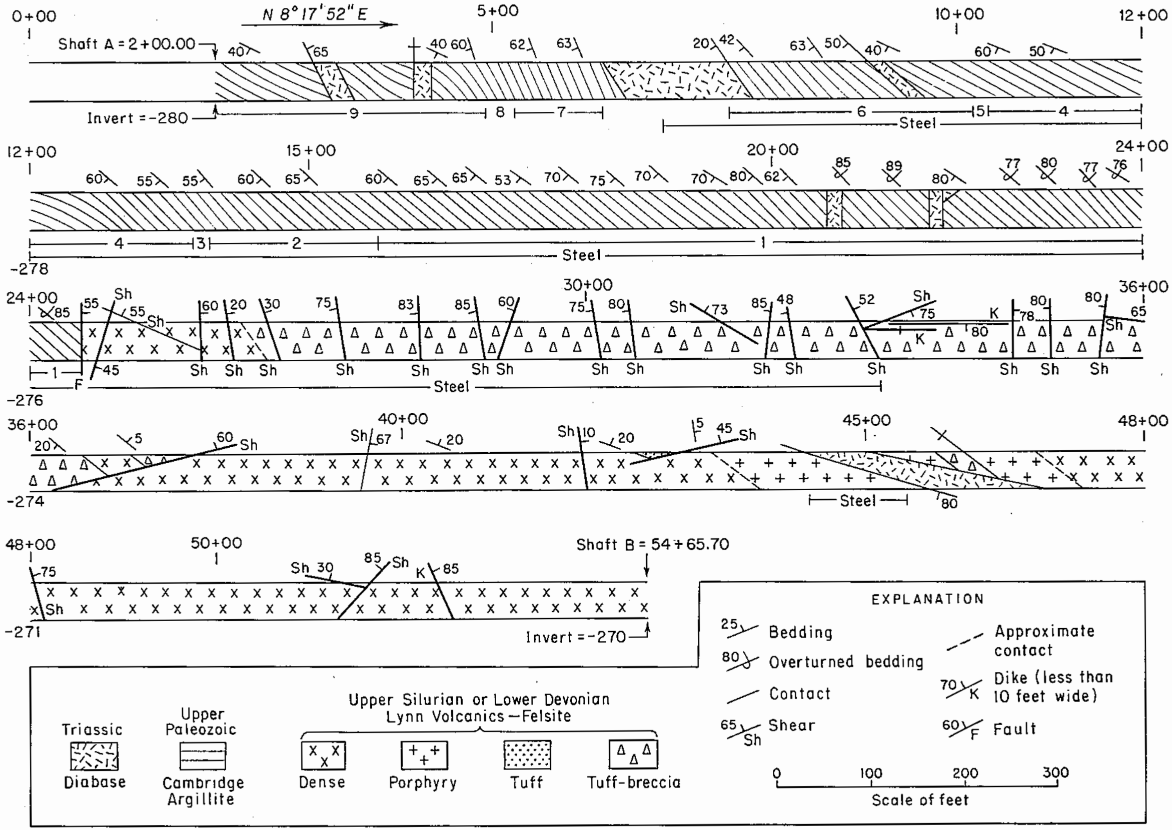

FIG. 2.—GEOLOGICAL MAP OF MALDEN TUNNEL

Top of each strip corresponds to west wall of tunnel. Bottom of each strip lies 40 feet east of the west wall, that is, 27 feet east of the east wall. Elevations of invert refer to Boston City Base. Numbers below strips refer to stratigraphic units in Table I.

sentative data are shown. Moreover, all the data on joints has been omitted to avoid crowding. Each strip represents 1200 linear feet, the top strip being the most southerly section of the tunnel, the bottom strip being the most northerly. The stations are given above each strip (12 + 00, for example, means 1200 feet N. 8° 17′ 52″ E. of station 0 + 00; Shaft A is at station 2 + 00). The altitude of the invert of the tunnel is shown in the lower left-hand corner of each strip. Altitudes are referred to the Boston City Base, which is 5.65 feet below the U.S. Geological Survey base. The upper (west) side of each strip shows the geology exposed at breast level on the west side of the tunnel. On the scale employed, the east side of the tunnel would be only 0.06″ below the top of the strip, as the tunnel was only 12.5 feet in diameter. To make a more readable map the base of each strip is shown 40 feet east of the west wall, that is about 27 feet east of the east wall.

Fig. 3 represents the geological structure along the line of the tunnel. It indicates the geology as it would appear on the west wall of a trench looking west, somewhat over 400 feet deep. Although considerable generalization and interpretation has been necessary, the section shows the thickness of the overburden (Quaternary), as well as the structure of the bedrock. Of course, the only "facts" are those observed in the tunnel, bore holes, and shafts. Shears and gouges, shown on the maps, have been omitted. Any upward or downward projection of these features would be largely conjectural. Moreover, an attempt to show them on an earlier version of Fig. 3 confused rather than clarified the diagram.

Lithology

General Statement

The superficial deposits along the line of the tunnel range in thickness from a minimum of 28.5 feet at bore hole 6 B to a maximum of 211.0 feet at bore holes 4 and 5 (Fig. 3). The samples of the surficial deposits obtained from the borings were not examined by the writers, but were studied by F. Lyle Tierney. Inasmuch as the present paper is concerned only with the bedrock geology, the surficial deposits are not considered further.

The bedrock geology along the tunnel line belongs to three units: the Lynn Volcanics in the northern half of the area, the Cambridge

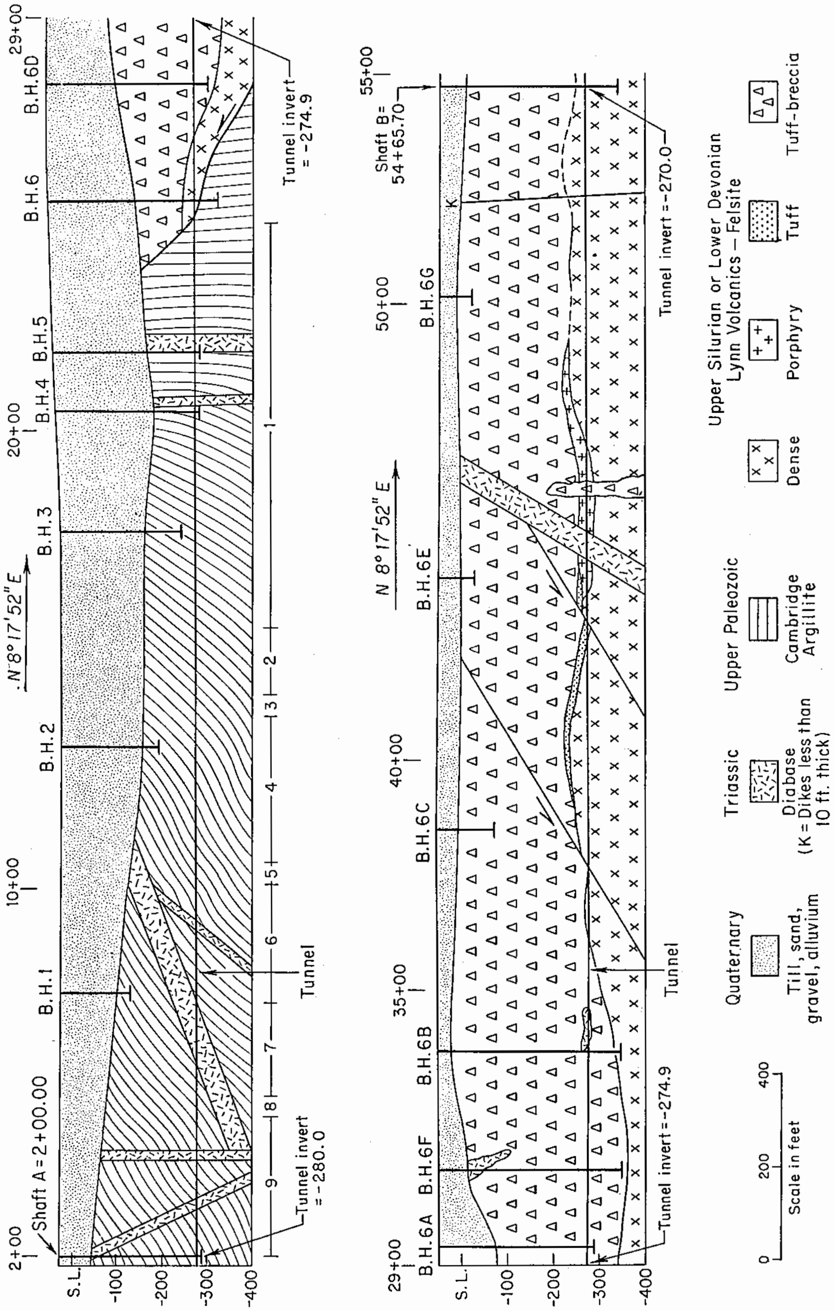

FIG. 3.—GEOLOGICAL STRUCTURE SECTION OF MALDEN TUNNEL
Elevations of invert refer to Boston City Base. Numbers below strips refer to stratigraphic units in Table I.

Argillite in the southern half, and mafic igneous rocks (diabase and altered diabase) occurring as occasional dikes and sills throughout the tunnel. Fifty-five per cent of the tunnel was in the felsites of the Lynn Volcanics, 37 per cent was in the argillite of the Cambridge Formation, and 8 per cent was in the diabase in the dikes and sills.

Lynn Volcanics

The Lynn Volcanics occupy all of the tunnel line north of station 24 + 56 (the Northern Boundary Fault), except for a few mafic dikes. In this area the Lynn Volcanics are composed entirely of felsite. Felsite is a general term used for fine-grained igneous rocks rich in potash feldspar and sodic plagioclase, with or without quartz, and low in dark minerals. Quartz-rich varieties are called rhyolite, quartz-poor varieties are called trachyte. Along the tunnel line the felsites are light-green-gray, gray, pink to red, and, in a few instances, white. For descriptive purposes four varieties of felsite are shown in Figs. 2 and 3. Although transitions are common, and exact assignment is not always possible, these varieties and the approximate percentages are as follows: dense felsite (52%), porphyritic felsite (10%), felsitic tuff-breccia (38%) and bedded felsitic tuff (trace).

The dense felsites are flinty, brittle rocks. The most common colors are light-green-gray, gray, and pink to red. Many tens of linear feet in the tunnel were of one color. But the change from one color to another was generally transitional in a zone not over a few feet wide. In places the dense felsite was mottled red and green-gray. Flow structure, consisting of alternating bands of somewhat different color a fraction of an inch thick, was noted in four places. The felsite is cut by numerous joints, as described below, but in many places it breaks along irregular hackly fractures between the joints.

Porphyritic felsite is the principal rock between stations 43 + 57 and 46 + 80. It is similar to the dense felsite, but contains phenocrysts of quartz and feldspar. Few of the former exceed 1 mm in diameter, but the latter range from 2 to 10 mm, in length.

The felsitic tuff-breccias are dense to fine-grained brittle gray, pink, or red pyroclastic rocks. The angular fragments, generally 1/4 to 1 inch across, but in places as much as 3 inches, are set in a dense groundmass. The fragments, although in many cases differing slightly in color from the groundmass, are dense to fine-grained felsite. Where the fragments are the same color and texture as the groundmass, it is difficult to distinguish felsitic tuff-breccia from dense felsite. Just like the dense felsites, many of the tuff-breccias break along hackly fractures between the joints.

Bedded felsitic tuff was exposed around station 42 + 64. It is light-green-gray, well-bedded, 3 feet thick, strikes N. 25° E. and dips 20° NW. It is underlain by gray felsite and overlain by tuff-breccia.

The Lynn Volcanics here are composed of lava flows and pyroclastic rocks. Since the dip of the bedding along the tunnel line is very gentle, the known thickness would not exceed a few hundred feet (Fig. 3) here.

A description of the Lynn Volcanics as a whole is given by LaForge (1932, pp. 30-33). He gives no thickness, but it may well be several thousand feet. LaForge (1932, p. 29) correlates the Lynn Volcanics with the Newbury Volcanics, which are Upper Silurian or Lower Devonian (Toulmin, 1964, p. 17).

Cambridge Argillite

The Cambridge Argillite occupies all of the tunnel, except for a few dikes and sills of mafic rocks, south of the Northern Boundary Fault at station 24 + 56.

Along the tunnel line the formation consists entirely of argillite. These are gray well-indurated siltstones. The beds, generally conspicuous and ranging in thickness from paper thin to 2 inches, are due to slight differences in grain size or color, or both. The colors are all in shades of gray. A very striking rock, composing about half the formation, is cyclically layered, consisting of alternating lighter and darker gray beds, generally from 1 to 2 inches thick.

In other parts of the formation the siltstone is a more uniform gray, but slight differences in texture or color or both show beds 1/32 to 1/16 inch thick. In a few instances beds as much as 5 feet thick show no internal bedding. Between stations 10 + 21 and 10 + 36 the beds, 1/32 to 1/4 inch thick, pinch and swell. Between stations 4 + 96 and 5 + 26 beds 1/4 inch thick show minute cross-bedding, indicating that the beds were derived from the south. As will be pointed out below, this unit is a value in correlating the strata in the Malden Tunnel with those in the City Tunnel Extension.

Petrographic and chemical studies (Rahm, 1962, p. 332) show that the argillites are composed chiefly of quartz, sericite, and chlorite, with small amounts of albite, and, locally, calcite and pyrite.

The rock is well jointed, but between joints the rock breaks with a hackly fracture.

A columnar section of the Cambridge Argillite exposed in the tunnel and Shaft A is given in Table I. Ten units have been established,

TABLE I
STRATIGRAPHIC COLUMN, CAMBRIDGE FORMATION
MALDEN TUNNEL

	Stations	Lithology	Unit thickness	Cumulative thickness
10.	Shaft A	Argillite. Gray. Thin laminae.	159.0	1210.1
9.	2 + 00 to 4 + 96	Argillite. Gray. Laminae paper thin to 1/16″ thick; but in many places bedding is obscure. Hackly fractures in places.	89.1	1051.1
8.	4 + 96 to 5 + 26	Argillite. Gray. Laminae paper thin to 1/32″ thick. Some beds as much as 5″ thick have obscure laminae. Minute cross-bedding, indicating source to south.	19.2	962.0
7.	5 + 26 to 6 + 21	Argillite. Gray. Bedding obscure.	66.3	942.8
		Dike		
6.	7 + 55 to 10 + 21	Argillite. Gray. Bedding generally conspicuous. Much of rock is cyclically layered, consisting of alternating lighter and darker gray layers 1/32″ to 1/2″ thick. Locally more uniform gray rock with laminae 1/32″ to 1/16″ thick.	104.8	876.5
5.	10 + 21 to 10 + 36	Argillite. Gray. Alternating lighter and darker gray bands 1/32″ to 1/4″ thick; beds pinch and swell somewhat.	4.0	771.7
4.	10 + 36 to 13 + 80	Argillite. Gray. Bedding generally conspicuous. Much of rock is thinly laminated in beds 1/16″ to 1/32″ thick. Some is layered, consisting of alternating lighter and darker gray beds 1/32″ thick. Pyrite locally present.	129.3	767.7
3.	13 + 80 to 13 + 82	Argillite. Very light gray.	1.5	638.4

TABLE I (*continued*)

Stations	Lithology	Unit thickness	Cumulative thickness
	Dike		
2. 13 + 82 to 15 + 68	Argillite. Gray. Rather uniform gray, but in places laminae are 1/32″ thick. Hackly fracture.	107.9	636.9
1. 15 + 74 to 24 + 56	Argillite. Gray. Bedding generally conspicuous. Much of rock is cyclically layered; alternating lighter and darker gray beds 1/32″ to 2″ thick. More uniformly gray rock shows laminae 1/32″ to 1/4″ thick. Locally splits into plates 2/5″ to 2″ thick.	529.0	529.0

but the formation is so relatively uniform throughout that the subdivisions have no great significance. In units 1, 4, and 6 cyclical layering is conspicuous. In units 2, 5, 7, 9, and 10 such cyclical layering is not conspicuous and in many cases bedding is obscure. In unit 5 the bedding pinches and swells, whereas unit 8 shows minute cross-bedding. Unit 3 was established primarily because it made a good break between differing units above and below it.

The total thickness of the Cambridge Argillite that was exposed in the Malden Tunnel was 1051 feet, but including the data from Shaft A the total is 1210 feet.

The thickness of the Cambridge Argillite that was exposed in the City Tunnel Extension was 6759 feet (Billings and Tierney, 1964, p. 111). How are the beds in the Malden Tunnel stratigraphically related to those in the City Tunnel Extension? Shaft A of the Malden Tunnel lies 3348 feet N. 50° E. of Shaft 9A of the City Tunnel Extension (Fig. 1). Since the strata at both shafts strike northeast and dip southeast we may assume, as a first approximation, that the beds at the foot of the two shafts are approximately correlative. This would mean that the strata in the Malden Tunnel are stratigraphically below those in the City Tunnel Extension.

Several different methods may be used to establish a more precise correlation. Because they all lead to the same general conclusion, only one will be discussed here. This method assumes that the units characterized by minute cross-bedding may be correlated, that is, unit 8 of the MaldenTunnel may be correlated with unit 2 of the north limb of the Charles River syncline in the City Tunnel Extension (dotted line of Fig. 1). This means that the uppermost 353 feet of the Cambridge Formation in the Malden Tunnel correlates with the lowest 353 feet in the City Tunnel Extension. The lowermost 857 feet of the Cambridge Formation in the Malden Tunnel is stratigraphically below the lowest bed in the City Tunnel Exension. Thus the thickness of the Cambridge Argillite is at least 6759 + 857 = 7616 feet. The equivalent of bed "zero," i.e., the lowest bed, of the City Tunnel Extension would be at station 7 + 90 in the Malden Tunnel.

The age of the Cambridge Argillite has not been definitely determined. But the Boston Bay Group is younger than the Mattapan Volcanics, which may be correlated with the Lynn Volcanics. Hence the Boston Bay Group is younger than the Upper Silurian or Lower Devonian. Fossil trees (Rahm, 1962, p. 329) in the Roxbury Conglomerate indicate that the age may be Upper Devonian to Permian. Moreover, the Triassic Medford Diabase is younger than the Boston Bay Group.

Mafic Igneous Rocks

Diabase, including altered diabase, occurs in dikes and sills. Seven sills and 16 dikes were mapped. Four hundred nineteen linear feet, or 8 per cent of the tunnel, was mafic igneous rock. More precisely, along a line at map level on the west side of the tunnel, mafic igneous rocks are the bedrock for 419 feet. Since the percentages obtained in a linear traverse are equivalent to the volume percentages, just as in petrographic studies, 8 per cent of the rock excavated from the tunnel must have been mafic igneous rock. However, inasmuch as many of these dikes and sills strike at an angle to the tunnel and dip at angles of less than 90 degrees, these mafic igneous rocks were found on one of the walls or in the roof over a linear distance considerably greater than 8 per cent of the tunnel.

The mafic igneous rocks are of two general types, diabase and altered diabase. The diabases are medium to coarse dark rocks with a typical ophitic texture and consist chiefly of plagioclase and augite, but contain biotite and secondary minerals such as hornblende, chlorite, and calcite. The diabases are found only in the dikes and not in the sills.

The altered diabases are light-gray, fine-to-medium-grained rocks that have not yet been studied in thin section. All the sills and many of the dikes are altered diabase.

Structural Geology

General Statement

The Boston Basin is structurally a synclinorium composed of alternating anticlines and synclines plunging east. Major faults, some parallel and others diagonal or perpendicular to the major folds, are present (LaForge, 1932; Billings, 1929). The Malden Tunnel is of special interest to geologists because it crosses the Northern Boundary Fault, which both Billings (1929, p. 113) and LaForge (1932, p. 63) considered to be a thrust dipping north.

The ensuing paragraphs will be first concerned with the larger structural features—the Cambridge Argillite constituting the northern part of the Boston Basin, the Lynn Volcanics constituting the southern part of the "crystalline rocks," and the Northern Boundary Fault. Later paragraphs will discuss the minor structural features, such as the joints, shears, and dikes.

Northern Part of the Boston Basin

The northern part of the Boston Basin was exposed between stations 2 + 00 (Shaft A) and 24 + 56 (Northern Boundary Fault). It is composed of the Cambridge Argillite which here strikes northeast and dips southeast except near the fault, where it is overturned and dips northwest (Fig. 3). Thus the southern part of the Malden Tunnel is on the northern limb of the Charles River syncline, the axis of which lies 4 miles to the south.

From station 2 + 00 to 20 + 50 the Cambridge Argillite dips southeast at angles ranging from 40° to 80° (Figs. 2 and 3). In general the dip increases toward the north, becoming vertical at station 20 + 50. Between stations 20 + 50 and 21 + 30 the dip ranges from 85° SE. to 75° NW., the beds being overturned where the dip is northwest. North of station 21 + 30 the dip ranges from 74° to 89° NW., all overturned. That is, the north limb of the Charles River syncline is overturned toward the south for a distance of 400 feet south of the Northern Boundary Fault.

Since all the strata in the Cambridge Argillite here "top", that is, get younger to the southeast, there is no synclinal axis in the tunnel.

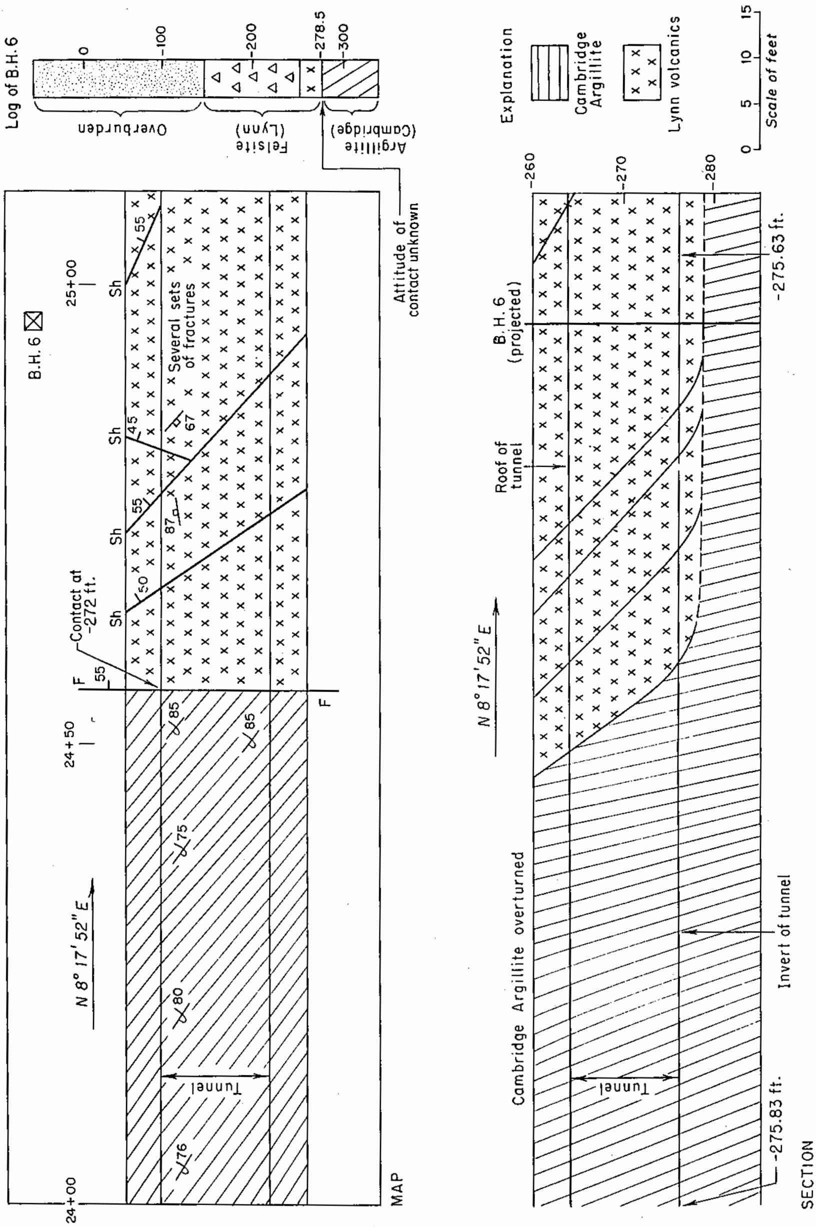

FIG. 4.—MAP AND STRUCTURE SECTION OF AREA NEAR NORTHERN BOUNDARY FAULT AT TUNNEL LEVEL
Symbol for bedding and shears same as in Fig. 2. Short lines with square on one side represent joints. Triangles are tuff-breccia; crosses are dense felsite.

Nevertheless, the variations in strike and dip show that broad open folds are present. The form of these folds can be analyzed most satisfactorily by a point diagram. Fig. 5A is such a diagram based on 97 readings of the bedding in the Cambridge Argillite. The plot is on the

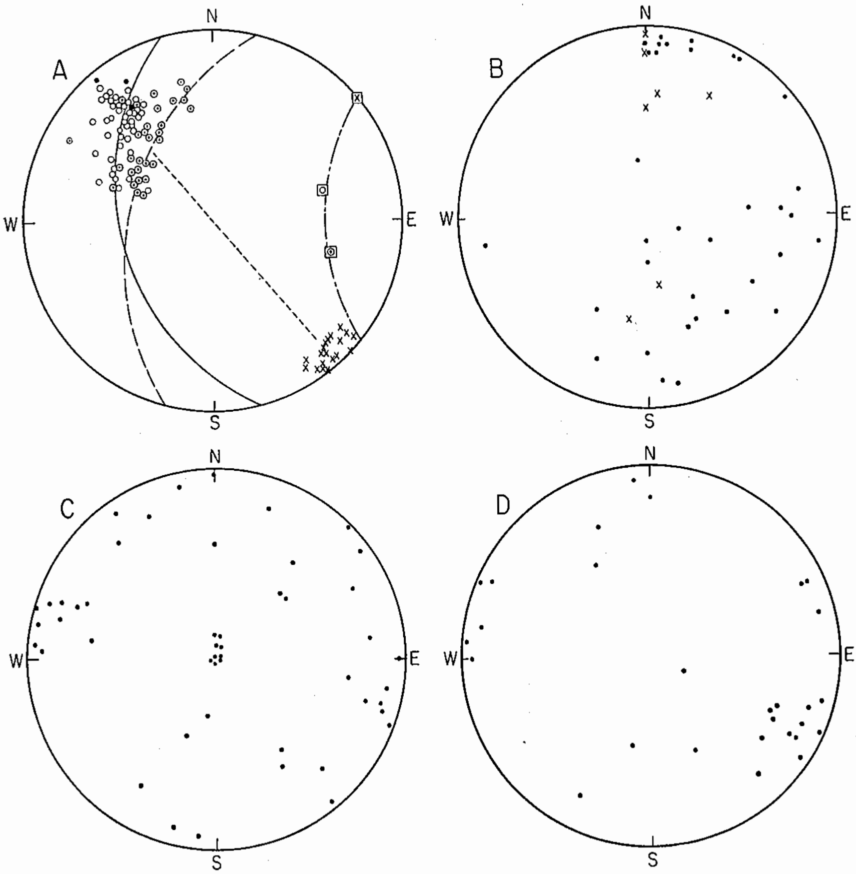

FIG. 5.—POINT DIAGRAMS. PLOTTED ON LOWER HEMISPHERE OF EQUAL AREA NET

A. Poles of perpendiculars to bedding. Circles with dots: between stations 2 + 00 and 10 + 00. Open circles: between stations 10 + 00 and 20 + 00. Solid circles: between 20 + 00 and 24 + 56, not overturned. Crosses: between 20 + 00 and 24 + 56, overturned.

B. Poles of perpendiculars to shears in Lynn Volcanics north of Northern Boundary Fault. Those marked by cross contain clay gouge.

C. Poles of perpendiculars to joints in Lynn Volcanics north of Northern Boundary Fault.

D. Poles of perpendiculars to joints Cambridge Argillite south of Northern Boundary Fault.

lower hemisphere and the projection is an equal area net (Billings, 1954, pp. 108-115). The concentration of marks in the northwest quadrant is consistent with the northeast strikes and southeast dips; the concentration in the southeast quadrant represents the overturned beds dipping northwest. The dots in open circles represent strata between stations 2 + 00 and 10 + 00. They lie on an arc trending north-northeast; the arc signifies open folds or warps plunging 35° in a direction S. 74° E. The open circles represent strata between stations 10 + 00 and 20 + 00. They lie on an arc trending north-northwest; the arc signifies open folds or warps plunging 40° in a direction N. 75° E. The solid circles and crosses are for strata between stations 20 + 00 and 24 +56, and represent, respectively, normal and overturned strata. They lie on an arc that is essentially a straight line trending northwest; this signifies broad open folds or warps plunging nearly horizontally N. 40° E.

Southern Part of Area of "Crystalline Rocks"

The structure of the Lynn Volcanics is difficult to deduce, inasmuch as bedding is rare. In the structural section (Fig. 3) the Lynn Volcanics are portrayed as consisting of two main units, an upper felsitic tuff-breccia and a lower dense felsite. The porphyritic felsite and felsite tuff are thin units.

The chief evidence favoring this interpretation is the following. Firstly, the bore holes in the Lynn Volcanics, except for their deepest parts, were all in felsitic tuff-breccia. The dense felsite was largely confined to the tunnel; its distribution is shown on Fig. 2. Secondly, bedding was observed in several places between stations 43 + 16 and 36 + 57; the average dip was 15°. Thirdly, in several places the tuff-breccia was observed to overlie the dense felsite. At station 42 + 58, where the strike is N. 25° E. and the dip is 20° NW., the following section was observed from bottom to top: (a) dense felsite; (b) three feet of well-bedded felsitic tuff; and (c) tuff-breccia. At station 37 + 05, where the strike is N. 45° E. and the dip 5° NW., the tuff-breccia overlies directly the dense felsite. The same relationship may be observed at station 36 + 73, where the strike is N. 45° E. and the dip is 20° SE.

Northern Boundary Fault

The Northern Boundary Fault of the Boston Basin, that is, the contact between the Cambridge Argillite and the "crystalline rocks" to the north, trends east-northeast (Fig. 1). For many decades this contact has been considered to be a fault. Although I. B. Crosby (1928) shows it as a normal fault, Billings (1929, p. 113) and LaForge (1932, p. 63) believed it to be a thrust fault.

Fig. 3 shows the Lynn Volcanics thrust southward over the Cambridge Argillite. Fig. 4 contains a map and section on a much larger scale than Figs. 2 and 3. The fault, exposed at station 24 + 56 at map level on the west wall, strikes N. 80° W. and dips 55° N. On the west wall the contact is knife-sharp and tight. In fact, a specimen right across the contact was collected. On the east wall the contact was an opening about an inch wide; clay gouge had presumably been present.

One might assume that the Northern Boundary Fault consistently dips 55° N. But data from bore hole 6 indicates that the fault flattens out a short distance below the invert of the tunnel. The upper part of Fig. 4 is a map. Bore hole 6 is located at station 24 + 96, L 20′, that is, it lies 20 feet N. 82° W. of a station 40 feet N. 8° E. of the trace of the fault in the tunnel. In BH 6 the contact of the Lynn Volcanics and the underlying Cambridge Argillite was encountered at an altitude of —278.5 feet, that is, 2.9 feet below the invert of the tunnel. The attitude of the contact could not be determined. The data from BH 6 are projected into the structural section in the lower part of Fig. 4. We would conclude that the Northern Boundary Fault flattens out just north of its exposure in the tunnel.

In projecting the data from BH 6 to the structure section in Fig. 4 it has been assumed that the contact does not dip away from or toward the tunnel. It cannot dip westward at any appreciable angle, otherwise it would come to tunnel level around station 24 + 96. On the other hand, if it were to dip eastward it would be lower than shown in Fig. 4.

Consideration has been given to the possibility that BH 6 may not be vertical. Geologists are well aware of inclined and crooked bore holes. The surface at BH 6 is at an elevation of 41.9 feet. The Lynn-Cambridge contact was reached at a distance of 320.4 feet. Assuming the bore hole to be vertical, it was calculated that the contact was at an altitude of —278.5 feet. A non-vertical bore hole could assume many different shapes. As one of many possibilities, let us assume that the bore hole was straight but inclined at an unknown angle. Let us further assume that the fault is a plane striking N. 80° W., dipping 55° N.

and located at map level at station 24 + 56. Let us further assume that the inclined straight bore hole plunges in a vertical plane striking at right angles to the strike of the fault, that is, it plunges S. 10° W. If such a bore hole crosses the fault at a distance of 320.4 feet from the surface, it would be inclined at an angle of 83°, that is, it would be 7° from the vertical. Bore holes inclined at lower angles in a plane striking S. 10° W. would also cross the fault, but at lesser distances. But bore holes inclined at higher angles would not reach the postulated fault in the measured distance.

Some data are available to solve this problem. In the tunnel the dip of the bedding between stations 24 + 56 and 20 + 50 is relatively uniform, is overturned (with one exception out of 20) and averages 82° NW. or 8° from the vertical. In a core from a bore hole inclined 7° in a direction S. 10° W. the bedding would make an angle of 15° with the axis of the core. A specimen in the author's collection is a piece of core 5 inches long from a distance of 330 feet (altitude of —288 feet, assuming the hole is vertical); the bedding is inclined 5° from the axis of the core. This agrees much more closely with what is expected from a vertical boring than with a boring inclined at 8°.

An intriguing problem concerns the eastward extension of the Northern Boundary Fault. Geologists are interested in this subject. Moreover, this matter may be of importance in some future engineering project. Also, deep borings for other purposes may supply valuable data. As shown in Fig. 8, bedrock is not exposed in Winthrop, Revere, and the southern part of Lynn, but the North Metropolitan Relief Tunnel indicates that Winthop is underlain by Cambridge Argillite. Nahant belongs to the older rocks here classified as "crystalline rocks." It appears, therefore, that the Northern Boundary Fault swings east-southeast to go south of Nahant.

Joints

The significance of joints in tunneling depends upon many variables, such as their orientation, spacing, and length. Vertical joints a few feet apart and crossing a tunnel at right angles are of no great concern. Flat joints a few inches apart in the roof would be of great concern.

In the Malden Tunnel the attitude of joint sets, that is, the attitude of a more or less parallel set of 3 to 10 joints, was measured in many places. In Fig. 5C each point represents a joint set in the

Lynn Volcanics. Gently dipping joints are represented by the dots in the center of the diagram. The strike of the other sets box the compass and the dip ranges from 30° to vertical. It is apparent that the joints in the Lynn Volcanics are diversely oriented. Fig. 5D shows the orientation of the joints in the Cambridge Argillite. Many of these joints dip steeply and most strike in the sector ranging from north-northeast to north-northwest. Joints striking northwest and west-northwest are rare.

Shears

The term shear as used in this report refers to planar features, generally a few inches to a few feet wide, in which the rock is platy, slickensided, or converted to clay gouge. A fault is a plane along which there has been visible offset of some older planar feature, such as bedding, a vein, or a dike. Many of the shears in the Malden Tunnel may be faults, but no displacement may be seen.

Forty shears were recorded in the Lynn Volcanics (Fig. 5B). Although they are diversely oriented, there is a slight tendency for two sets. One set has an average strike of northeast and an average dip of 45° NW., but there is considerable spread. A second set has an average strike of N. 80° W. and dips steeply south.

Veins and Gash Veins

Sixteen veins other than gash veins were recorded in the Lynn Volcanics. They range in thickness from 1/4″ to 4″, but most are an inch thick. The filling is mostly calcite, but some quartz is associated. The attitude of these veins is shown by crosses in Fig. 6A. Most strike east-west and dip steeply. One is horizontal and two strike north, dipping steeply west.

The gash veins are a rather unusual feature. They occur in a group of 6 to 10 veins arranged en echelon. The individual veins are generally 6″ to 12″ long, but range from 3″ to 24″. They rarely exceed 1/4″ in thickness, but range from 1/16″ to 1″. Fig. 6A shows that the attitude of the gash veins is more systematic than the joints or shears. Although there is considerable spread, the average strike is N. 80° W., the average dip 45° S.

The en echelon zones always dip south at angles of 30° to 70°. In some instances the zone dipped more steeply than the individual veins. This indicates that the hanging wall of the vein moved upward

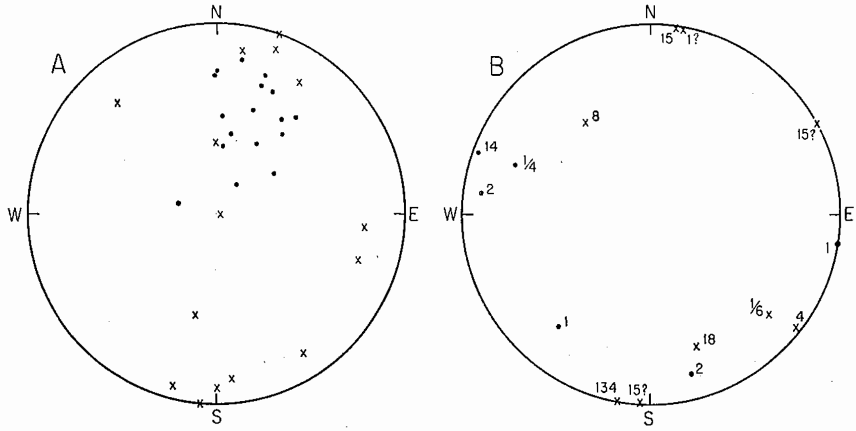

Fig. 6.—Point Diagrams. Plotted on Lower Hemisphere of Equal Area Net

A. Poles of perpendiculars to veins north of Northern Boundary Fault. Each dot represents 5 to 10 gash veins in a single set; each cross represents single veins.

B. Poles of perpendiculars to diabase and related dikes; numerals give thickness of dikes.

relative to the footwall, that is, a "reverse" movement. In other instances the zone dips less steeply than the individual veins. This indicates that the hanging wall moved down relative to the footwall, that is, a "normal" movement.

Summary of the Attitude of Joints, Shears, and Veins

It is clear that these planar features are diversely oriented. The lack of a uniform or systematic pattern in these rocks is of significance in planning future projects in bedrock. Moreover, any attempt to deduce the orientation of the principal stress axes when the rocks were being deformed is fraught with difficulties.

Dikes and Sills

In a previous page it has been stated that seven sills and 16 dikes of mafic igneous rock, diabase or altered diabase, were recorded. By definition a sill is parallel to the bedding, a dike is crosscutting. Since bedding is rare in the Lynn Volcanics, all the mafic igneous rocks in it are classified as dikes.

The seven sills range in thickness from 3 inches to 14 feet, and average 4.4 feet. They are confined to the Cambridge Argillite, that is, the area south of the Northern Boundary Fault.

The five dikes north of the fault range in thickness from one foot to 14 feet, averaging 4 feet. The dikes south of the fault range in thickness from 1-1/2 feet to 134 feet, and average 20 feet. Excluding the dike that is 134 feet thick, the average thickness is 7 feet.

Fig. 6B shows that the dikes dip steeply. Although there is considerable spread in the strike, a general northeasterly strike is more common than a northwesterly strike.

Engineering Aspects of the Geology

Two subjects deserve special consideration: the amount of support necessary and the amount of water encountered.

In the planning stages it was realized that the tunnel would cross the Northern Boundary Fault. It was anticipated that a wide wet shear zone might be present. This did not materialize, but the fault was accountable for other problems.

Structural steel was used for support continuously between stations 6 + 85 and 33 +17, a distance of 2632 feet, and between stations 44 + 40 and 45 + 45, a distance of 105 feet. Thus 52% of the tunnel was supported by structural steel. About 35 roof bolts were used. Twenty-two bolts were used between stations 4 + 05 and 4 + 31, nine were used between stations 5 + 20 and 5+41, and the rest were used elsewhere.

The tunnel was unusually wet. Table II gives the average number of gallons of water pumped daily per month. The engineers indicate that this is an exceptionally large amount for a tunnel of this size and length. Detailed data on places where water came into the tunnel are unavailable, but the writers' notes record that unusually large amounts came into the roof at stations 26 + 93 and 27 + 14, 137 and 158 feet, respectively, north of the fault.

Fig. 7 shows the distribution by 500 foot intervals of the various fractures recorded in the Lynn Volcanics north of the Northern Boundary Fault. Although the data are somewhat subjective, they appear to be significant. Structural steel was used for support where the gouge zones are present, where the shear zones exceed 5 per 500 foot interval, and where the total number of recordings exceeded 16 per 500 foot interval. The number of joint sets does not show such a definite relationship, but a satisfactory method of recording joints within a reasonable time has not been devised. Moreover, no effort was made to record the density of the joints.

TABLE II
AVERAGE NUMBER OF GALLONS OF WATER PUMPED DAILY

Month	Gallons per Day
May, 1957	45,602
June	195,994
July	220,500
August	537,000
September	1,115,000
October	997,000
November	982,000
December	1,200,000
January, 1958	948,500
February	1,462,000
March	1,353,000
April	1,107,000
May	994,000
June	414,000
July	389,000

Unfortunately, satisfactory data were not recorded in the Cambridge Argillite. In this section of the tunnel the writers concentrated on the attitude of the bedding and neglected the details of the shears and joints.

The use of structural steel continuously for 861 feet north of the fault and 1771 feet south of the fault, as well as the large amount of water, indicates that the rocks were fractured more than usual. The Cambridge Argillite required little support in the Main Drainage Tunnel (Rahm, 1962) or in the City Tunnel Extension (Billings and Tierney, 1964). Similarly, the Mattapan Volcanics (correlated with the Lynn Volcanics) in the West Roxbury Tunnel, now under construction, required little support. It is apparent that the rocks on either side of the Northern Boundary Fault were greatly strained and consequently fractured more than elsewhere.

General geological experience shows that conditions elsewhere along the Northern Boundary Fault may be different. All the deformation may occur in a single wide shear zone or even this may be absent.

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We wish to express our appreciation to Frederick W. Gow, Chief Engineer of the Construction Division of the Metropolitan District Commission, and to Martin W. Cosgrove, Deputy Chief Engineer, for

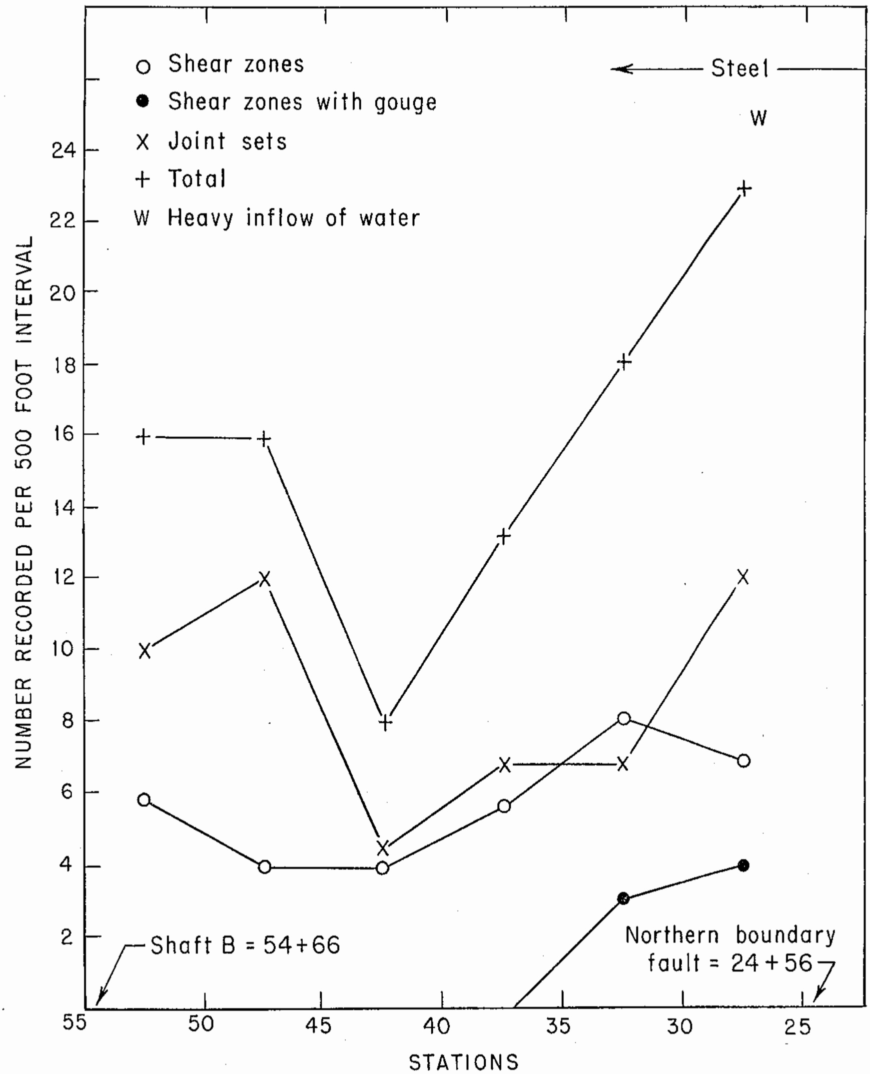

Fig. 7.—Density of Fractures in Lynn Volcanics North of Northern Boundary Fault

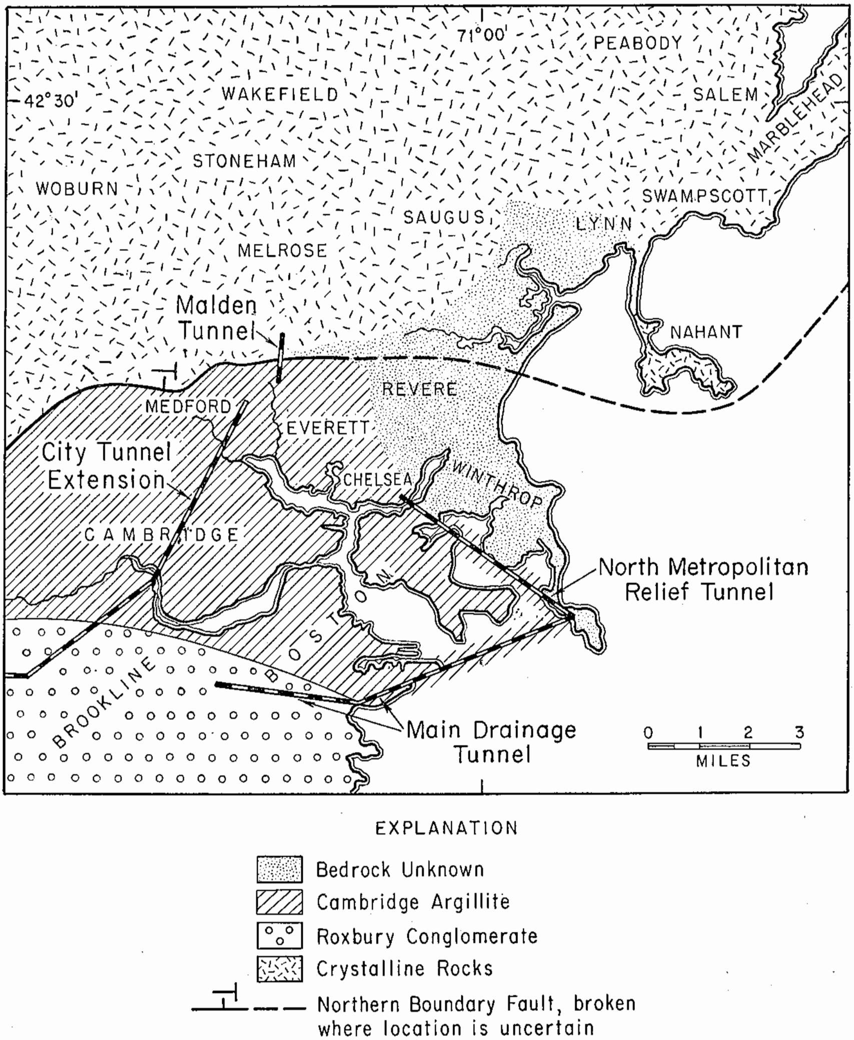

FIG. 8.—NORTHERN BOUNDARY FAULT SHOWS PRESUMED EASTWARD EXTENSION

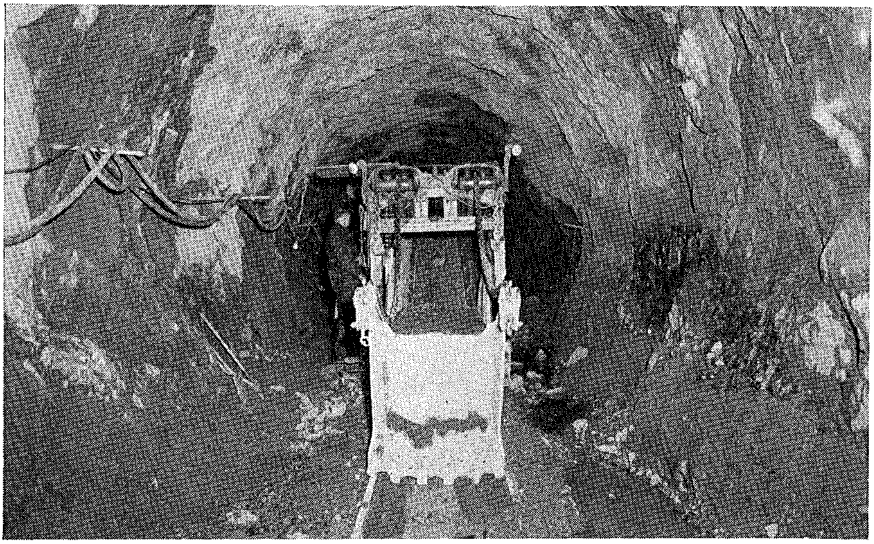

Fig. 9.—Conway Mucking Machine. Looking Southerly from Heading at Station 34 + 35. Rock Is Tuff-Breccia of Lynn Volcanics

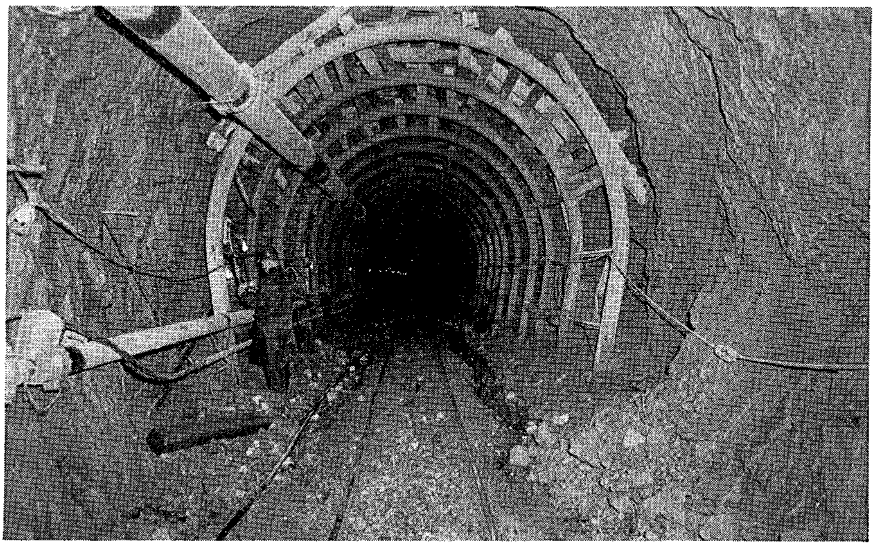

Fig. 10.—Looking Southerly Toward Long Section of Structural Steel, Northern end of Which Is at Station 33 + 17. Rock Is Tuff-Beccia of Lynn Volcanics

FIG. 11.—LOOKING SOUTHERLY FROM STATION 7 + 65 NEAR SOUTH END OF LONG SECTION OF STRUCTURAL STEEL. ROCK IS ARGILLITE OF CAMBRIDGE FORMATION IN IMMEDIATE FOREGROUND; ROCK IS DIABASE FURTHER SOUTH

the opportunity to study the geology. Mr. F. Lyle Tierney, geologist of the Construction Division at the time of the mapping, expedited the the logistics. Mr. Douglas S. Maclain furnished us with data on the support and amount of water pumped.

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