GEOLOGY OF THE CITY TUNNEL, GREATER BOSTON, MASSACHUSETTS

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ABSTRACT

The City Tunnel, part of the water supply system in Metropolitan Boston, extends for 4.78 miles in a general easterly direction from Shaft 5, near the junction of Route 128 and the Massachusetts Turnpike in Weston, to Shaft 7, at the Chestnut Hill Reservoir in the extreme western part of Boston. A branch tunnel extends 0.65 mile southeast from Shaft 7 to Shaft 7B near the Chestnut Hill Pumping Station. These tunnels, ranging in depth from 233 to 446 feet beneath the ground surface, are entirely in bedrock. The inner diameter of the concrete lining of the main tunnel is 12 feet, that of the branch tunnel is 10 feet.

The tunnel cuts diagonally across the east-northeasterly trending northern limb of the Central Anticline of the Boston Basin. Thus the oldest stratigraphic units are found at the east end of the tunnel, the youngest at the west end. The tunnel is entirely in the Boston Bay Group, except for some mafic (diabasic) dike rocks. The westernmost 1160 feet of the tunnel is in the gray argillites of the Cambridge Formation. Directly east of this the tillite of the Squantum Member of the Roxbury Formation extends for 1300 feet. Still further east the Dorchester Member, consisting of sandstone, arkose, argillite, and conglomerate, and associated with sheets of Brighton melaphyre, extends for 12,160 feet. The easternmost part of the main tunnel, 10,639 feet long, as well as the branch tunnel, 3422 feet long, are driven through the conglomerate, argillite, and sandstone of the Brookline Member.

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The major structure is comparatively simple. The beds dip gently north or northwest. The average strike of 251 sets of joints is N.10° E. and the average dip is steep; there is, however, considerable range in strike and dip. The average strike of 74 faults is N.30°E. and the average dip is steep. Most of the faults appear to be minor; 6 of the faults are vertical, 48 are normal, and 20 are reverse.

One hundred nine mafic (diabase) dikes were recorded. With few exceptions they dip steeply, but the strikes were not recorded. The width averages about 5 feet, and rarely exceeds 15 feet.

The quality of the rock was excellent for tunneling. Only sixteen feet of the entire tunnel needed support. Since the strength of the rocks in Greater Boston depends on their origin, the effect of later deformation, and subsequent hydrothermal alteration, this is an exceptional situation.

INTRODUCTION

Location, Size and Construction

The City Tunnel, a water supply tunnel built under the supervision of the Construction Division of the Metropolitan District Commission, Commonwealth of Massachusetts, extends for 25,259.5 feet (4.78 miles) in a general easterly direction from Riverside to Chestnut Hill Reservoir (Fig. 1). Shaft 5, station 0 + 00, is in Weston on the west bank of the Charles River. From here the tunnel extends S. 82° 25′ 56″ E. for 11,920.94 feet to Shaft 6 which is 900 feet southwest of the junction of Commonwealth Avenue and Lowell Street. Except for the westernmost 460 feet, this part of the tunnel is in Newton. From Shaft 6 the tunnel trends S. 89° 46′ 55″ E. for 13,338.56 feet to Shaft 7, which is 1400 feet south of the junction of Commonwealth Avenue and Lake Street, on the east end of the Boston College campus. That portion of the tunnel between Shafts 6 and 7 is in Newton, except for the easternmost 1030 feet, which is in Boston. The depth of the tunnel beneath the surface ranges from 233 feet to 446 feet. The invert of the tunnel is −312.5 feet at Shaft 5, −150.0 feet at Shaft 6, and −100.0 feet at Shaft 7; all elevations are based on Boston City Base, which is 5.65 feet below the U.S. Geological Survey base. The inner diameter of the concrete lining is 12 feet.

From Shaft 7 a branch tunnel extends southeasterly for 3421.98 feet to Shaft 7B, at the Chestnut Hill Pumping Station on the east side of the Chestnut Hill Reservoir. This branch tunnel goes 821.23 feet S. 53° 53′ 20″ E. from Shaft 7, curves into a more easterly trend for 252.41 feet, then assumes a trend S. 81° 51′ 10″ E. for 2348.25 feet. This branch tunnel is entirely in Boston, although Shaft 7B is only a few hundred feet from the Brookline boundary. The depth of this branch tunnel beneath the surface ranges from 233 feet to 252 feet. The invert of the tunnel at Shaft 7B is − 100.0 feet. The inner diameter of the concrete lining is 10 feet.

The present paper deals with the geology of the main tunnel and the branch tunnel. The geology of the City Tunnel Extension, which extends N. 44° 53′ 05″ E. from Shaft 7 has been described by Billings and Tierney (1964).

Shaft 5, at the east end of the pressure aqueduct, was sunk under contracts 94 and 110 by the John MacDonald Company and C. and R. Construction Company; it was completed in 1940. Shafts 6 and 7 were sunk under contract 117 by the Marinucci Brothers and Company in 1946 and 1947. The tunnel itself was driven under contract 115 by a combine consisting of the Perini, Maney, Walsh, and Rugo construction companies; work extended from 1947 to 1951. Shaft 7B was part of this contract.

Author Responsibility

Tierney is responsible for mapping the geology of the tunnel. A folio, consisting of 29 sheets, has been deposited with the Construction Division of the Metropolitan District Commission. This folio contains maps and a sketch of the geology exposed on the north wall, both on a scale of one inch to 20 feet. The sketches show the lithology and apparent dips of bedding and contacts. The maps show the attitude (strike and dip) of all faults and of representative joints. A 63-page written report accompanied this folio. In 1961 Cassidy, under the supervision of Billings, mapped in detail the surface geology exposed in the vicinity of the tunnel. Billings prepared the present report, including text and diagrams, using the data obtained by Tierney and Cassidy. One task was to calculate the thickness of the various lithologic units and to prepare the stratigraphic columns given in Tables 1 and 2.

GEOLOGICAL SETTING

LaForge (1932) gives the best general account of the geology of the Boston area, where the rocks belong to two groups, the relatively young unconsolidated surficial deposits and the much older consolidated bedrock (LaForge, 1932, Pl I and II).

The surficial deposits range in thickness from zero — where the bedrock crops out — to hundreds of feet. They consist largely of glacial deposits, such as till, gravel, sand, and clay, as well as river deposits. The maximum known thickness of the surficial deposits along the line of the City Tunnel, based on bore holes, is 120 feet near Water Street in Newton. The average thickness is about 50 feet. The present paper is not concerned with these surficial deposits.

The bedrock in the Boston Basin (Fig. 1) belongs to the Boston Bay group, which has traditionally been divided into two formations, a lower one called the Roxbury Conglomerate and an upper one called the Cambridge Argillite. Some poorly preserved cylindrical casts and molds of roots or trunks of trees (Burr and Burke, 1899) are either *Calixylon* or *Cordaites,* genera that together span a period from the Upper Devonian to the Permian (Elso Baarghoorn, personal communication). The Roxbury Conglomerate has been subdivided into the Brookline, Dorchester, and Squantum Members. These subdivisions can be recognized in the Newton area.

The City Tunnel is on the northern flank of the east-west trending Central Anticline of the Boston Basin. Toward the west, however, this northern limb assumes a southwesterly strike. Consequently, although the beds strike east-west and dip northerly in the eastern part of the area of the tunnel, toward the west the beds strike northeast and dip northwest. As a result, the tunnel is in progressively higher stratigraphic units toward the west. Whereas Shafts 7B and 7 are in the Brookline Member, Shaft 6 is in the Dorchester Member, and Shaft 5 is in the Cambridge Argillite.

PRESENTATION OF DATA

This paper consists essentially of two parts. The first, essentially observational, is presented under the headings of lithology and structural geology. Although primarily an account of facts, it does involve some integration of the geology exposed in the tunnel with the geology exposed on the surface. The second part of the paper is analytical. The stratigraphic sequence is determined from the observed lithological and structural data. There is also a brief discussion of the origin of the structural features and an analysis of the factors influencing the amount of support needed in tunnels in the Greater Boston area.

Figures 2 to 5 are geological maps of the tunnel on a scale of one inch to 240 feet. The explanations for the symbols are given in Fig. 5. Since these maps have been reduced 12 times from the original folio, some generalization has been necessary and in places only representative data can be given. Each strip represents a section of the tunnel 1000 feet long. The stations are given in the upper left-hand and upper right-hand corners of each strip. For example, 50 + 00 means 5000 feet east (strictly S. 82° 25′ 36″ E.) from Shaft 5. The elevation of the invert (bottom) of the tunnel is shown in italics at the lower left-hand corner of each strip (Boston City base).

The north side (top) of each strip corresponds to the north wall of the tunnel. Mapping was done at breast level, that is, about 4 feet above the floor of the tunnel. In order to make the map readable, it has been necessary to show a strip 50 feet wide. In other words, the south side (bottom) of each strip is 50 feet south of the north wall. Strictly, the map represents the geology along a line on the north wall and 4 feet above the floor.

The meanings of the various symbols are indicated in Fig. 5. Many are standard geologic symbols. But a few special symbols need explanation. "Dip", as used in geology, refers to the angle of inclination of a planar feature — such as bedding, a joint, a fault, or a dike — in a vertical plane perpendicular to the strike of the planar feature. "Apparent dip" refers to the angle of inclination of the planar feature on any vertical plane.

"Dip" and "apparent dip" are related as follows:

$$\tan \rho = \tan \delta \sin \alpha$$

where p is apparent dip, δ is dip, and α is the angle between the strike of the planar feature and the trend of the vertical face. If the vertical face is perpendicular to the strike of the planar feature, the apparent dip equals the dip. If the trend of the vertical face is parallel to the strike of the planar feature, the apparent dip is zero, regardless of the dip. If the vertical face trends diagonally to the strike of the planar feature, the apparent dip is less than the dip.

In most instances in the folio the true strike and dip of bedding and dikes were not recorded, but apparent dips were shown on the sketch of the north wall. Thus, to keep Fig. 2 to 5 as objective as possible, special symbols are used for apparent dips. Thus 5 symbols, as shown in the explanation in Fig. 5, refer to apparent dips. Moreover, from a combination of various data it was possible in some instances to infer the strike and dip of the bedding; a special symbol is used for this.

Figures 6 to 8 show the geological structure along the line of the tunnel. Figures 9 to 12 summarize the facts concerning the joints, faults, and dikes. All these figures are discussed in greater detail below. Figures 13 to 25 are photographs.

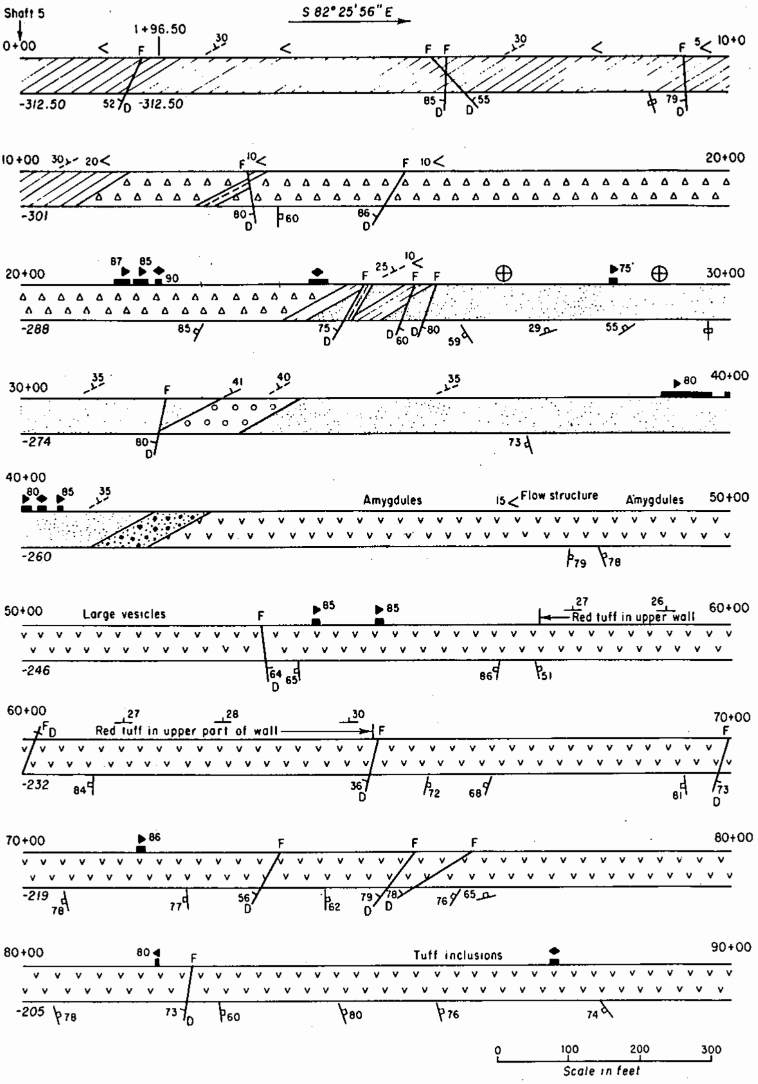

FIG. 2. — GEOLOGICAL MAP, STATIONS 0 + 00 to 90 + 00.

Top of each strip corresponds to north wall of tunnel; bottom of each strip is 50 feet south of north wall. Figures in upper-left and upper-right corners of each strip are stations; figures in italics in lower-left corner are altitude of invert (bottom) of tunnel, Boston City base. See Fig. 5 for explanation of symbols. D along faults refers to fault-trace separation.

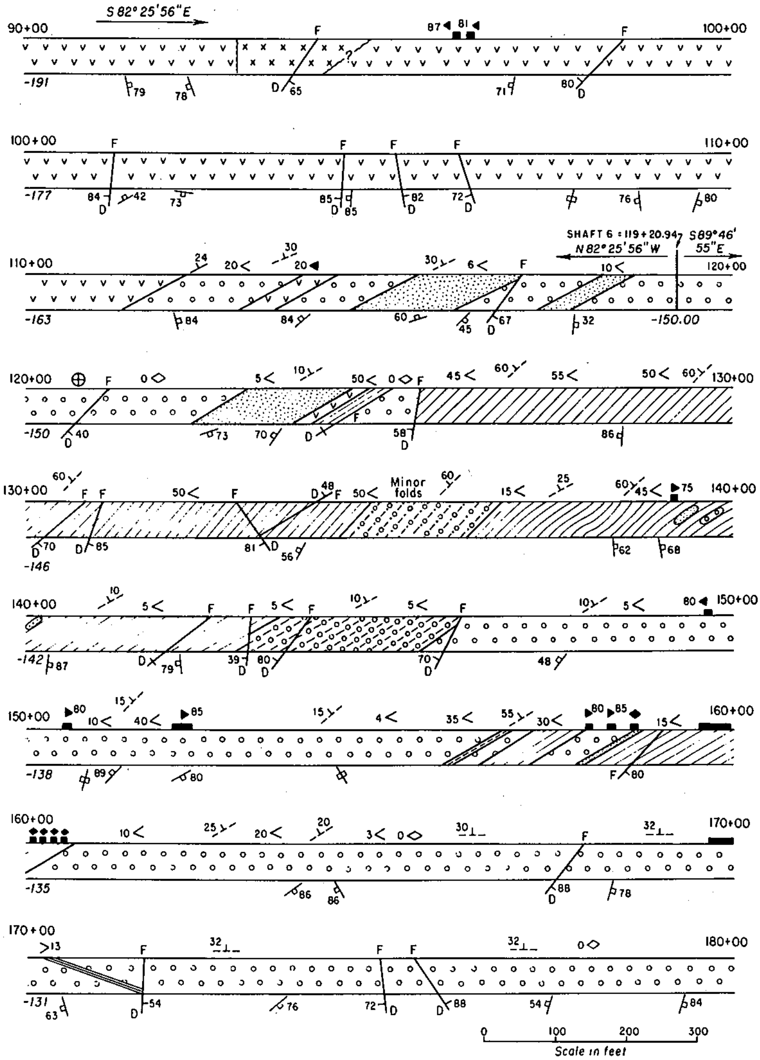

FIG. 3. — GEOLOGICAL MAP, STATIONS 90 + 00 to 180 + 00. See caption for Fig. 2.

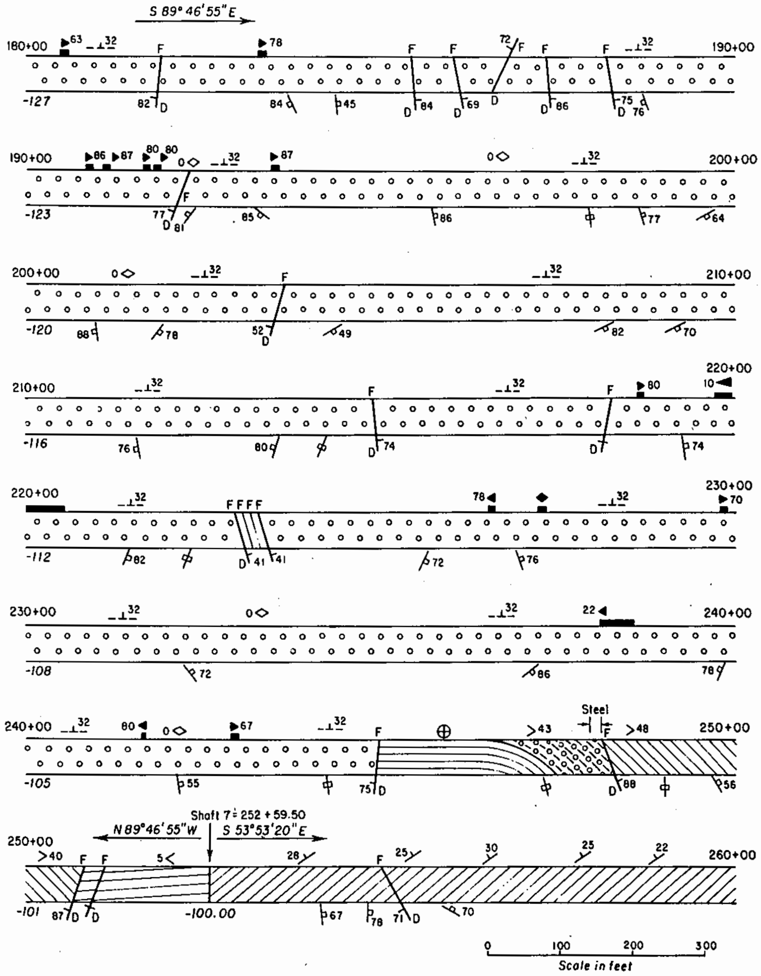

FIG. 4. — GEOLOGICAL MAP, STATIONS 180 + 00 to 260 + 00.
See caption for Fig. 2.

LITHOLOGY

General Statement

The rocks exposed in the City Tunnel are both sedimentary and igneous. The sedimentary rocks are conglomerate, sandstone (including arkose), and argillite. The igneous rocks are melaphyre, reddish tuff, and diabase (including altered diabase). The percentages of these rocks, expressed as linear feet of exposure at map level in the tunnel, are as follows. In the main tunnel, between Shafts 5 and 7, the percentages are: conglomerate 42%, tillite 4%, melaphyre 27%, argillite 16%, sandstone and arkose 7%, diabase 3%, and red tuffs 1%. If we include the branch tunnel between Shafts 7 and 7B, the figures are: 38%, 4%, 24%, 23%, 6%, 4%, and 1% respectively.

The lithological data obtained in the tunnel will be supplemented by surface data. But in the ensuing pages a clear distinction will be made between surface and tunnel data. The descriptions refer to data obtained in the tunnel unless otherwise stated.

Conglomerate

Conglomerates, constituting 38% of the linear footage of the tunnel, including the branch tunnel, were exposed in many places east of station 32 + 90. In many instances they were homogenous rocks in which bedding could not be observed. Locally, thin beds of sandstone, arkose, or argillite were interbedded. In still other places thin irregular lenses of conglomerate were interbedded with argillite. The color is generally gray, but where red felsite clasts are common the rock as a whole has a reddish tinge.

The conglomerates are similar to those found elsewhere in the Boston Basin. The clasts are well-rounded pebbles, generally ranging from 1 to 3 inches in diameter, but locally as much as 12 inches. The largest clasts observed in surface outcrops are 10 inches in diameter. The average maximum size in 87 outcrops is 4½ inches. In the surface exposures east of station 150 + 00 the average maximum size in 62 exposures is 4 inches; as will be shown below, this is within the Brookline Member. In the surface exposures north and south of that section of the tunnel between stations 150 + 00 and 70 + 00 the average maximum size of the clasts in 25 outcrops is 5½ inches; as will be shown below this is in the Dorchester Member.

The clasts are chiefly gray quartzite, pink granodiorite, variously colored felsites, with lesser amounts of red granite, green melaphyre, and gray argillite. The matrix of the conglomerates is a gray feldspathic sand-

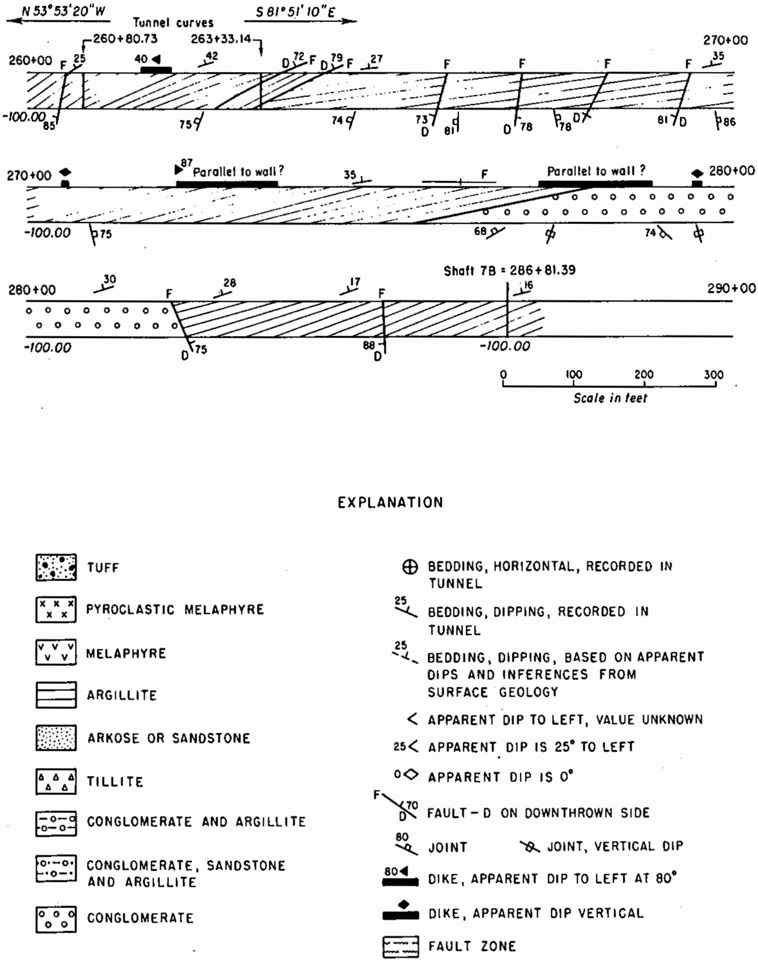

FIG. 5. — GEOLOGICAL MAP, STATIONS 260 + 00 to 287 + 11, AND EXPLANATION OF SYMBOLS.

See caption for Fig. 2. Explanation applies to Fig. 2-5, inclusive.

stone in which the individual grains of quartz and feldspar average 0.05 inch in diameter.

Tillite

The conglomerate between stations 11 + 60 and 24 + 60 differs greatly from the conglomerate farther east. The clasts are round to subround, averaging 3 to 6 inches in diameter, but some are well over 12 inches. They are chiefly gray quartzite and pink granodiorite, but also variously colored felsites. None is striated. The matrix is hard and gray; much of it is argillaceous, but locally it is sandy. At least one block of argillite, 20 feet long, is incorporated in the rock. Many pebbles have been stretched parallel to a slaty cleavage. Regardless of what one may think of the origin of this rock, it is obvious that it has all the features characteristic of the Squantum Member of the Roxbury Formation.

The best surface exposure of this stratigraphic unit is a mile north of Shaft 6, on the south side of the Massachusetts Turnpike Extension, 3000 feet west of the intersection of Washington and Walnut Streets in Newtonville. Unfortunately this outcrop cannot be inspected without special permission. Sparse subangular clasts a few inches in diameter are embedded in a massive argillaceous matrix. A similar rock was formerly exposed in Auburndale on the south side of the Massachusetts Turnpike Extension 1000 feet east of Commonwealth Avenue. This original outcrop has been largely destroyed by construction of the turnpike.

Sandstone and Arkose

Detailed descriptions of the sandstones and arkoses in the tunnel are not available. In surface exposures and other tunnels the sandstones are fine-grained to medium-grained rocks composed primarily of rounded quartz grains 0.03 to 0.08 inch in diameter, but containing some feldspar, mica, chlorite, and an occasional rock fragment of similar size. Bedding is generally absent or poor.

Argillite

The typical argillite is a gray, hard, well-indurated brittle rock. The beds generally range in thickness from 0.03 to 3 inches. The shades of gray differ in intensity. In general the fractures parallel to the bedding are many inches apart; hence in the classification prepared by McKee and Weir (1953) the rocks would be called slabby, blocky, or even massive. Slaty cleavage is rare.

In the west end of the tunnel, between stations 0 + 00 and 11 + 60, the color is dark-gray to almost black. Between stations 11 + 60 and 161 + 00 the color is generally gray. East of station 245 + 00 the color is purple-gray.

Studies elsewhere (Rahm, 1962, p. 339-340) show that the argillites are composed of silt-size and clay-size particles. The principal minerals are quartz, sericite, chlorite, and small amounts of albite. Possibly some kaolin is present in places. The purple-gray color is probably due to hematite or goethite.

Melaphyre

The term melaphyre has been traditionally used in the Boston area for altered basalts or andesites. In the City Tunnel the melaphyre is a dark-green to yellow-green medium-grained rock. Locally it is brown to black. Amygdules of epidote and quartz, generally 0.1 to 0.2 inch in diameter, are present in places. Flow structure is shown by alternating layers of somewhat different color and composition with an apparent dip westward from 5° to 25°. Microscopic study shows that the melaphyres of Greater Boston are composed of such secondary minerals as albite, hornblende, chlorite, epidote and calcite. The melaphyre between stations 93 + 00 and 95 + 00 is a deep-purple melaphyre breccia of explosive origin.

Tuff

Between stations 41 + 90 and 42 + 70, just west of the large melaphyre body, is a pink rock believed to be volcanic tuff.

Diabase (including altered diabase)

The diabases are fine-grained to medium-grained dark-green to black rocks. In the folio most of them are called basalt because of their fine grain. Diabase is composed of labradorite and augite, but such secondary minerals as hornblende, chlorite, and epidote are present in many of them.

STRUCTURAL GEOLOGY

General Statement

The structural geology of this tunnel is concerned with folds, joints, faults, and dikes.

Folds

In the central part of the Boston Basin the axes of the folds trend east-west (Billings and Tierney, 1964, p. 113). The axis of the Charles

River Syncline is near the Charles River (Fig. 1). The axis of the Central Anticline lies two miles south of the Chestnut Hill Reservoir. Thus the width of the north limb of the anticline (the same as the south limb of the syncline) is about 4 miles. In the westerly part of the Boston Basin the fold axes assume a northeast-southwest trend. The City Tunnel cuts diagonally across the northwest limb of the anticline and progressively younger stratigraphic units are exposed to the west.

The structure along the tunnel line is shown in Fig. 6 and 7. The symbols used are explained in Fig. 8. This is essentially what one would see on the north wall of the tunnel, but extended upward to the surface and downward to 500 feet below base. Generalizations are necessitated by the greatly reduced scale. Moreover, dikes and joints are not included, and only the larger faults are shown, and somewhat diagrammatically.

Figures 6 and 7 show the apparent dip, because the tunnel is subparallel to the strike of the strata. However, this portrayal is objective, inasmuch as it was the apparent dips that were recorded in the sketches of the north wall.

But for a complete understanding of the structure and in order to calculate thicknesses, it is necessary to know the strike and dip of the strata. In some instances the strikes and dips were recorded in the folio or could be readily calculated from data given in the folio. But in general the strike and dip of the bedding had to be determined from the observations on the surface geology. Such information was not completely divorced from the observations in the tunnel. The apparent dips calculated from the surface observations had to agree with the observed apparent dips in the tunnel. The "inferred strike and dip" shown on the geological maps — Fig. 2 to 5 — are based on the surface observations.

A detailed statement concerning the attitude of the bedding throughout the tunnel follows. This is an important part of the record on which the conclusions given in the later pages are based.

The bedding symbols given on the maps (Fig. 2-5) between Shaft 7B and 7, as well as between Shaft 7 and station 245 + 00, are based directly on data in the folio. They are either apparent dips shown on the sketches of the north wall or are true attitudes calculated from data in the folio.

For the section between stations 245 + 00 and 180 + 00 surface data are available to supplement the information from the tunnel. Bedding is rare in the conglomerate exposed in the tunnel. The only five instances recorded show the apparent dip to be zero. But in 18 outcrops north and south of the tunnel the strike of the bedding ranges from N. 65° E. to N.

80° W. and the dip ranges from 22° N. to 38° N. The average strike is N. 90° E. and the average dip is 32° N. Consequently, in Fig. 4, 14 symbols have been placed on the geological map to show the inferred attitude of the bedding to be N. 90° E., 32° N. This, of course, is consistent with the recorded apparent dips of zero in the tunnel.

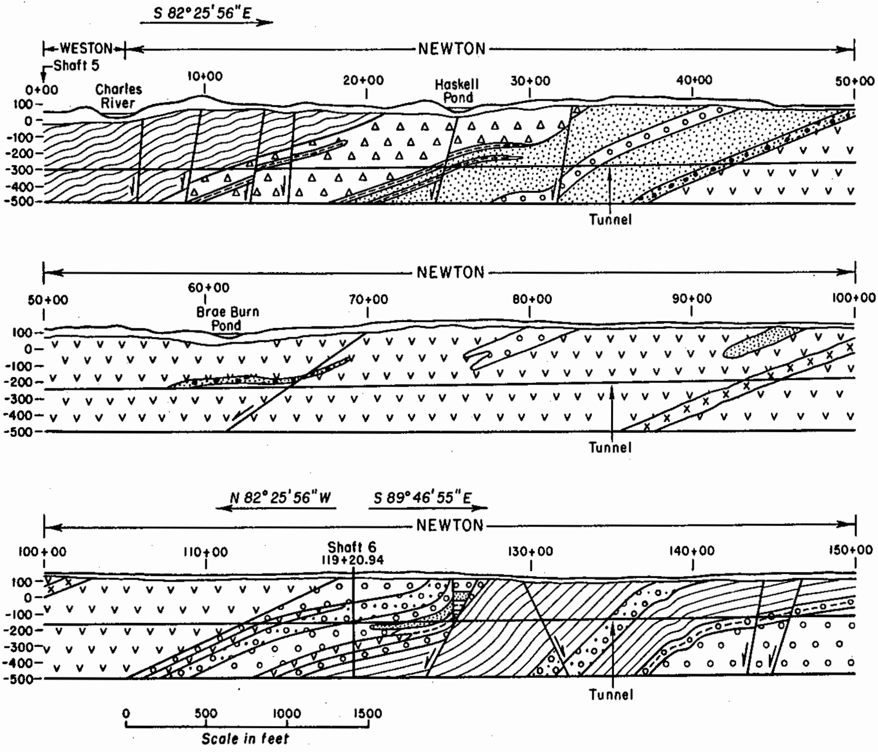

FIG. 6. — GEOLOGICAL STRUCTURE SECTION, STATIONS 0 + 00 to 150 + 00.

Explanation of symbols in Fig. 8. Dikes and joints omitted, and only some of the faults are shown. Arrows on faults refer to fault-trace separation.

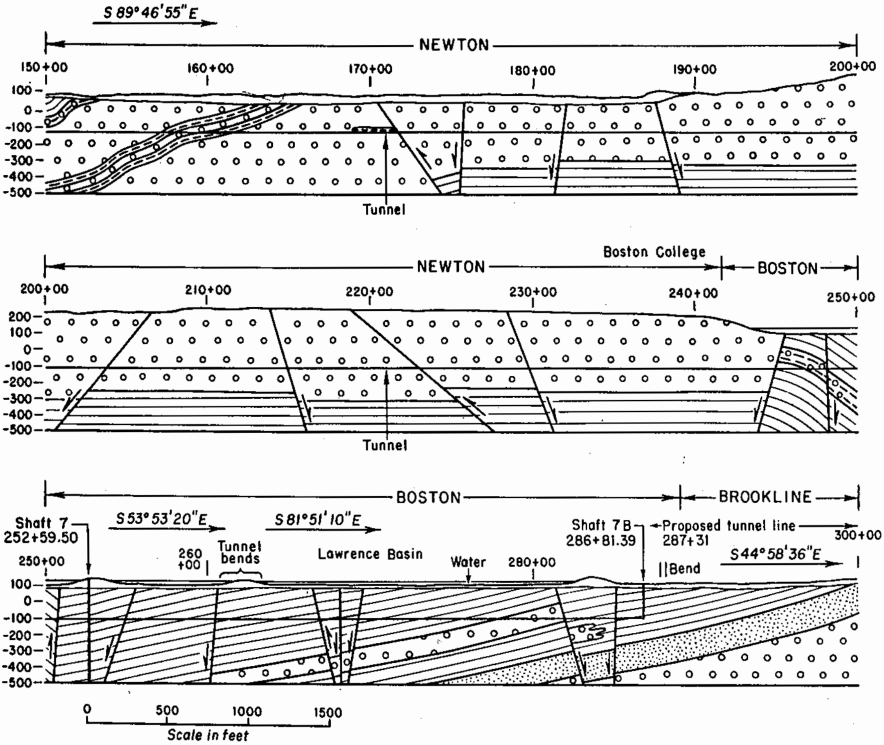

FIG. 7. — GEOLOGICAL STRUCTURE SECTION, STATIONS 150 + 00 to 300 + 00.
See caption for Fig. 6.

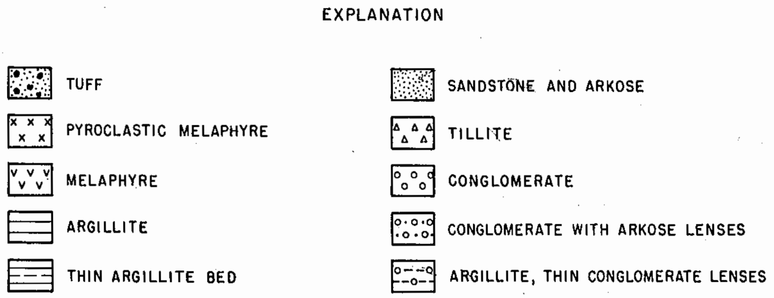

FIG. 8. — EXPLANATION OF SYMBOLS USED IN FIG. 6 AND 7.

Between stations 180 + 00 and 140 + 00 there are no surface outcrops to supplement the data from the tunnel.

Between stations 180 + 00 and 171 + 00 the one apparent dip recorded in the tunnel is zero. It is assumed that the attitude of the bedding is the same as that farther east, and that the beds strike N. 90° E. and dip 32° N; two such symbols have been placed on the map (Fig. 3).

An exceptional, in fact unique, situation was recorded at station 170 + 25, where the apparent dip is 13° E.

Between stations 170 + 00 and 165 + 00 the one recorded apparent dip is zero. Again, as farther east, it is assumed that the strike is N. 90° E. and the dip is 32° N.

Between stations 165 + 00 and 140 + 00 the apparent dips are consistently west, ranging from 3° to 40°, but averaging 13°. On the basis of the regional geology of this part of the Boston Basin it is assumed that the average strike here is N. 60° E.; thus the presumed true dips can be calculated from the observed apparent dips in the tunnel. Accordingly, eight inferred strike-dip symbols have been entered between stations 165 + 00 and 140 + 00.

Between stations 140 + 00 and 126 + 00 the apparent dips in the tunnel range from 15° to 55° W., and average 40° W. In five surface outcrops the average attitude of the bedding is N. 60° E., 60° NW. Accordingly, five symbols with this inferred attitude are shown on the geological map in this area. A sixth symbol, with a somewhat lower dip, has been entered at station 137 + 50 to be consistent with the lower apparent dip here.

At station 125 + 40 the apparent dip is zero, at station 125 + 00 it is 50° W. A minor fold would explain these differences.

Between stations 125 + 00 and 112 + 30, 5 readings of the apparent dip range from 0° to 20° W., averaging 8° W. In a surface outcrop of conglomerate the strike is N. 65° E., the dip is 28° NW. Three symbols for the inferred attitude of the bedding in this section of the tunnel are shown in Fig. 3; the strike was assumed to be N. 65° E., whereas the true dip was calculated from apparent dips.

Between stations 112 + 30 and 42 + 00 is the great mass of melaphyre. The basal contact of the melaphyre is sharp. The folio indicates the contact dips 24° NW. The apparent dip in two photos is 16° W. A strike of N. 65° E. is consistent with these data. The upper contact of the melaphyre is not sufficiently sharp to supply any data concerning the attitude of the contact, but the apparent dip of the flow structure in the melaphyre ranges from 5° to 25° W.

Although the melaphyre is continuous in the tunnel, surface outcrops indicate it may consist of more than one body. An outcrop of sandstone lies 300 feet north of station 99 + 00; the attitude of the bedding is N. 70° E., 30° NW. It would project to station 96 + 00 on the tunnel line; it is shown in the geological cross section. An outcrop of conglomerate lies 800 feet south of station 86 + 00; the bedding strikes N. 70° E., dips 54° NW. It would project to the tunnel line at stations 80 + 00 and 83 + 00.

These observations indicate that the melaphyre is a large concordant sheet or series of sheets striking N. 70° E. and dipping about 36° NW. The average apparent dip in the tunnel would be about 20° W. The body would be 983 ± feet thick. It may be either a surface flow or a shallow intrusive.

Significant surface data on the attitude of the beds are not available for locations west of station 42 + 00. At station 32 + 90 the attitude of the bedding is N. 70° E., 41° NW. At stations 29 + 00 and 26 + 70 the bedding is horizontal. Farther west the apparent dip is consistently west, ranging from 5° to 20°, averaging 15° W. Assuming the strike to average N. 70° E., the true dip would average 30° NW.

In summary, the tunnel crosses the northwest limb of an anticline. Although the values of the dips differ considerably, they are with only one exception (station 170 + 25) to the north or northwest. Minor folds, with a wave length of a few feet, are rare; some were recorded in argillite at station 135 + 40.

Joints

Joints are smooth fractures that may be only a few inches apart or many tens of feet apart. A joint may be many feet or hundreds of feet long. Strictly speaking, there is no movement of the opposite walls parallel to the joint plane. If there had been such movement, the fracture would be called a fault. Joint sets consist of several more or less parallel joints. The distinction between joints and small faults is not rigorous, and some joints may show evidence of movement.

Figure 9 is a point diagram (Billings, 1954, p. 112-115) of 251 joint sets in the City Tunnel. It is clear that the most common joints are those striking north-northeast or north, and dipping steeply west-northwest, east-southeast, west or east.

Faults

Seventy-four faults were mapped in the City Tunnel. Many of them are recorded on the geological maps in Fig. 2 to 5. Some are also shown on the structural sections, Fig. 6 and 7, where they are necessarily rather diagrammatically portrayed because of the restricted scale and lack of information outside the tunnel. As shown in the point diagram, Fig. 10, most of them strike north-northeast or north and dip steeply west-northwest, and east-southeast or west and east.

Twenty-nine of the faults have gouge and/or breccia that ranges in thickness from a smear to 11 feet, but averaging 3 feet.

The geometry of faulting is a complex subject and can not be fully treated here. Many pages are devoted to it in texts on structural geology (Billings, 1954, p. 124-225, 455-480). Moreover, a rather elaborate terminology, much to the annoyance of those unfamiliar with the subject, has been evolved to describe the movements and especially the effects on the disrupted planar features (beds, dikes, veins, older faults, etc); but only two of the many terms need concern us here. The *net slip* is the total displacement, measured in the fault plane, of two formerly adjacent points in the fault plane. What may be called the *fault-trace separation* is measured along the trace of the fault on any designated surface; it is the distance between the two ends of the trace of the disrupted planar feature. In this study the surface of observation is the north wall of the tunnel. Of course, the two parts of the disrupted planar feature may not be present; one part may be beyond the periphery of the tunnel. In such a case the fault-trace separation is indeterminate.

The fault-trace separation will be different for two differently oriented planar features. For example the separation of the bedding will be different than that of a dike that is transverse to the bedding. If the surface of observation is longer than the wave-length of the folds, different portions of a displaced bed will show different separations. This, however, is not a factor in this tunnel, because minor folds are absent. Moreover, on the sections the fault-trace separation always refers to bedding or contacts parallel to the bedding. Of course, the magnitude and direction of the fault-trace separation is by itself no indication of the magnitude and direction of the net slip.

The symbols in Fig. 2 to 7 refer to the fault-trace separations. That is, in Fig. 2 to 5 the letter *D* is on the side of the fault that appears to have gone down. In Fig. 6 to 8 the arrow shows the direction of the apparent movement. A normal fault is one in which the hanging wall appears to have gone down relative to the foot wall, a reverse fault is one in which the hanging wall appears to have gone up relative to the foot wall.

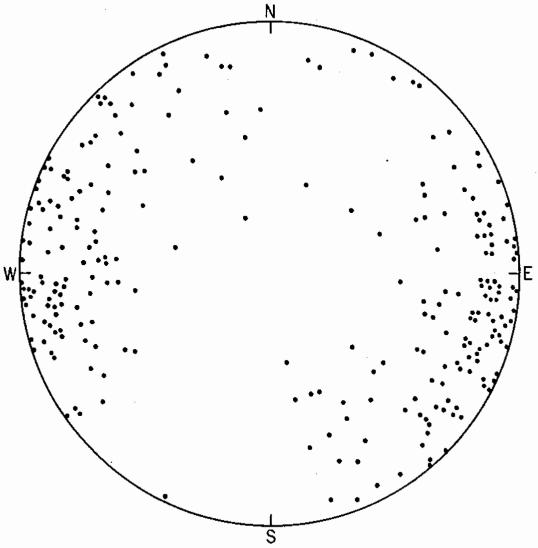

FIG. 9. — POINT DIAGRAM OF JOINTS.

Plotted on lower hemisphere of equal area net; 251 sets of joints. Each plot represents pole of perpendicular to joint set.

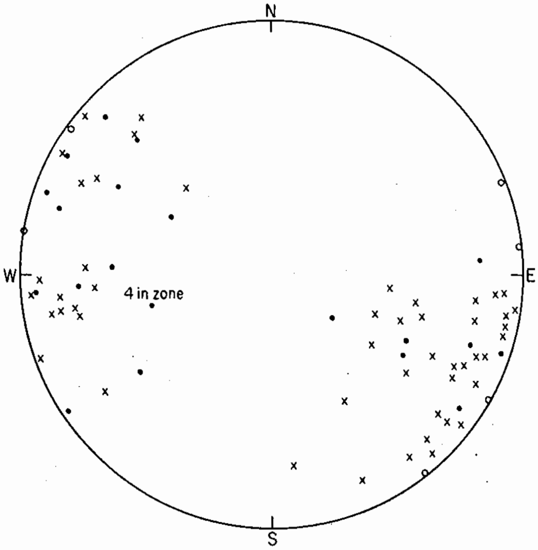

FIG. 10. — POINT DIAGRAM OF FAULTS.

Plotted on lower hemisphere of equal area net; 74 faults. Crosses are normal faults, dots are reverse faults, and circles are faults dipping 90°.

Strictly, these terms should be used only if the trend of the vertical wall is perpendicular to the strike of the fault, but in this tunnel most of the faults strike at a high angle to the trend of the tunnel. Of the 74 faults, 48 are normal, 20 are reverse, and 6 are neutral because they dip 90°.

The actual movement along a fault, that is, the net slip, can be calculated only if adequate data are available (Billings, 1954, p. 135, 455-480). (1) If both ends of *two* disrupted planar features that *have different attitudes,* can be observed on opposite sides of the fault, a unique solution can be obtained. (2) If both ends of *one* disrupted planar feature can be observed on both sides of the fault and if *slickensides* that can be relied on to show the direction of movement on the fault are present, a solution can be obtained. (3) If both ends of *one* disrupted planar feature can be observed on both sides of the fault and if drag along the fault can be relied upon to show the direction of movement, a solution can be obtained.

In general in geological investigations it is impossible to get enough data to calculate the net slip along faults. This tunnel is no exception. Moreover, even if it is possible to get a solution, gathering the data is time consuming. In any case, along none of the 74 faults recorded were sufficient data obtained to calculate the net slip.

Along 16 of the 74 faults the fault-trace separation ranged from a few inches to 10 feet, averaging 3 feet. Along 6 faults it exceeded 12 feet, the height of the tunnel. Along 52 faults precise data were not obtained, but in 36 of these the fault-trace separation was certainly only a few inches or feet. In summary, the fault-trace separation along 22 of the faults may exceed 12 feet, but along the others it is probably to be measured in inches or feet.

Since the net slip along the faults in unknown, it is impossible to discuss quantitatively the component of the faulting parallel to the strike of the faults (that is, the strike-slip component). But the regional geology and narrow width of the faults suggest that it is generally small. There is one possible exception.

The surface geology suggests that the net-slip along the fault at station 245 + 00 may be hundreds of feet. An analysis of the surface exposure may give a more precise solution.

A much more detailed discussion of the faults is contained in the report by Tierney (1951, p. 29-60).

About 1760 feet west of Shaft 5 the east edge of a series of outcrops are exposed. These outcrops are composed of Dedham granodiorite intruded by diabase dikes. Similar outcrops are exposed farther north on the west side of the Charles River. The distribution of outcrops in Wellesley, Weston, and Waltham indicates that this contact trends about N. 20° E. Bore hole data obtained in another project indicate the contact is located under the sands of the Charles River 1600 feet N. 30° W. of Shaft 5. This contact is the northern boundary fault of the Boston Basin. Data obtained in the Malden Tunnel indicate that this fault dips northwest and is a thrust (Billings and Rahm, 1966, p. 131-133). The stratigraphic throw west of Shaft 5 is at least 5000 feet and the net slip would be greater.

Dikes

One hundred and nine dikes are shown on the geological folio. Of these, 101 are in the main tunnel, whereas 8 are in the branch tunnel that goes southeast from Shaft 7 to Shaft 7B. Most of the dikes are fine-grained to medium-grained diabase or altered diabase, but a few are melaphyre. The location of each dike is known, as they are shown in the folio on the sections of the north wall (northeast wall in the branch tunnel). Moreover, the apparent dip is shown. But the attitude of the contacts was not recorded, and hence it was impossible to calculate the true thickness.

Figure 11 is a histogram of the apparent dips of the 101 dikes in the main tunnel; 5° intervals were used. In the few instances where the two contacts were not parallel or the contact was irregular, an average attitude has been used. Where the dip fell on the boundary of two blocks — for example 80° — one-half dike was assigned to the 80°-85° block and one-half dike to the 80°-75° block. The apparent dip of 82 percent of the dikes is greater than 70°; also, more dip east than west. Since the true dip is always as great as or greater than the apparent dip, it is correct to say that 82 percent or more of the dikes dip more steeply than 70°. It is also probable that most of the dikes strike at a high angle to the tunnel, that is, between N. 30° E. and N. 30° W.

Figure 12 is a histogram showing the width of the 101 dikes exposed on the north wall of the main tunnel.

The widths of 57 percent of the dikes are 5 feet or less; the widths of 91 percent are 15 feet or less. The thicknesses would be less than the widths. Of the three dikes with a width greater than 50 feet, the width of one is 53 feet, that of a second is 72 feet, and that of a third is 85 feet.

The data for the branch tunnel are somewhat different. Of the eight dikes recorded, four have an apparent dip of 90° and an average width of 7 feet; these are in the portion of the branch tunnel striking S. 82° E., and probably strike in a general northerly direction. A fifth dike, 1 foot wide,

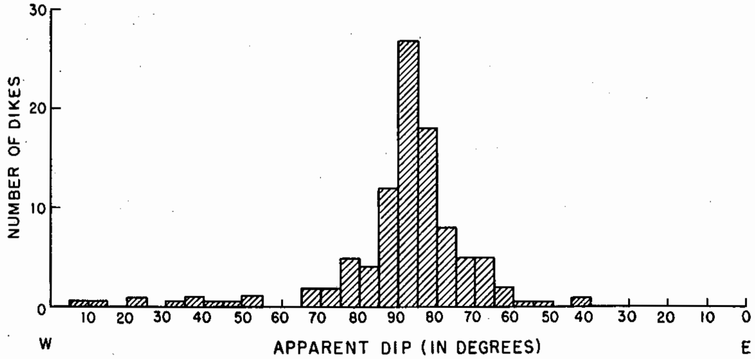

FIG. 11. — APPARENT DIP OF DIKES.
Apparent dip of 101 mafic dikes in main tunnel, stations 0 + 00 to 252 + 90.50. Plotted as if tunnel trended east-west; error resulting from this assumption is less than errors of measurement.

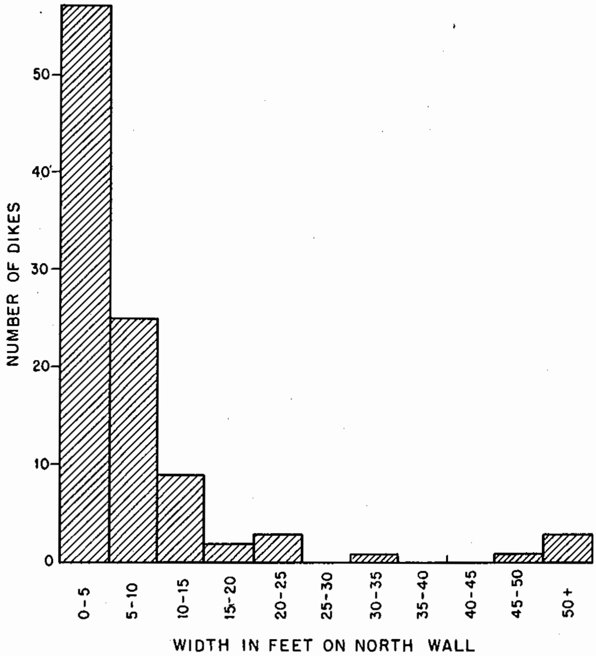

FIG. 12. — WIDTH OF DIKES.
Width of 101 mafic dikes on north wall of main tunnel.

dips NW. Three dikes with irregular contacts and an average width of 112 feet presumably strike parallel to the tunnel.

STRATIGRAPHY

Having described the lithology and structure, we are now prepared to determine the stratigraphy, that is, how the various lithologic units are stacked on top of one another and how they correlate with similar rocks elsewhere in the Boston Basin.

Sixty-nine precent of the linear footage in the tunnel is composed of sedimentary rocks; 61% of this is conglomerate, 23% is argillite, 10% is sandstone and arkose, and 6% is tillite. These rocks form beds that range in thickness from a few feet to hundreds of feet. As shown in Table 1, these various lighologic types in the tunnel may be grouped into 38 stratigraphic units. Some of these units consist exclusively of one lithologic type, others are interbedded mixtures of two or more types. Three additional units, based on core drilling southeast of Shaft 7B, are also shown in Table 1.

The thickness of a stratigraphic unit is calculated by the following equation Billings, 1954, p. 433).

$$t = s(\sin \delta \cos o \sin \alpha \pm \sin o \cos \delta) \tag{2}$$

where t is thickness, s is breadth of unit as measured along the wall of the tunnel, δ is angle of dip of bed, o is angle of slope of invert of tunnel, and α is angle between strike of bed and trend of tunnel. If slope and dip are in the same direction, the second term in the parentheses is added, otherwise it is subtracted.

The slope of the invert is 0° between shafts 7B and 7, 0.2° between shafts 7 and 6, and 0.8° between shafts 6 and 5. Its effect on the calculations is so slight, particularly when compared with errors introduced by other factors, that it may be neglected. Hence the equation reduces to:

$$t = s(\sin \delta \sin \alpha) \tag{3}$$

It is because δ and α are so important that so much attention was given in an earlier section of the paper to the determination of the strike and true dip of the beds. The errors in calculating the thicknesses in this tunnel may be as great as 10 percent.

In general it has been assumed that the faults are small and introduce only minor errors in the calculations of the thicknesses. However, the fault at station 245 + 00 is important. West of the fault an unknown amount of conglomerate is present beneath the tunnel. If the beds dip 32° N., the

Table 1

STRATIGRAPHY, CITY TUNNEL

	Thickness	*Stations*
Cambridge Formation:		
41. Argillite	295	0 + 00 to 11 + 60
Squantum Member of Roxbury Formation:		
40. Tillite	48	11 + 60 to 13 + 26
39. Purple-gray argillite	12	13 + 26 to 13 + 60
38. Tillite	241	13 + 60 to 24 + 60
Dorchester Member of Roxbury Formation:		
37. Argillite	11	24 + 60 to 24 + 95
36. Sandstone	13	24 + 95 to 25 + 45
35. Argillite	10	25 + 45 to 25 + 80
34. Sandstone	84	25 + 80 to 32 + 90
33. Conglomerate	32	32 + 90 to 34 + 00
32. Sandstone	230	34 + 00 to 41 + 90
31. Tuff	20	41 + 90 to 42 + 70
(Melaphyre	983	42 + 70 to 112 + 30)
30. Conglomerate	73	112 + 30 to 114 + 00
(Melaphyre	17	114 + 00 to 114 + 45)
29. Conglomerate	38	114 + 45 to 115 + 56
28. Arkose	12	115 + 56 to 117 + 06
27. Conglomerate	30	117 + 06 to 118 + 17
26. Arkose	10	118 + 17 to 118 + 64
25. Conglomerate	8	118 + 64 to 119 + 21
24. Conglomerate, thin arkose lenses	20	119 + 21 to 123 + 20
23. Arkose	14	123 + 20 to 124 + 72
(Melaphyre	5	124 + 72 to 124 + 85)
22. Argillite	13	124 + 85 to 125 + 26
21. Conglomerate	15	125 + 26 to 125 + 60
20. Argillite	564	125 + 60 to 134 + 80
19. Conglomerate, arkose and argillite	117	134 + 80 to 136 + 70
18. Argillite	142	136 + 70 to 139 + 20

Table 1, Stratigraphy, Cont.

	Thickness	Stations
Dorchester Member of Roxbury Formation (Cont.):		
17. Argillite, some conglomerate and arkose	60	139 + 20 to 140 + 60
16. Argillite	44	140 + 60 to 143 + 60
15. Argillite, some conglomerate	32	143 + 60 to 146 + 20
Brookline Member of Roxbury Formation:		
14. Conglomerate, some arkose and argillite	185	146 + 20 to 156 + 70
13. Argillite	4	156 + 70 to 156 + 80
12. Conglomerate	15	156 + 80 to 157 + 20
11. Argillite	27	157 + 20 to 157 + 90
10. Conglomerate	17	157 + 90 to 158 + 60
9. Arkose	4	158 + 60 to 158 + 70
8. Argillite	60	158 + 70 to 160 + 60
7. Conglomerate‡	254	160 + 60 to 245 + 00
6. Argillite#	556	245 + 00 to 278 + 00
5. Conglomerate and red Sandstone	19	278 + 00 to 282 + 00
4. Argillite	27	282 + 00 to 287 + 31
*3. Gap	118	287 + 31 to top of B.H.D.T. 1
*2. Feldspathic sandstone	143	B.H.D.T.1 = 300 + 66
*1. Conglomerate	82	

‡ A thickness of 111 feet exposed in the tunnel; the extra 143 feet is assumed to be beneath tunnel level; calculation is discussed in text.

321 feet of argillite were exposed in the branch tunnel between Shaft 7 and station 278 + 00; the additional 235 feet of argillite were exposed in Shaft 7. The argillite between Shaft 7 and station 245 + 00 is a repetition of the section in the branch tunnel between Shaft 7 and station 278 + 00.

* Based on bore hole data southeast of Shaft 7B.

conglomerate exposed in the tunnel should come to the surface 480 feet south of the tunnel line. The surface geology indicates that the base of this conglomerate unit comes to the surface 750 feet south of the tunnel line. Thus 143 additional feet of conglomerate are present in unit 7.

The diabases and altered diabases, occupying 3% linear feet of the tunnel, are dikes and clearly not part of the stratigraphic sequence. The melaphyres constituting 27% of the linear footage of the tunnel are more enigmatic. If they are surface flows they are properly considered part of the stratigraphic sequence. If they are intrusives, such as sills, that are much later than the accumulation of the sediments, they would not be considered part of the sequence. But if, as seems probable, they are shallow sill-like intrusives contemporaneous with the sedimentation, some might consider them part of the sedimentary sequence, others might not.

In Table 1 the 41 lithologic units have been assigned to four of the traditional stratigraphic units of the Boston Bay Group. At the top is argillite belonging to the lower part of the Cambridge Formation; 295 feet are exposed in the tunnel. Below this is the Squantum Member of the Roxbury Formation, 301 feet thick here, and composed of two bands of tillite separated by 12 feet of purple-gray argillite. The Squantum has sometimes been considered a formation. Below this is the Dorchester Member of the Roxbury Formation. A heterogeneous mixture of conglomerate, sandstone, arkose, argillite, and a little tuff, it is 1592 feet thick. It is 56% argillite, 26% arkose and sandstone, 17% conglomerate, and 1% tuff. Three sheets of associated melaphyre are 983, 17, and 5 feet thick. The lowest unit is the Brookline Member of the Roxbury Formation; the 1511 feet recorded in Table 2 belongs to the upper part of this member. Here it is 55% argillite, 43% conglomerate, and 2% sandstone. The thicknesses of the various units are given in Table 2.

Undoubtedly most of the 41 units shown in Table 1 are irregular lenses that thicken and thin. That is, they are not simple tabular sheets of uniform thickness extending for thousands of feet or miles. The chief argument that they are lenses is based on effort to correlate individual units with those in the City Tunnel Extension (Fig. 1, Billings and Tierney, 1964). Although large units may be correlated, the individual units can not. Moreover, experience in similar sediments in other areas indicates that the units would be lenses.

The Boston Bay Group has been traditionally considered to be nonmarine. The absence of marine fossils, despite the Late Paleozoic age, is the principal reason for believing this. Secondly, conglomerates of the type

Table 2

THICKNESS OF PRINCIPAL STRATIGRAPHIC UNITS IN CITY TUNNEL

Cambridge Formation	295 feet
Roxbury Formation	
Squantum Member	301 feet
Dorchester Member	1592 feet
Brookline Member	
In tunnel	1168 feet
Southeast of Shaft 7B	343 feet
TOTAL:	3699 feet

found here were presumably deposited as river gravels.

The evidence from the City Tunnel, as well as from other tunnels in the Greater Boston area, indicates that the sediments were deposited in a subsiding basin and were derived from the south (Billings and Tierney, 1964, p. 148-149). The argillites and sandstones were deposited mostly in shallow lakes, although some may have been laid down on the flood plains of rivers. The conglomerates were deposited largely by streams that periodically invaded the lakes as the water level fell. The melaphyres consolidated from molten basalt or andesite. Although some of this magma erupted as surface flows, much of it congealed beneath the surface as shallow sills.

REGIONAL STRESSES

The regional stresses that produced the major folds, joints, and faults in the Boston Basin have been discussed in an earlier paper (Billings and Tierney, 1964, p. 146-147). If an essentially horizontal compressive force were acting in a north-south direction, the fold axes would trend east-west. If the intermediate principal stress axis were vertical, two sets of shear fractures would form, striking approximately N. 30° E. and N. 30° W. and dipping vertically. (Billings, 1954, p. 164-177.) Extension fractures would strike north and dip vertically. Because of the heterogeneity of the rocks, the fractures would undoubtedly diverge greatly from these patterns. Nevertheless, the joints, as shown in Fig. 9, can be interpreted as shear and extension fractures formed in this way. The faults may be explained in the same way, except that members of the theoretical set striking N. 30° W. are rare. If the displacement along the faults were caused by the same stresses, they should be strike-slip faults. Insufficient data are available to state whether or not this is correct. But the pattern is similar to that found elsewhere in the Boston Basin (Billings and Tierney, 1964, p. 142).

ENGINEERING ASPECTS OF GEOLOGY

The rocks through which the tunnel was driven were unusually good and needed little support. No roof bolts were used, but the tunnel was driven before this type of support was extensively employed. Structural steel support was used in only 16 linear feet or 0.06% of the tunnel. Thus the rock was superior to that encountered in tunnels driven subsequently in the Greater Boston Area, in which structural steel support was used as follows: City Tunnel Extension, 5.6%; North Metropolitan Relief Tunnel, 25%; Main Drainage Tunnel, 35%; and Malden Tunnel, 52%. Because the City Tunnel was driven in an area of relatively extensive outcrops, it might have been anticipated that little support would be needed. Moreover, after the tunnel had been driven it might have been erroneously concluded that such units as the Brookline, Dorchester, and Squantum Members of the Roxbury Formation, as well as the Cambridge Formation — at least its lower part — are sufficiently strong to require little or no support. But this is not so. The Dorchester Member required extensive support in the Main Drainage Tunnel and parts of the Cambridge Formation required support in both the Malden and North Metropolitan Relief Tunnels.

Experience in the driving of bedrock tunnels in Greater Boston during the last two decades shows that three major factors are involved in determining whether or not a specific rock will require support. One concerns the inherent properties of the rocks related to their origin; normally, most bedrock in the Greater Boston area, such as granite, conglomerate, or argillite is sufficiently strong to necessitate little or no support. A second factor concerns the stresses to which the rocks have been subjected subsequent to their formation, especially during times of folding. Fractures, notably joints and faults, although in many instances of no concern, may locally necessitate support. For example, in the Malden Tunnel the Lynn Volcanics and the Cambridge Formation north and south of the Northern Boundary Fault became so fractured that support by structural steel was required. A third factor, as yet not fully understood, concerns the amount of kaolin in the rocks (Rahm, 1962, p. 330-334; Billings and Tierney, 1964, p. 134-138). Much of this kaolin is apparently not an original constituent of the rock; rather, it is a product of the alteration of feldspar in arkose, the matrix of conglomerates, and perhaps even in siltstones and argillites. Moreover, it appears that this alteration may be extensive and irregularly distributed (Kaye, 1967). The difference in the strength of the Dorchester Member in the Main Drainage Tunnel, where it is weak, and in the City Tunnel and City Tunnel Extension, where it is strong, may be chiefly due to the erratic distribution of this alteration.

ACKNOWLEDGMENTS

We wish to express our appreciation to Frederick W. Gow, formerly Chief Engineer of the Construction Division of the Metropolitan District Commission for permission to publish this material and for many past courtesies. We are also indebted to Martin F. Cosgrove, Deputy Chief Engineer, for aiding this investigation in many ways.

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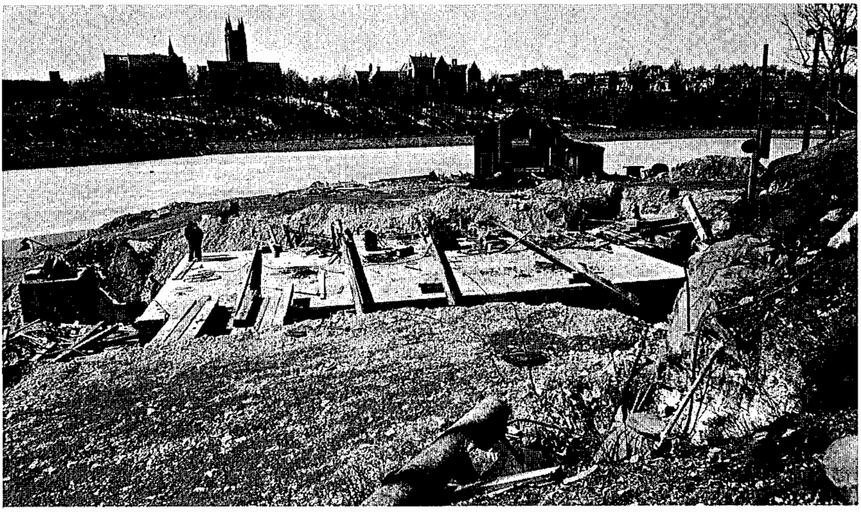

Fig. 13. — Concrete roof slab over Shaft 7, looking westerly toward Boston College across Lawrence Bsin of Chestnut Hill Reservoir. This portion of the reservoir has now been filled in and converted to an athletic field and parking lot. The slope, 70 feet high and composed of conglomerate, is a fault-line scarp that was exposed in the tunnel at station 245 + 00. 3/20/50.

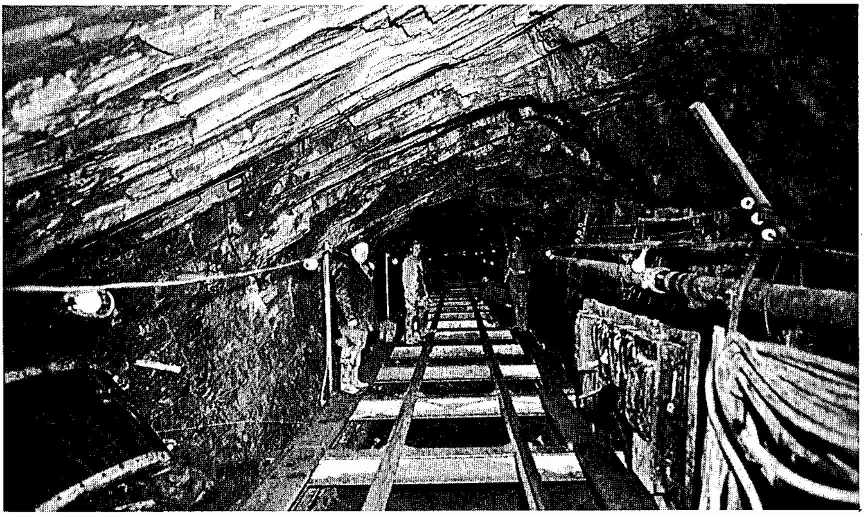

Fig. 14. — Branch tunnel between shafts 7 and 7B, looking east. Slabby argillite striking parallel to tunnel and dipping about 30° N. 12/30/48.

Fig. 15. — Station 280 + 71. Looking east. Red sandstone interbedded with conglomerate. Bedding strikes parallel to tunnel and dips about 25° N. 1/19/49.

Fig. 16. — Station 11 + 13, north wall. Contact of tillite of Squantum Formation with argillite of overlying Cambridge Formation. Apparent dip 20° W. Quartz veins dip east. 2/15/50.

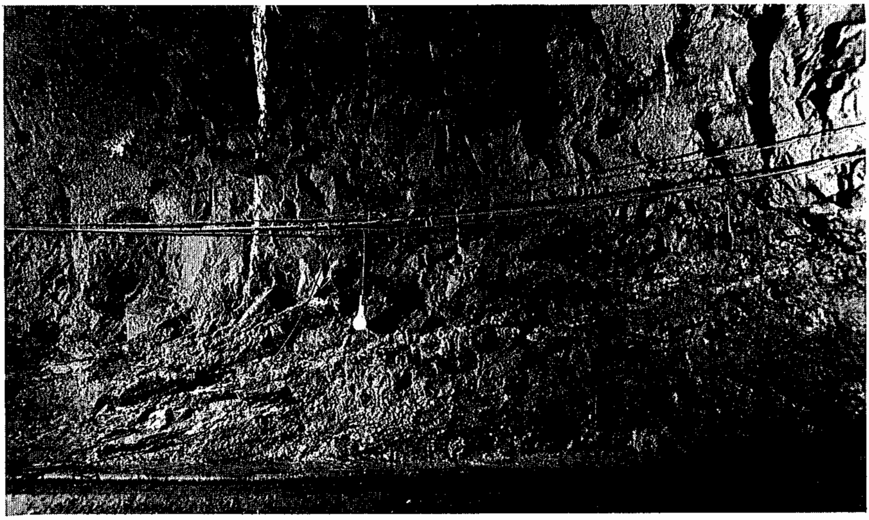

Fig. 17. — Station 112 + 25, north wall. Contact of conglomerate with overlying melaphyre. Apparent dip 25° W.

Fig. 18. — Station 285 + 06, north wall. Fault zone several feet wide; left part is a breccia, right part is fractured argillite. Country rock is argillite. On left side of fault the bedding strikes parallel to the tunnel and dips gently north. On right side of fault the strike of the bedding is diagonal to the tunnel and dips gently northwest. The fault-trace separation along the fault appears to be very small. 1/21/49.

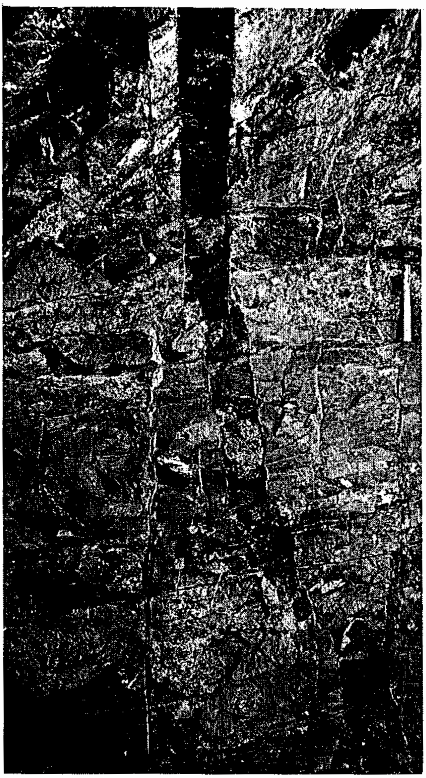

Fig. 19. — Station 279 + 60. Thin dike of fine-grained diabase cutting red fine-grained sandstone and conglomerate. The apparent dip of the sandstone is 10° to the left (west). Dikes as narrow as this have not been shown on the geological map (Fig. 5). 1/21/49.

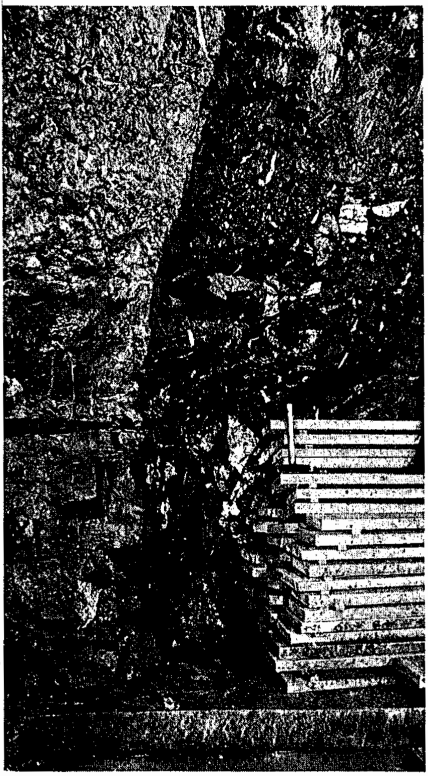

Fig. 20. — Station 279 + 50. West contact of diabase dike, 8 feet wide, full of angular inclusions, mostly quartz. Country rock is conglomerate above and fine-grained red sandstone below. Strike of bedding nearly parallel to tunnel. 1/21/49.

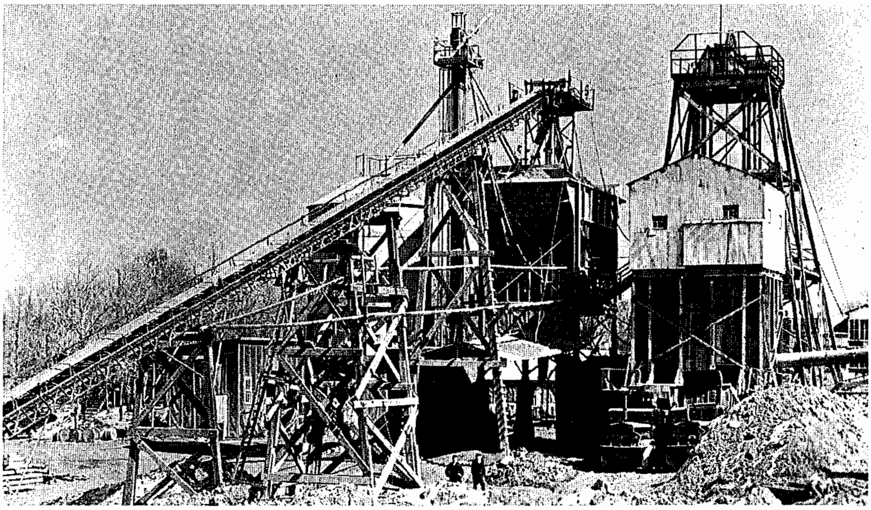

Fig. 21. — Shaft 6. Headframe to right, concrete batching plant in middle, and cement silo in left background. 3/16/50.

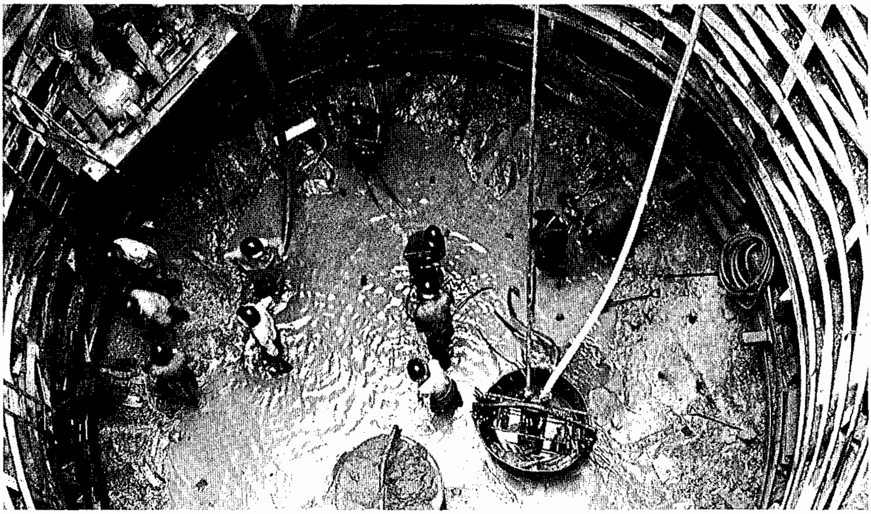

Fig. 22. — Sinking Shaft 7B. Has reached elevation +48 feet. 8/24/48.

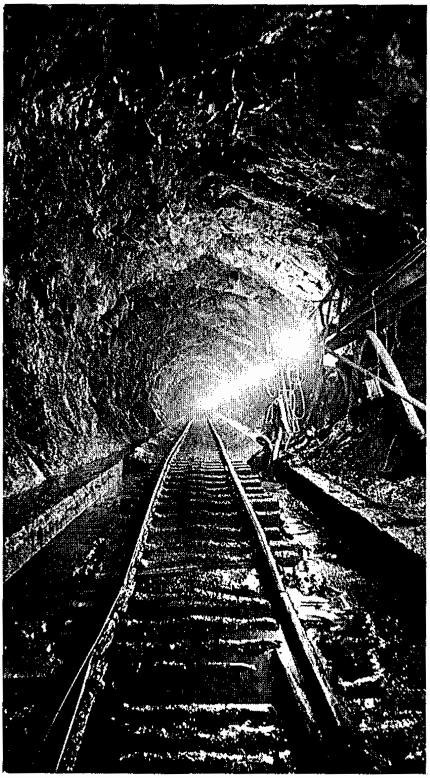

Fig. 23. — View west from station 117 + 50. In the foreground only the concrete curbing has been placed. In the background the invert has also been placed. 3/16/50.

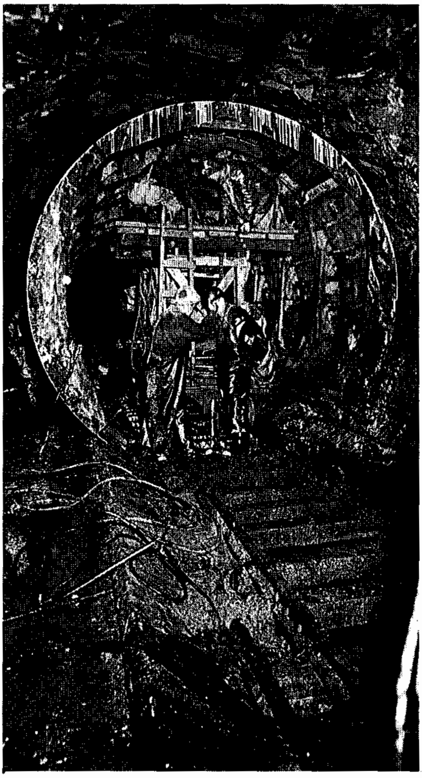

Fig. 24. — View west from station 68 + 30. Concrete curbing and invert show in the foreground. Twelve foot diameter steel form is ready to receive concrete for lining. 3/14/50.

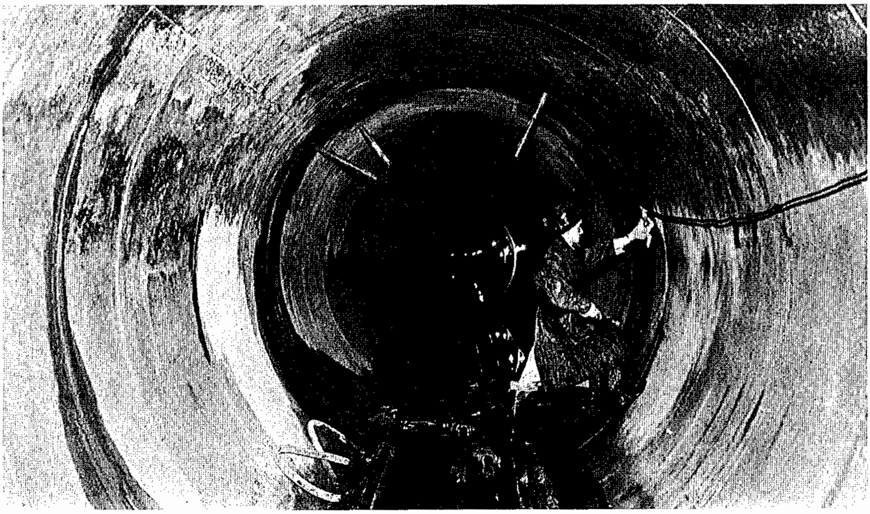

Fig. 25. — Between shafts 7 and 7B, showing concrete lining, which, in this branch tunnel is only 10 feet in diameter. 4/20/49.