THE GEOLOGY OF THE UNCONSOLIDATED SEDIMENTS OF BOSTON HARBOR

by

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B.Sc., McGill University

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ABSTRACT

This thesis describes a geological investigation of the unconsolidated sediments lying beneath Boston Harbor. Pleistocene and Recent sediments lie on an irregular bedrock surface of Cambridge Siltstone. From a study of the literature and various borehole sections on land a generalized stratigraphic sequence is proposed for the Boston Basin. The Pleistocene deposits are all attributed to the Wisconsin stage of the Pleistocene glaciation, which in the Boston area included a minor readvance of the ice during Late Wisconsin time. Related to each ice advance is a sequence of till, with associated outwash, and clay. Investigations in the harbor with the Edgerton 12 k.c. sonar sediment probe show, for the most part, a succession of clay, overlying till and bedrock. This succession is correlated with the deposits laid down by the Late Wisconsin ice sheet. Recent black mud is ubiquitous on the harbor floor.

The results of the S.S.P. work delineate areas of good and poor acoustic penetration. Poor penetration is due to acoustic impenetrability of the Recent black mud by 12 k.c. sound.

An extensive till or bedrock subsurface occurs east of Castle Island whereas in the President Roads area, Pleistocene clay has accumulated to a considerable thickness. In areas where no penetration was obtained, similar clay thicknesses may be present. A bedrock ridge beneath a thin sediment cover has been traced from Hangmans Island to Rainsford Island. A less distinctive bedrock ridge occurs south of Georges Island.

Thesis Supervisor: Ely Mencher
Associate Professor Department of Geology.

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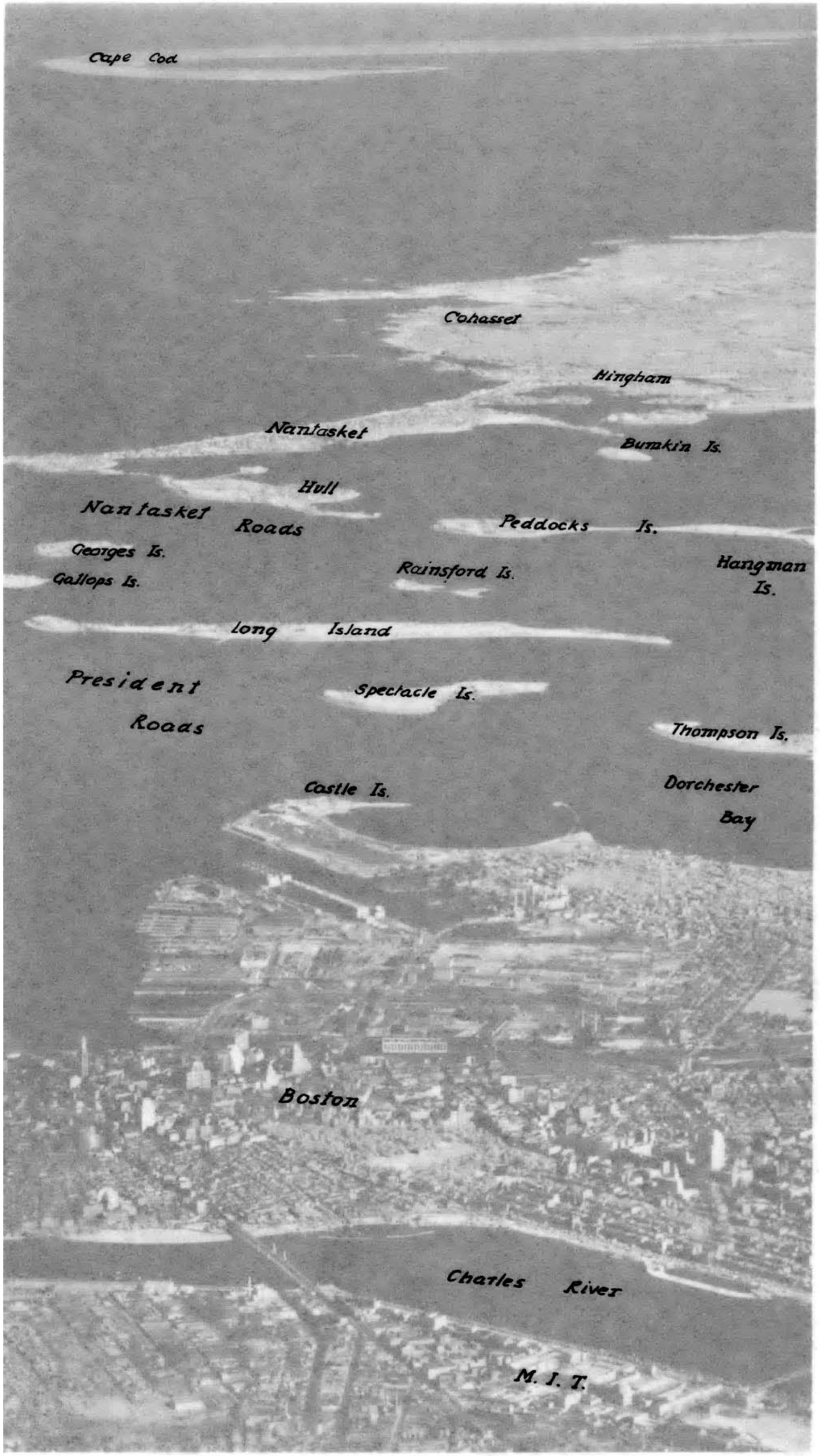

Cape Cod
Cohasset
Hingham
Nantasket
Bumkin Is.
Hull
Nantasket
Roads
Peddocks Is.
Georges Is.
Gallops Is.
Rainsford Is.
Hangman Is.
Long Island
President
Roads
Spectacle Is.
Thompson Is.
Castle Is.
Dorchester
Bay
Boston
Charles River
M. I. T.

THE GEOLOGY OF THE UNCONSOLIDATED SEDIMENTS OF BOSTON HARBOR

1. INTRODUCTION

Several years ago Dr. Harold E. Edgerton of the Department of Electrical Engineering at M.I.T. developed a low frequency "Sonar Sediment Probe" to be used to search for objects of archeological interest buried in sediments beneath water. Results from the instrument clearly showed that good acoustic penetration could be obtained through certain unconsolidated sediments, and that stratification and structures of the sediment was revealed. The usefulness of the sonar probe as a geological tool was soon appreciated.

Professor Edgerton kindly offered to loan the Sonar Sediment Probe (S.S.P.) to the Department of Geology and Geophysics in order to evaluate more precisely the capabilities and limitations of the instrument as a geological tool. In October 1962, a group led by Captain Harold Payson undertook to carry out investigations with the S.S.P. in Boston Harbor and Narraganset Bay. A report of the first phase of the investigation is written up in Payson's Thesis (H.Payson, Jr., S.M.Thesis, M.I.T. 1963, unpublished). The project has now been expanded under the direction of Professor Mencher and Captain Payson, and receives financial aid from the National Science Foundation.

Boston Harbor was selected for the investigations because of its easy accessibility to M.I.T. and because Professor Edgerton's previous surveys in the harbor had indicated areas of good penetration with many sub-bottom features. In addition, the Harbor, which includes many islands, is almost completely surrounded by land on which the geology has generally been well established by conventional mapping and from borehole data, so that interpretation of the S.S.P. records is more easily accomplished by correlation with known land geology. Numerous easily visible landmarks and buoys in the Harbor aid in navigation and location.

Although the general nature of the sediments underlying Boston Harbor can be deduced from surrounding land exposures, the vertical and horizontal distribution and stratigraphic relationships of these sediments have never been investigated on a large scale. The work in the Harbor with the S.S.P. represents the first attempt to present a clear picture of the three dimensional distribution of the sediments.

This thesis covers, primarily, the geological aspects of the S.S.P. work. An excellent description of the S.S.P. and its operation can be found in Captain Payson's thesis and will not be duplicated here.

To evaluate the geological data derived from the S.S.P. records it was essential to obtain all known available information on the surficial geology of the Harbor area. An extensive literature exists, but the topics usually relate to isolated locations. No complete analysis of the surficial geology of the Boston area has yet been written, though at the present time Mr. C. Kaye of the U.S.G.S. is compiling information to prepare a map of the Pleistocene sediments of the Boston area. It is hoped that the off-shore work will supplement his efforts.

Before considering the work carried out in Boston Harbor, a chapter is devoted to a brief description of the Geology of the Boston Basin, with the emphasis on the surficial deposits. This is followed by a description of the field work and the results obtained.

The literature shows considerable diversity of thought on the stratigraphic succession and time sequence among the various surficial deposits of the Boston area. An attempt is made to describe a generalized glacial history of the Boston Basin, based on information gathered from the literature. Associated with the glacial events are definite stratigraphic horizons which occur in sections on land. This knowledge is applied to the resulting sections obtained from the S.S.P. records in an effort to interpret the geology of the sediments beneath Boston Harbor.

It is not the purpose of this thesis to present a complete picture of the geology. This is impossible because there are so many gaps which remain to be filled in. The thesis can be considered as a record of the progress on the geological aspects of the work of the Boston Harbour Group. It will serve to indicate the course of further geological work with the S.S.P. in the Harbor area.

2. GEOLOGY OF THE BOSTON BASIN

The work carried out with the S.S.P. is concerned with the unconsolidated sediments lying above the bedrock. For an understanding of the records it is essential to have a background knowledge of the geological character and history of these deposits and how they are distributed. Although the bedrock is not of direct interest, it is found to outcrop in many places within the harbor area and features on the records. For completeness, a condensed description of the bedrock geology is given.

2.1. Bedrock Geology

The bedrock geology of the Boston Area has been a subject of investigation for over one hundred years, resulting in an abundance of literature on the subject. Several investigators have attempted comprehensive studies of the whole area. In chronological order, these are: W. O. Crosby, who wrote many papers on the subject; Emerson (1917); Billings (1929); LaForge (1932); and finally, Bell (1948). Each author, with additional information available to him, presented an increased understanding of the geology.

The Boston Basin is defined geographically by the low-lying area centered on Boston, and is defined geologically by the extent of the stratigraphic and structural unit of the Paleozoic rocks of the Boston Bay Group. These rocks which appear to be non-marine in origin were deposited unconformably on a surface consisting of Lower Paleozoic metasediments and intrusives. The sequence in the Boston Bay Group is:

Cambridge Siltstone

Squantum Formation

Roxbury Conglomerate

Although the rocks of the Boston Bay Group are usually listed in the sequence on the preceding page, their stratigraphic relationships are not entirely understood. It is possible that the formations were deposited contemporaneously, and represent a facies change from the edge to the center of the sedimentary basin.

The Roxbury Conglomerate and Squantum Formation tend to occupy the periphery and western portions of the Boston Basin, while the Cambridge Siltstone occupies the center and eastern parts of the basin. It is this rock which underlies most of the harbor area. The Cambridge Siltstone is a dark argillaceous rock which has been variously termed slate, argillite and siltstone. Its generally massive nature hardly qualifies it for a slate, and the use of the terms siltstone or argillite is a question of semantics. Siltstone, the term adopted by Bell, will be used here.

The Boston Bay Group rocks were folded at the time of the Appalachian orogeny to form gentle folds, the axes of which strike approximately east-west and plunge gently to the east. Along the southern boundary of the Boston Basin a northward thrusting of blocks resulted in a zone of imbrication. North-south tear faults were also activated. These features are illustrated on the geological sketch map and section of the Boston Basin in figure 1.

The harbor area itself is underlain predominantly by Cambridge Siltstone. The Squantum Formation outcrops at Squantum Head and again on Moon Island,but east of this point there are no known outcrops except those of the Cambridge Siltstone and the basic intrusives which intrude it. This is not including the zone of imbricate structure in the extreme south of the harbor.

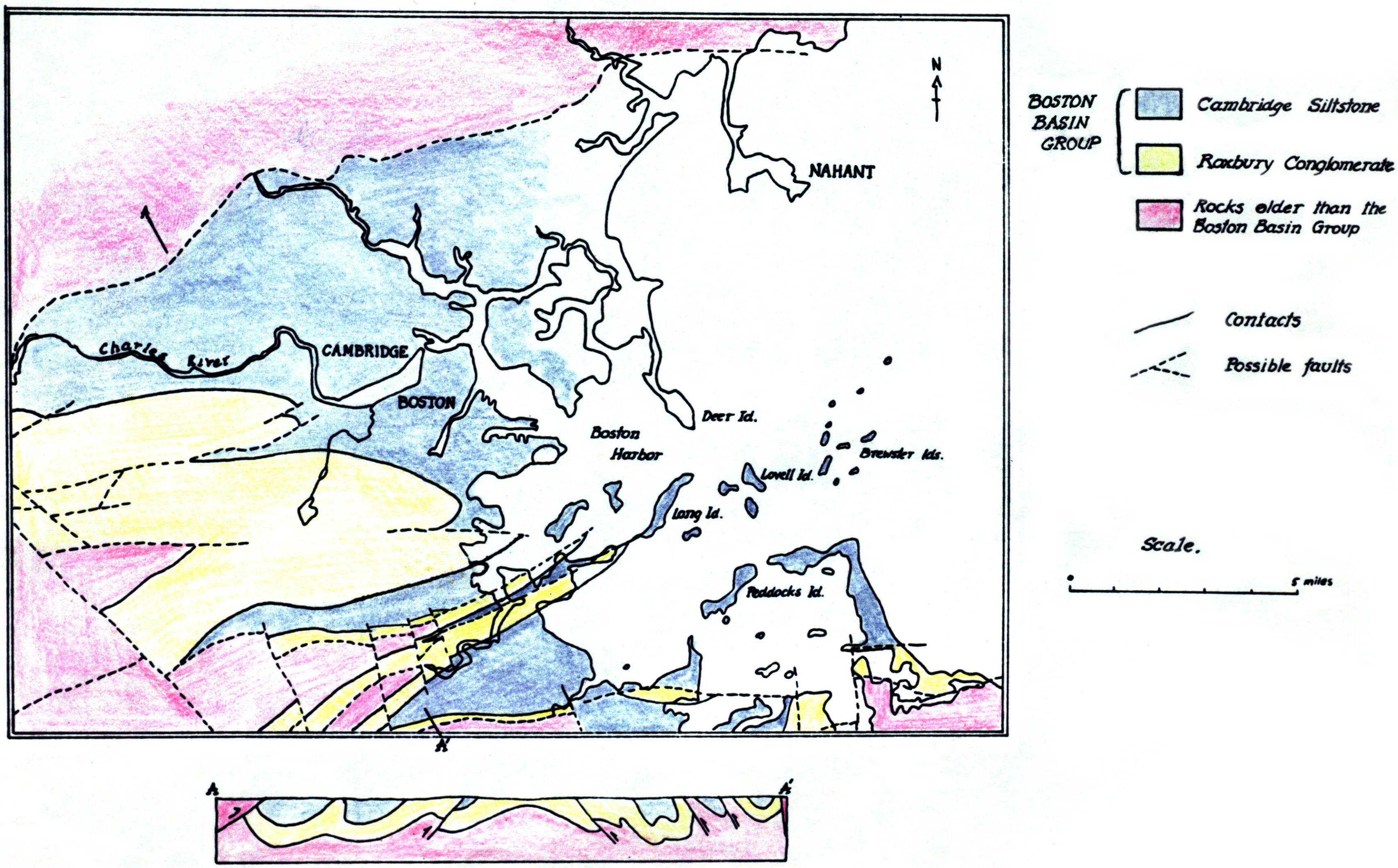


FIG. 1. Geological Sketch Map and Section of the Boston Basin (from LaForge 1932).

Governors Island has a compact grayish-black siltstone outcropping on the western shore of its southern extremity. On Rainsford Island there are outcrops of a similar rock which extend southwards as the Quarantine Rocks. Further south still, Hangmans Island also consists of Cambridge Siltstone, but here it is traversed by numerous fine-grained basic dykes. The Racoon, Slate, and Grape Islands in the southern extremity of the harbor, all have outcrops of the Cambridge Siltstone, generally homogeneous and varying in color from gray to black. (Crosby, 1880) The other islands in the harbor are covered by glacial deposits with drumlins forming the core.

Crosby, in his paper on the geology of the Outer Islands of Boston Harbor (1888), describes the outcrops on the islands and rocks east of Lovell Island. All these islands are rocky except for Great Brewster, which retains its glacial covering. The rock type is consistently Cambridge Siltstone traversed by numerous large and small diabase dikes, showing many intrusive features. Variations in the dip of the siltstone indicate that a synclinal axis passes between Calf Island and the Brewster Islands. This would appear to be an eastward extension of one of the synclinal folds mapped on the mainland, but the distance is too great for confident correlation.

It is obvious that these Outer Islands and many within the harbor owe their existence to the greater resistance of the basic intrusives to erosion, as well as the toughening of the country rock by heat action. There appears to be a factor which localizes the intrusion of the basic rocks, and one might speculate that the intrusives are concentrated at the crests of anticlinal folds due to the weaknesses induced at the crest by folding.

It has been pointed out (Crosby, 1888) that while the drumlins have their long axes in a N.N.W. direction, the long axes of many of the islands and peninsulas are roughly at right angles to this direction; that is, at approximately E.N.E. The drumlins lie along the direction of ice movement while the islands lie along the general bedrock structural trend. Those islands which do not conform to this pattern are the result of the linking of several drumlins by wave-built beaches as, for example, along Nantasket.

There exists a very large gap in the stratigraphic sequence between the final deposition of the Boston Bay Group rocks in the late Paleozoic(?) and the deposition of the Pleistocene glacial deposits. It is frequently thought that in the Boston area continuous erosion was active during the period of the stratigraphic gap, but several references have been made (Crosby, 1903, p. 354; Clapp, 1907) to a gray to white clay of possible Cretaceous age, sometimes encountered below the till, especially in the deeper borings. This clay is unlike the usual clays associated with the glacial deposits and its similarity to other clays of Cretaceous age (Raritan Formation) from Long Island (New York) and Martha's Vineyard, supports the notion that Cretaceous sediments may have been deposited over the Boston area. The presence of Tertiary deposits along many parts of the eastern seaboard of the United States also supports this notion though it is evident that in the Boston area the Tertiary deposits were eroded away, except possibly for some isolated low-lying pockets.

2.1.2. Bedrock Topography

The present bedrock topography is the result of past erosion which

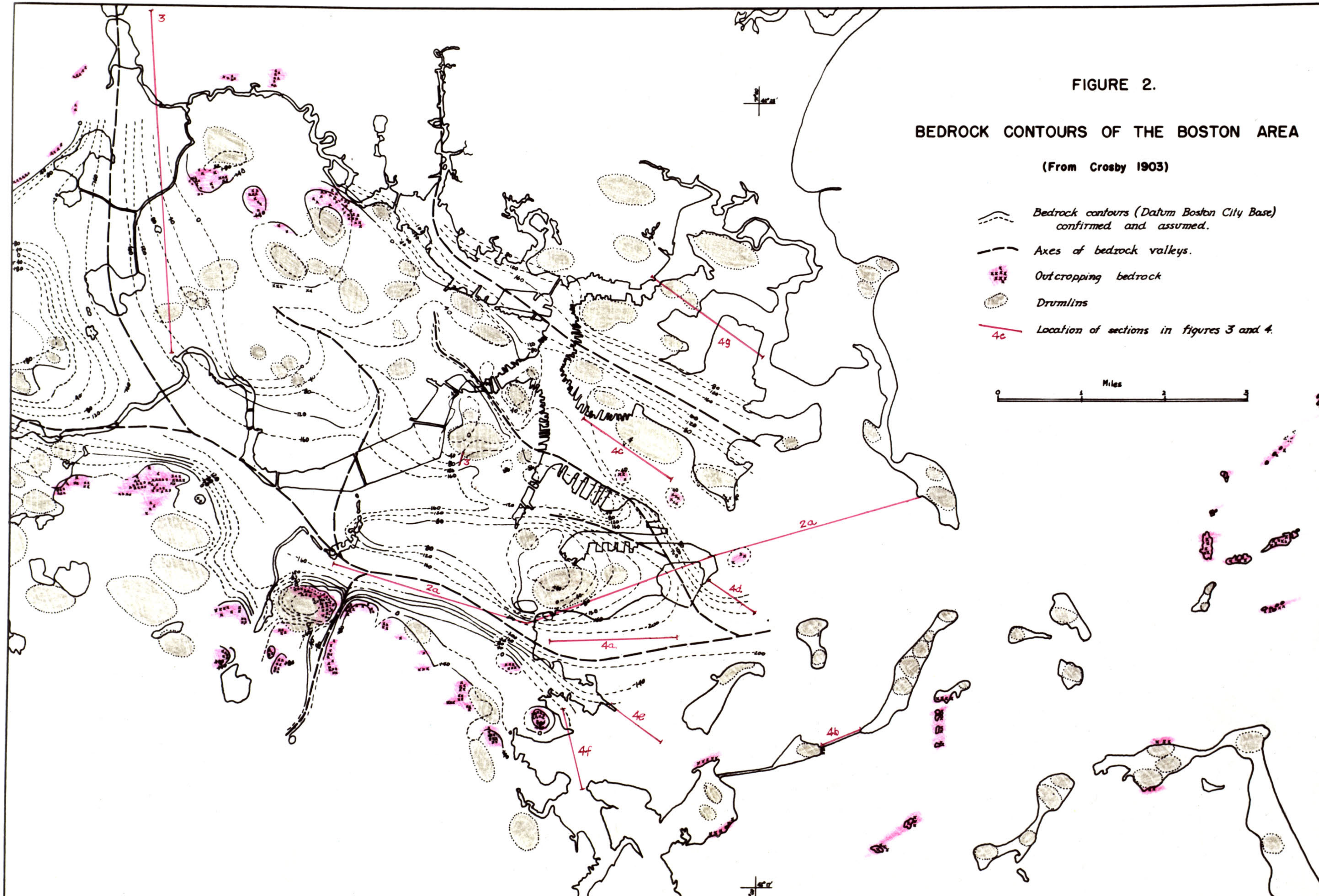


FIGURE 2.
BEDROCK CONTOURS OF THE BOSTON AREA
(From Crosby 1903)
Bedrock contours (Datum Boston City Base) confirmed and assumed.
Axes of bedrock valleys.
Outcropping bedrock
Drumlins
Location of sections in figures 3 and 4.
4c
Miles
0
1
2
3
2a
4a
4b
4c
4d
4e
4f
4g

was active from the end of the Paleozoic, when the Boston Bay Group rocks elevated. As mentioned, it is possible that Cretaceous beds were deposited unconformably on this erosion surface, but, if so, they were subsequently completely removed, and the area was eroded further until the end of the Pleistocene glaciation. No doubt the lowering of sea level, which accompanied the growth of the Pleistocene ice cap, and the powerful action during the glaciation of the area, gave the last emphasis to the bedrock topography. The infilling by glacial deposits of irregularities in the bedrock surface resulted in a modified topography which bears little relationship to the bedrock configuration.

The bedrock topography can be determined from outcrops, boring data, and by geophysical methods. It is frequently accepted that drumlins form around rock obstructions, but this is an over-generalization, and may frequently prove to be not so, as can be seen on Spectacle Island where bedrock is at a depth of greater than 360 ft. (Crosby, 1903, p. 354). The bedrock contour map of fig. 2 indicates where outcrops occur and these form a good starting point for plotting the bedrock surface. Much of the boring done around Boston has been compiled in the publication of the Boston Society of Civil Engineers (1949-50, 1951, 1953, 1954, 1956) under the title of "Boring Data of Greater Boston". The logs of the holes were made for engineering purposes so that the data are usually not so specific as a geologist would require. The area covered by these data is restricted predominantly to the mainland which results in information only for the western end of the harbor. Unfortunately, many of the holes do not reach bedrock, but from those that do, it is possible to obtain a fairly general picture of the bedrock topography.

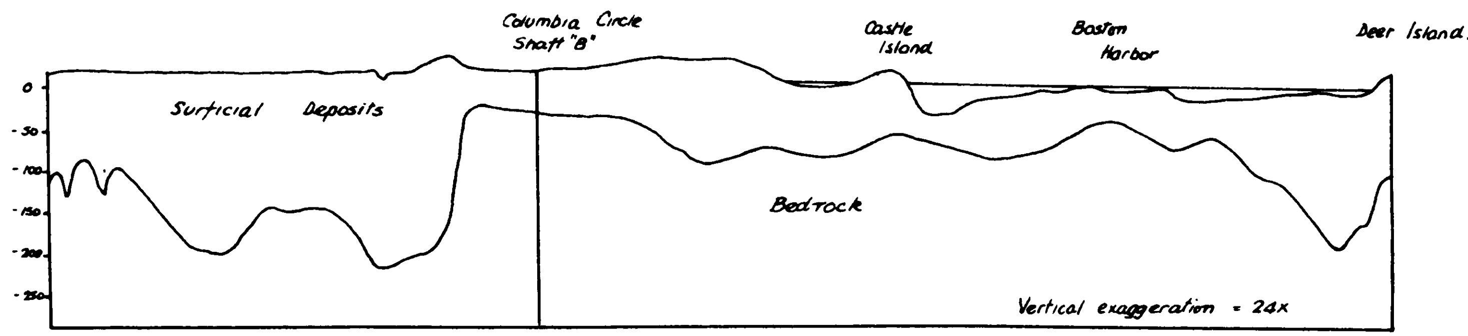


FIG. 2a Bedrock surface along the line of the Boston Main Drainage Tunnel.

The U.S. Geological Survey office in Boston is in the process of compiling data, under the direction of Mr. C. A. Kaye, for the plotting of bedrock contours in the Boston area, and it is hoped that this will be supplemented with depths of bedrock under the harbor obtained by geophysical methods such as the S.S.P.

Other sources of data include the Metropolitan Development Commission which has carried out borings in the harbor in connection with their projects such as the Deer Island sewer tunnel.

In addition to the work with the S.S.P., geophysical probing for bedrock has been carried out,using the seismic method, on Governors Island (Lee, 1942), and along the line Columbia Circle - Castle Island - Deer Island (Linehan, 1956). The bedrock profile obtained by Linehan was later checked by a series of borings along the line (fig. 2a).

An attempt was made by W.O. Crosby (1903) to draw a contour map of the bedrock topography, but with the scant information available to him at the time, only the broad features can be considered as correct. (Fig. 2.) The map indicates the locations of the deeper bedrock valleys, these being the courses of the pre-Pleistocene drainage system. It is evident that these courses differ from the present-day courses.

The deepest identified bedrock valley of the Boston area, known as the Fresh Pond buried valley, has been traced (Chute, 1959) from the town of Wilmington southwards along a line passing through Mishawum Lake, the Mystic Lakes and Fresh Pond. It then turns southeastwards to pass around the south of South Boston and thence eastwards into the harbor, where its course has not yet been traced. The pre-glacial course of the Charles River formed a tributary of the Fresh Pond buried valley, and at that time the

Charles did not follow its present course east of Boston University Bridge. W. O. Crosby (1899, p. 302) speculated that the Fresh Pond buried valley was the pre-glacial course of the Merrimack River, but several authors (LaForge, 1932, p. 79; I.B.Crosby, 1939, p. 376; Chute, 1959, p.190) have expressed their doubts concerning this suggestion. Whatever the case, our main concern is that these bedrock valleys do exist and pass eastwards into the harbor area.

Profiles across the Fresh Pond buried valley (Chute, 1959, pl.15) show that there is an inner gorge cut 60 to 90 feet into the floor of an older, broader bedrock valley, the floor of which lies at about 80 feet below sea level. In places the valley is so narrow that only the younger inner gorge exists as is shown in sections across Upper Mystic Lake. Other sections drawn by Chute show the bedrock valley as deep as 270 feet below sea level. Nearer the harbor, borings along the Castle Island-Columbia Circle line show the depth of the bedrock valley to be greater than 200 feet.

Other bedrock valleys enter the harbor area, and when instruments are available for probing to depths greater than 100 feet through the sediments it will be of great value to trace these valleys, as well as the Fresh Pond valley, into the harbor and beyond. With the S.S.P. the maximum depth of penetration that can be represented on the paper of the recorder is approximately 80 feet so that only bedrock at shallower depths can be detected. The bedrock topography of the harbor area, in the light of the S.S.P. work will be considered in the discussion section.

2.2. Surficial Geology

The surficial deposits include the unconsolidated sediments covering the bedrock, and it is with these deposits that we are primarily concerned in the S.S.P. work. A broad division of the surficial sediments into Pleistocene and Recent can be made, the former deposits being a product of glaciation.

2.2.1. Pleistocene Deposits

In North America and elsewhere it has been established that the Pleistocene glaciation consisted of four stages of advancing ice, separated by three interglacial periods when conditions were warmer and the ice receded. Some sections in North America present a complete stratigraphic record of the sequence of events during the Pleistocene, showing four layers of drift separated by soils and peats formed during the warmer interglacial periods. Generally, the section is not complete because later glaciations obliterated the evidences left by previous glaciations. In New England the last glaciation, the Wisconsin, was the most extensive, its southern limit being marked by the terminal moraine of Long Island. In the Boston Basin the existence of Wisconsin glacial deposits is evident, but the presence of deposits from the earlier glaciations, if they did extend this far south at all, is not easy to determine.

A sure criterion for the recognition of earlier glacial deposits is the presence of till with an upper oxidized or weathered zone on which lies a fossil soil, possibly with plant remains. Interglacial periods may also be distinguished by the presence of considerable thicknesses of clay, deposited by glacial streams as the ice retreated. Both the evidences mentioned above may be obliterated by ensuing glaciations. Another complication is the occurrence of glacial substages which are minor readvances of the ice front during the general retreat of the ice. Such substages have been recognized in the Boston area by Judson (1949) and Chute (1959, p.197).

In the Boston area, borings and excavations have exposed many sections of the Pleistocene deposits so that they can be studied in detail. However, local variations in stratigraphic sequence have led to different interpretations of the glacial history of the Boston Basin.

The glacial deposits consist of till, sands and gravels, and fine clays. The till, also known as unmodified drift or boulder clay, occurs as various moraines (ground and end moraines) and as drumlins which form a distinctive topographic feature of the Boston Basin. The till is an admixture of rock particles varying in size from boulders as much as two feet in diameter to the finest clay particles. The till appears as boulders, cobbles and pebbles embedded in a fine clay matrix. A grain size analysis from an average of sixteen samples (W.O. Crosby, 1890) gave: gravel 24.9%, sand 19.51%, clay 55.53% (with the clay fraction consisting of 43.86% rock flour and 11.67% true clay mineral). The rock flour is extremely fine quartz. Crosby doubted if cobbles and boulders greater than two inches in diameter make up more than 10 or 20% of the till.

In some sections several layers of drift, separated by glacial clays, sands and gravels have been identified (Kaye, 1961; Chute, 1959); but more frequently in the Boston area, especially in the low-lying areas, only one layer of till is seen, lying directly on bedrock and sometimes piling up to form drumlins. The distribution of the drumlins is given in figure 2. The long axes of the drumlins are oriented roughly in a S.S.E. direction, this being also the direction of ice movement. The majority of the islands in the harbor consist of a drumlin core, and it is probably correct to assume that the till forming the drumlins also extends in a sheet under the harbor.

Evidence of pre-existing drumlin islands in the harbor which have been destroyed by wave and current action is the presence of abundant boulders on the harbor bottom (Curtis, 1910). The winnowing action of currents has removed the finer material leaving the coarse cobbles and boulders. W.O. Crosby (1903, opp.p.359) shows Bird Island Flats, lying between the Camp Hill and Governors Island drumlins, as being a denuded drumlin. Many drumlins in the harbor present steep cliff faces to the shore which is evidence of their seaward erosion.

The sands and gravels have a very erratic distribution. The deposits are small, irregular and local in extent, but the more distinctive occur as eskers, kames and outwash fans which are generally found around the periphery of the basin or associated with drumlins within the basin.

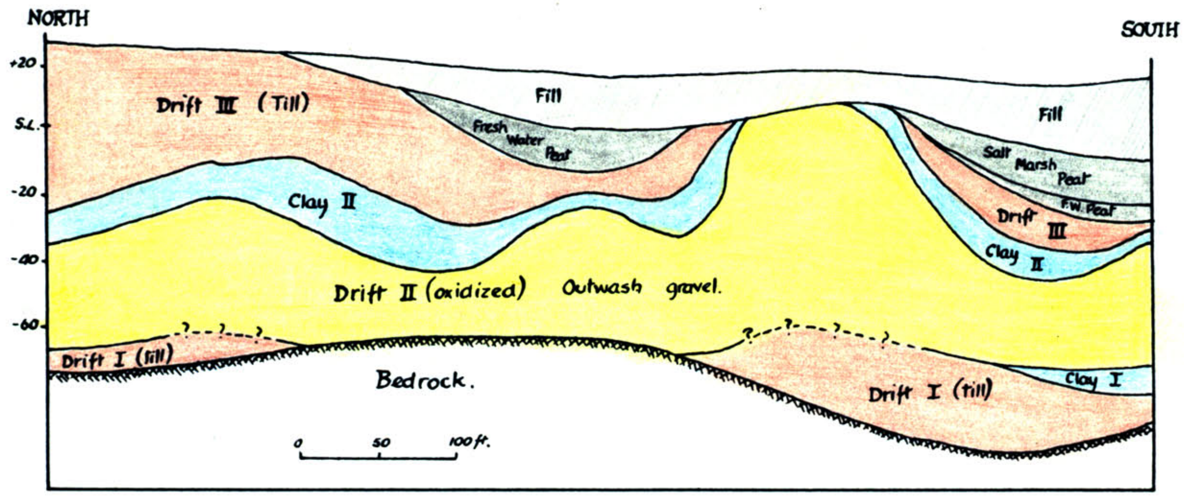
Kaye (1961) has recognized in the Boston Common section (Fig. 3) three horizons of fine plastic glacial clay separated by drift. During the retreat of an ice sheet a great amount of sediment is released from the ice and is carried down by glacial streams to be deposited in a sedimentary basin. The coarser material is deposited around the edge of the basin, while the clay-size fraction is transported further and deposited more towards the center of the basin. The clay horizons recognized by Kaye each represent a period of retreating ice with rapid deposition of clay in standing water. The clays are very similar to each other (Kaye, 1961) and are virtually indistinguishable in the field. They have a blue-gray to slightly greenish-gray color when unoxidized; oxidized they become yellow-brown. The fresh clays are tough and plastic but contain a large proportion of extremely fine quartz. Layers of sand and/or silt, varying in thickness from less than one inch to more than one foot, occur in the clays and appear to be rhythmically deposited, but on too coarse a scale to be classified as varves. The sandy layers represent deposition under more turbulent conditions, but the reason for the periodic nature of the turbulence is unknown. Small oscillations in the level of the standing water could result in periodic turbulence. In the S.S.P. work the sandy layers are a useful feature because they give a very characteristic banded pattern on the records (fig.7). Sparse cobbles and small stones embedded in the clay suggest ice rafting.

Various opinions have been given as to the marine or non-marine origin of the clays. W.O. Crosby (1903, p.362), considered it to be deposited in a fresh-water glacial lake which he called Lake Shawmut. He assumed that the eastward flowing glacial streams were dammed by a great mass of ice located to the east of Boston and that the clays were deposited in the lake so formed. Noting the absence of varves in the clay of Cambridge, Hörner (1929, p.130) thought the clays to be deposited in an arm of the sea. Stetson and Parker (1942, p.42) reported foraminifera in the clay from the Back Bay district of Boston and Kaye (1961) found marine mollusks in the uppermost clay at West Lynn at the north edge of the Boston Basin. All these indications point to a marine origin of the clay.

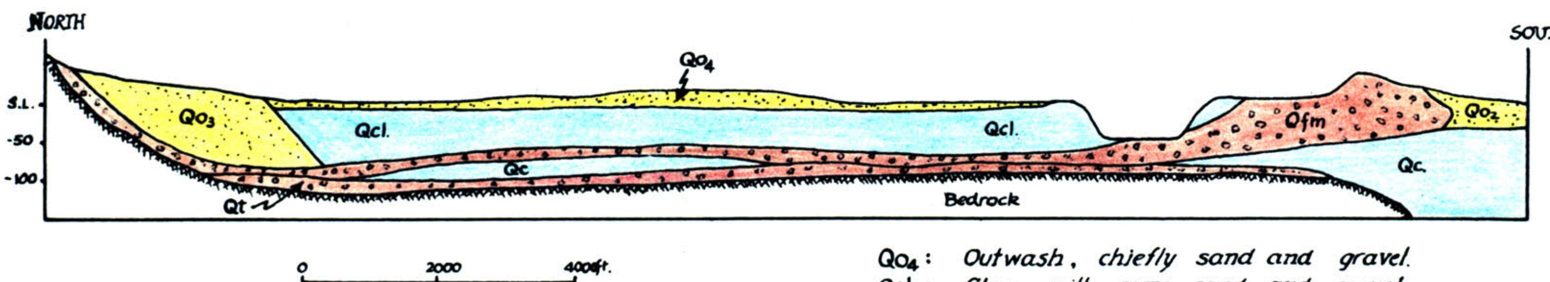
There has been much discussion concerning whether the drift overlies the clay or vice-versa (Brown, 1902; I.B. Crosby, 1934). As indicated above, the Pleistocene stratigraphy includes more than one drift horizon and more than one clay horizon, and in any discussion on the relationships between drift and clay it is essential to state specifically which horizons are being considered.

The most informative and stratigraphically complete sections of the Pleistocene deposits in the Boston Basin available in the literature are those by Chute (1959) and Kaye (1961) which are illustrated in figure 3. Such complete sections are the exception and not the rule. Kaye identifies four layers of drift separated by three clay horizons at the Boston Common. The uppermost clay and drift horizons are not represented on this particular section. Drift I is a typical ground moraine which is overlain either by Clay I or directly by Drift II which is mostly gravelly outwash and is oxidized throughout. Drift II is overlain by Clay II, a fresh unoxidized clay which is in turn overlain by Drift III. The latter is the drift which forms most of the drumlins in the Boston area and frequently contains fossil shells. In other sections this drift has been shown to be oxidized to a depth of 65 feet, though in this section the oxidation only extends 25 feet down. Clay III is the clay usually exposed in excavations and shallow borings, and it is frequently found to be oxidized in its upper portions (See figure 4b). Drift IV occurs intermittently over Clay III as outwash gravels which Kaye correlates with the "poorly compacted and barely oxidized tills that are found with patchy distribution on the uplands surrounding the Boston Basin." These represent the final advance of the ice over the area.

Kaye ascribes Drift I to the Kansan or Nebraskan stage, Drift II to the Illinoian stage, Drift III to the Early Wisconsin or Iowan substage, and Drift IV to the Late Wisconsin or Lexington substage (Judson, 1949). The local absence of some sections of the sequence is due to the erosion by later ice.



Boston Common Section (from Kaye, 1961.)



Mystic Lakes — Fresh Pond Section.

(from Chute, 1959.)

Qo4 : *Outwash, chiefly sand and gravel.*
Qcl : *Clay, with some sand and gravel.*
Qo3 : *Outwash, chiefly sand and gravel.*
Qfm : *Till, Fresh Pond moraine and associated ground moraine*
Qc : *Clay, with some interbedded sand and gravel.*
Qo1 : *Outwash, chiefly sand and gravel. (Not represented)*
Qt : *Till, ground moraine.*

FIG. 3.

Chute's section is located in the Mystic Lakes-Fresh Pond area, about five miles northwest of Boston Common. The elevations of the two sections are approximately the same. Chute finds roughly the same sequence as Kaye but ascribes all the sediments to the Wisconsin stage, probably on the basis that there are no substantial weathering zones present in his section. If the Clay I of the Boston Common section is considered to be a clayey phase of the outwashed gravel of Drift II, the two sections become completely compatible, except that Chute records outwash lying above his second layer of till. A correlation between the two sections is:

<u>Kaye</u> (Boston Common)	<u>Chute</u> (Mystic Lakes-Fresh Pond)
Drift IV. Mostly outwash.	Qo_4. Outwash, chiefly sand and gravel.
Clay III. Clay, sometimes oxidized in upper portions.	Qcl. Clay containing some sand and gravel. Qo_2 and Qo_3. Outwash, chiefly sand and gravel.
Drift III. The drumlin till, with upper portions oxidized.	Qfm. Till, Fresh Pond moraine and associated ground moraine.
Clay II. Clay.	Qc. Clay containing some interbedded sand and gravel.
Drift II. and Clay I. Mostly gravelly outwash with some associated till and clay oxidized throughout.	Qo_1. Outwash, chiefly sand and gravel.
Drift I. Compact till.	Qt. Till, ground moraine.

- Bedrock -

Fossil mollusks have been found in Drift III (W.O. Crosby and Ballard, 1894: Morse, 1920) and are assumed to be derived from Clay II by incorporation of the clay in advancing ice and then deposition with the till. A similar situation exists in the Fresh Pond area where the Fresh Pond moraine, a very clayey moraine, is believed to be partly derived from the underlying clay horizon, but in this case the clays are devoid of macrofossils. This conflicts with the proposed origin of the fossils in the till unless one assumes localized shelly beds near the top of the original clay.

Clay III (also Qcl.) is the topmost clay and the one most commonly seen in clay pits, excavations and borings. It is also the thickest and most extensive of the clays. Folding in the clay has been noted (Shaler, Woodworth and Marbut, 1896, pp. 990, 995; Brown, 1902) and is thought by some to be due to dragging by an overriding ice sheet which deposited the drift sometimes found overlying the clay, i.e. the Drift IV of Kaye. But Chute considers this drift as outwash deposits (1959, p.207) and not as a glacial till, thus excluding the theory of folding by overriding ice. He explains the folds as being due to drag of grounded icebergs, sliding of clay deposited in unstable positions, and impact of large ice-rafted boulders. Another possible cause is the differential compaction of the clay over an uneven surface.

Triaxial compression tests carried out on the Boston blue clay show that it is precompressed, i.e. it was subjected to loads greater than those exerted upon it at present (Taylor, 1948, fig.10.13a). This precompression could be due to a load of glacial ice, as suggested by Kaye(1961), but it could also be due to the load of overlying portions of the clay which have since been eroded away.

The uppermost clay is frequently weathered to depths of up to ten feet indicating its exposure to subaerial weathering. Erosion channels in the clay surface show the effects of erosion before deposition of the recent sediments.

From the sections discussed above it is possible to deduce the events taking place during the glaciation of the Boston Basin. A sequence compatible with the available knowledge is as follows:

i). Advance of ice front and deposition of ground moraine.

ii). Retreat of ice front and local deposition of outwash sands, gravels, and clays. Local oxidation of outwash followed by widespread deposition of clay, with minor interbedded sand and gravel, in ponded water or a marine embayment.

iii). Readvance of ice front and deposition of second till layer of which the upper part may be oxidized.

iv). Retreat of ice front and local deposition of sands and gravels followed by widespread deposition of clay, with minor interbedded sand and gravel or marine embayment.

v). Possible readvance of ice but more probably a widespread deposition of outwash sands and gravels derived from the erosion of accumulations of drift.

Subsequently the land was elevated in post-glacial times and erosion became active and frequently extended well into the uppermost clays.

The readvance of the ice front in event (iii) is considered to be a minor local incursion of the ice and is not to be confused with one of the major glacial stages.

From borehole data, sections located in and around Boston Harbor have been drawn (fig.4). Generally, the stratigraphic sequence is simple

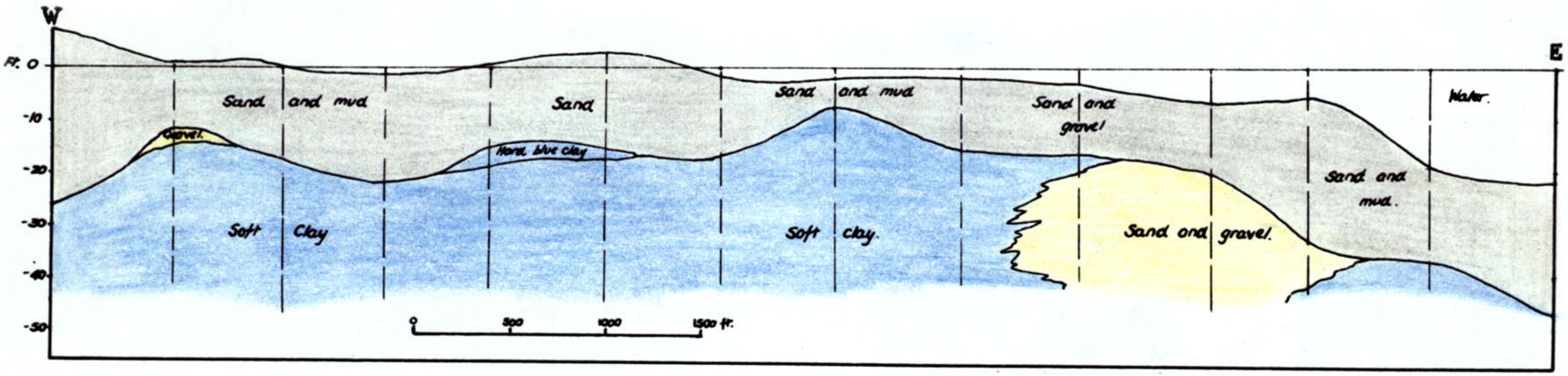


FIG. 4a : Section in Dorchester Bay from Old Harbor towards Thompson Island.

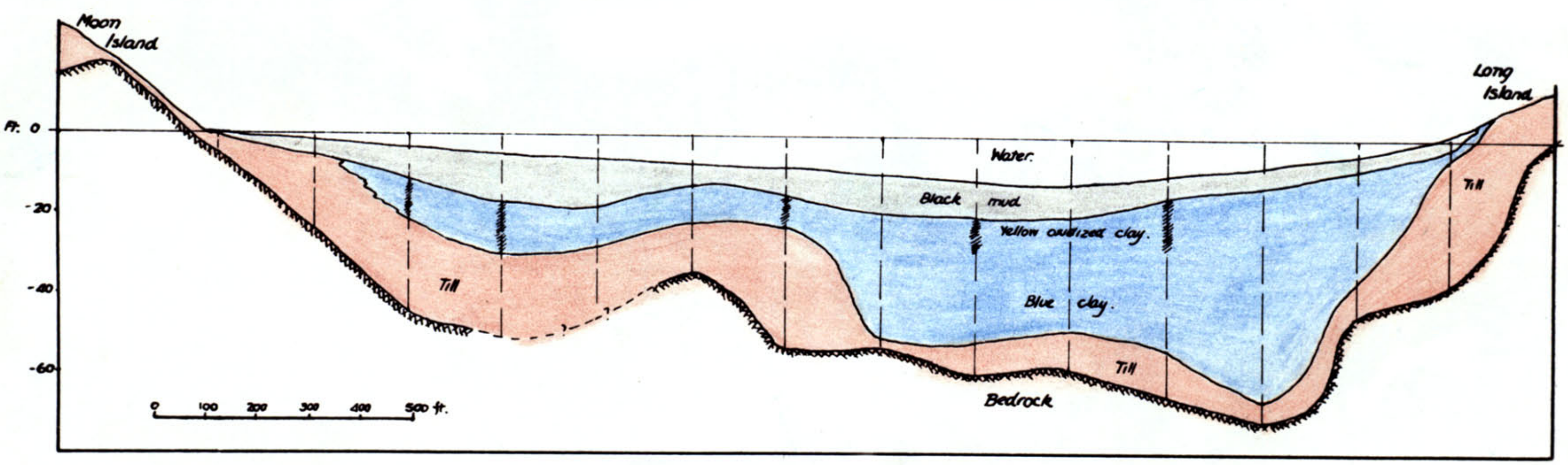


FIG. 4b. Section along Causeway from Moon Island to Long Island.

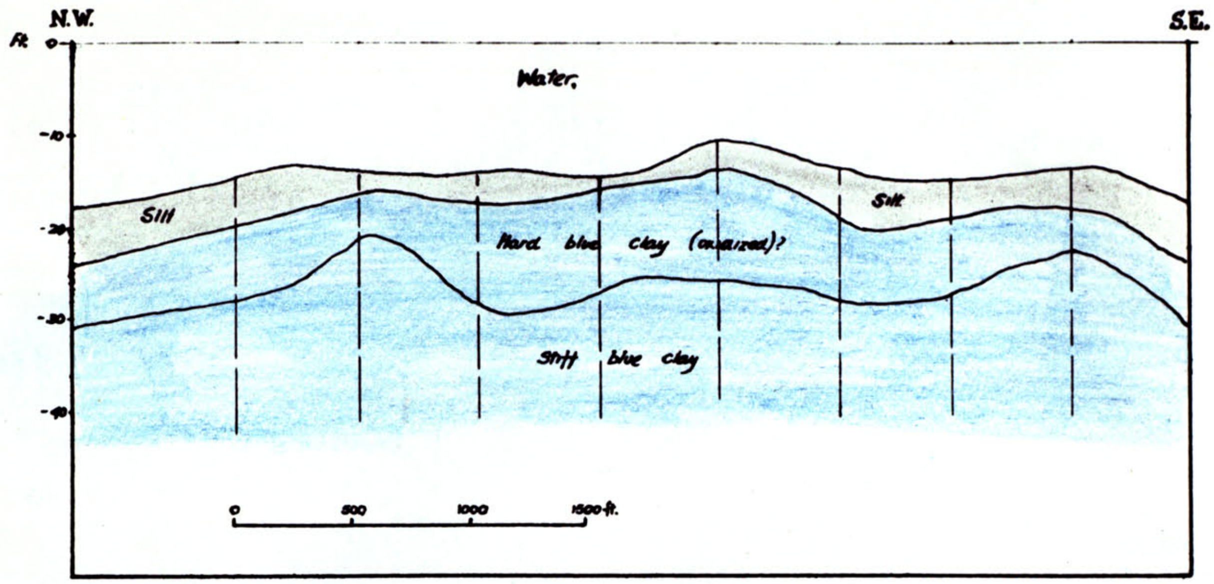


FIG. 4c. Section southwest of Bird Island Flats.

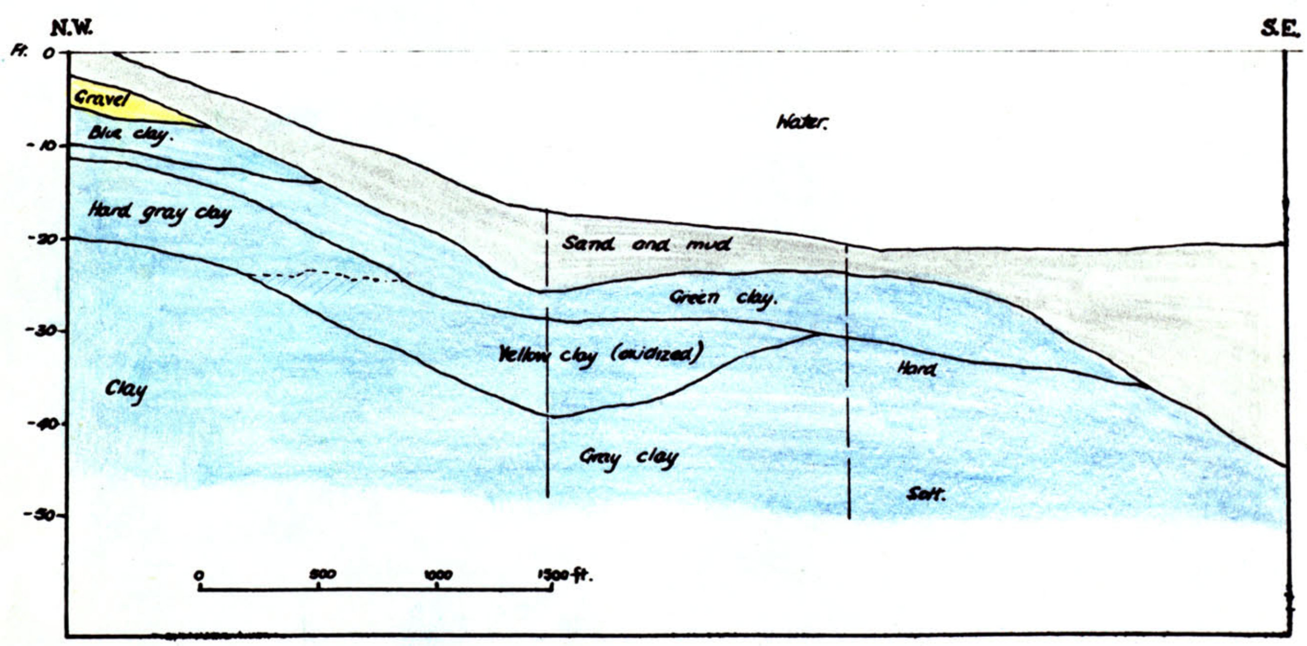


FIG. 4d. Section extending southeastwards from Castle Island.

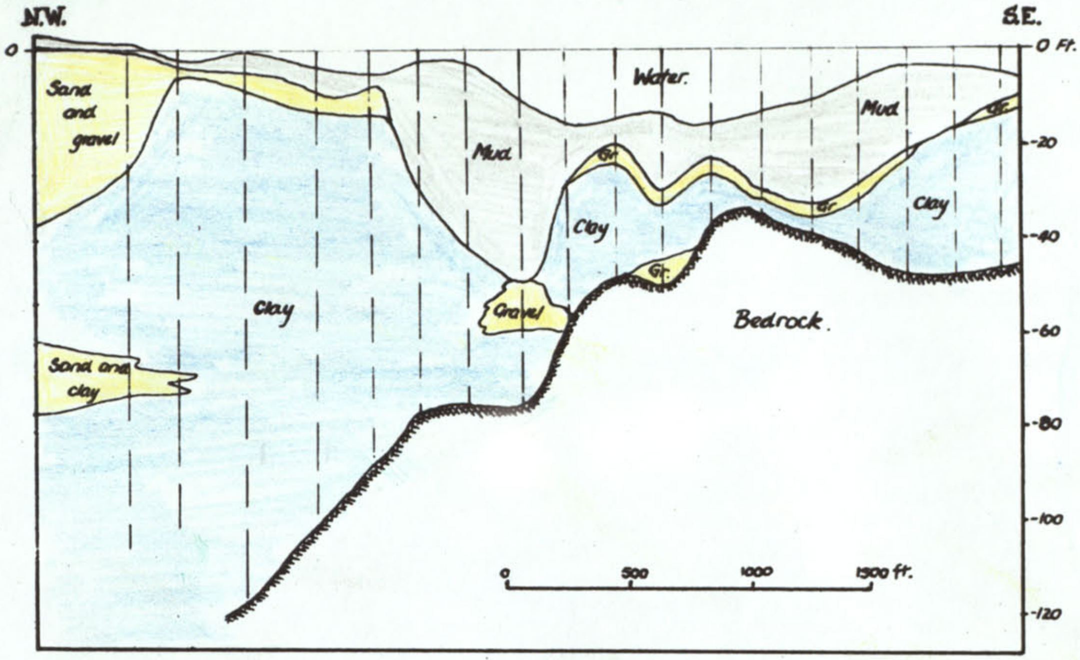


FIG. 4e. Section in Dorchester Bay; Mt Vernon to Thimble Is..

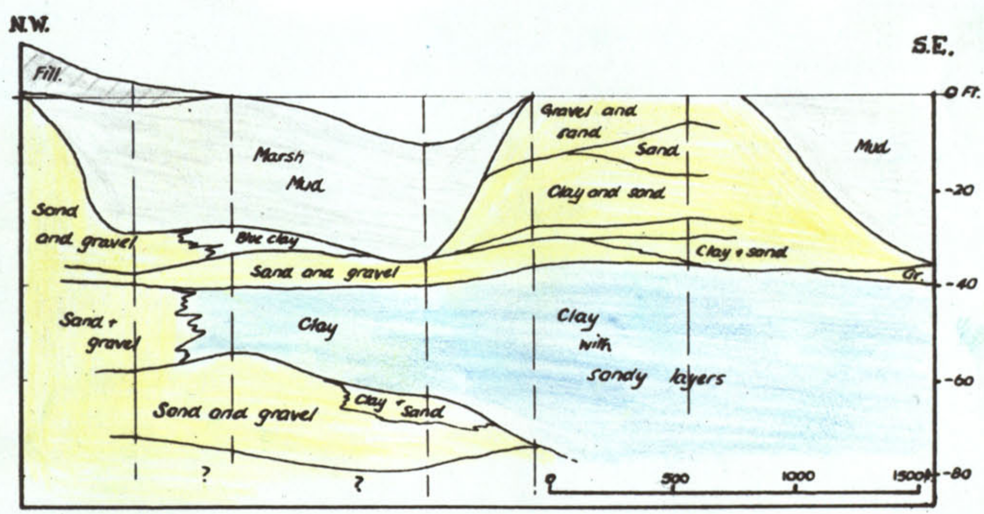


FIG. 4f. Section through Fox Point to Squantum Point.

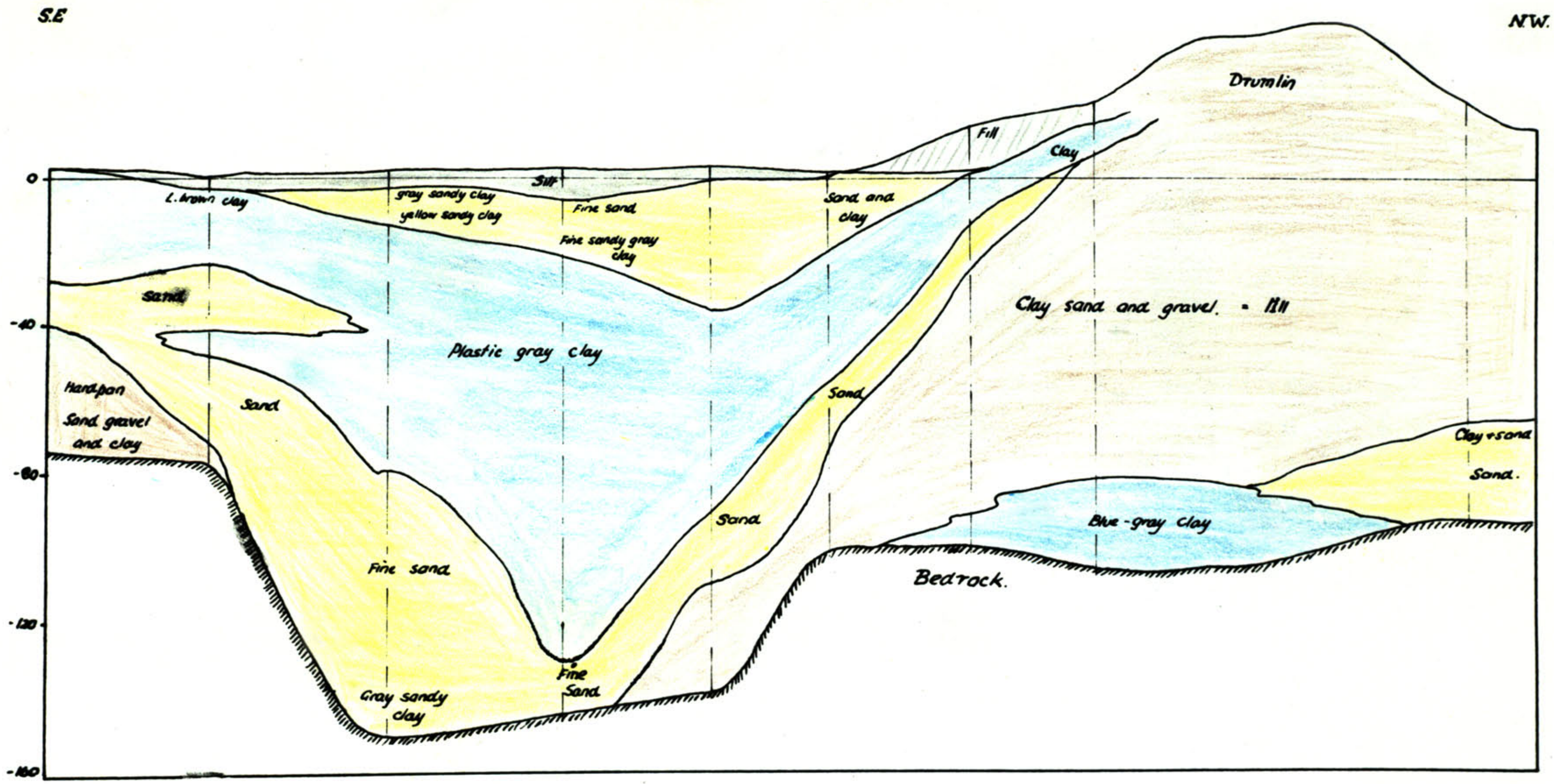


FIG. 4g N.W.-S.E. Section across the northern part of Logan Airport.

with an ascending succession of bedrock, till, clay and black mud (figs. 4a, b,c and d), but in the vicinity of drumlins outwash, deposits. cause intricate and complex relationships (figs. 4e, f and g). In the sections the underlying till and the clay above it correspond to events (iii) and (iv), the deposits events (i) and (ii) having been obliterated by the second advance of the ice.

2.2.2. Recent Sediments.

After the exposure and erosion of the upper clay, sea level rose and recent sedimentation commenced. Sections through the post-glacial deposits in the Back Bay district of Boston have been described by Shimer (1915). Similar sections can be seen in many building excavations in and around Boston.

As the land sank relative to sea level, first fresh water peats and then salt water peats were formed. Further subsidence resulted in flooding of the land and the peats became overlain by black silty sediments similar to those now being deposited in the harbor. In certain horizons the black silt contains many fossils, mainly mollusks. Many of the same species are living today but exist in waters warmer than those of Boston Harbor today. Shimer (1915) has characterized this faunal assemblage as the "Virginian fauna". Hence the post-glacial climate was warmer than that experienced today. Oyster beds existed in historical time, but interference with their habitat by severe climate, damming, pollution and filling has exterminated them. The oysters lived on mudbanks of the tidal estuaries around the harbor, and the remains of these shelly banks may be encountered, for example, a few inches below the black silt in the Charles River opposite M.I.T. (Payson, 1963, unpublished S.M. Thesis, figs. 10, 11, 12).

One has only to look at the old maps of Boston to appreciate the great amount of infilling carried out by man. This is the latest deposit of the Recent sedimentation.

Today, the rate of sedimentation in Boston Harbor is very slow. Very little material is contributed by the rivers flowing into the harbor, the bulk of the material being derived from erosion of the islands and shore line of the harbor (W.O. Crosby, 1903, p.366). Although several drumlin islands have been completely reduced to sea level by erosion, the sheltered aspect of the harbor prevents any rapid erosion by wave action.

3. FIELD WORK.

To evaluate the capabilities of the S.S.P. several traverses were made by Professor Edgerton and Captain Payson in Boston Harbor and elsewhere. No special effort was made to record the exact position of the runs in this preliminary work. Later, accurately plotted courses were run so that the information obtained could be plotted and compiled on a map. These traverses were made in Boston Harbor during the fall of 1963 and in the following spring. Figure 14. illustrates their locations.

The instrument has been adequately described by Payson (S.M. Thesis M.I.T. 1963, unpublished). Proper adjustment of the variables according to different situations is essential in order to obtain maximum information from the instrument. These variables include the gain, the pulse length and the pulse power which can be varied in many combinations to produce maximum information.

The vessels used were the "Coleen", a small launch belonging to the M.I.T. Sailing Pavilion, and the "Kathy", a forty-foot lobster boat with ample deck space. The "Coleen", although somewhat cramped, was found adequate for work in the harbor during calm days but became unsafe if any sea was running.

Traverses were mapped out along lines between buoys or along sightings to prominent landmarks. The speed of the vessel was maintained as constant as possible at approximately two knots, so that by knowing the time of start and finish of a particular line, the location of any part of the S.S.P. record could be determined. To check the position of the vessel while on a traverse, fixes were made whenever possible by referring to landmarks. Notes made directly on the S.S.P. record also aided in accurate positioning. Inaccuracies in plotting of course are involved due to the drift effects of tidal currents which are very strong at certain times. Occasionally it is impossible to maintain a straight-line course, as when going around islands, and in these cases only approximate tracks can be determined.

Bottom samples were taken using a Phleger gravity corer. The necessity of having to stop in the middle of a traverse to take samples complicates position-keeping, and it is probably better to complete a traverse and then return to selected spots for samples.

From borings around the periphery of the harbor it is possible to draw stratigraphic sections which are illustrated in figures 4a to 4g. Some of the section lines extend into the harbor and the first plan was to run traverses with the S.S.P. over these section lines to see how the records obtained compared with the sections drawn. For the most part this was unsuccessful, because the traverses were usually in shallow water and/or the bottom covered with the acoustically impenetrable black mud so that there was little or no penetration.

From the navigation chart of Boston Harbor (scale 1:25,000) a 1:12,500 scale base map was produced. Traverse lines were plotted on this map and the data from the S.S.P. records added in the form of fence diagrams (see fig.14). Also plotted on the map are the locations of the sections drawn in figures 4a to 4g, the distribution of drumlins and some bedrock elevations.

To a first approximation the width of the record paper of the S.S.P. is equivalent to about 80 feet depth in water. Corrections for variations of the velocity of sound in the sediments cannot be made unless these velocities are determined. It has been shown, using ultrasonics, that the velocity in some samples of deep-sea sediments and in Boston blue clay differs very little from that in water (F.V. Lawrence, personal communication). Contrary to the usual supposition that sound velocity increases from water to sediments, Fry and Raitt (1961) have shown that, for some upper layers of deep-sea sediments in the Pacific, the sound velocity decreases. It appears that for the purpose of this work it is safe to assume a constant sound velocity in both water and sediment because there are other far greater inaccuracies involved. In the plotting of the data the state of the tide was not taken into consideration. With a mean average tide range of approximately ten feet this will introduce an error of up to ten feet relative to Boston City base which is taken as mean low water.

4. CHARACTERISTICS OF THE RECORDS.

In descending order the records may show, depending on the penetration, the following features: (a) bottom configuration, (b) top layer

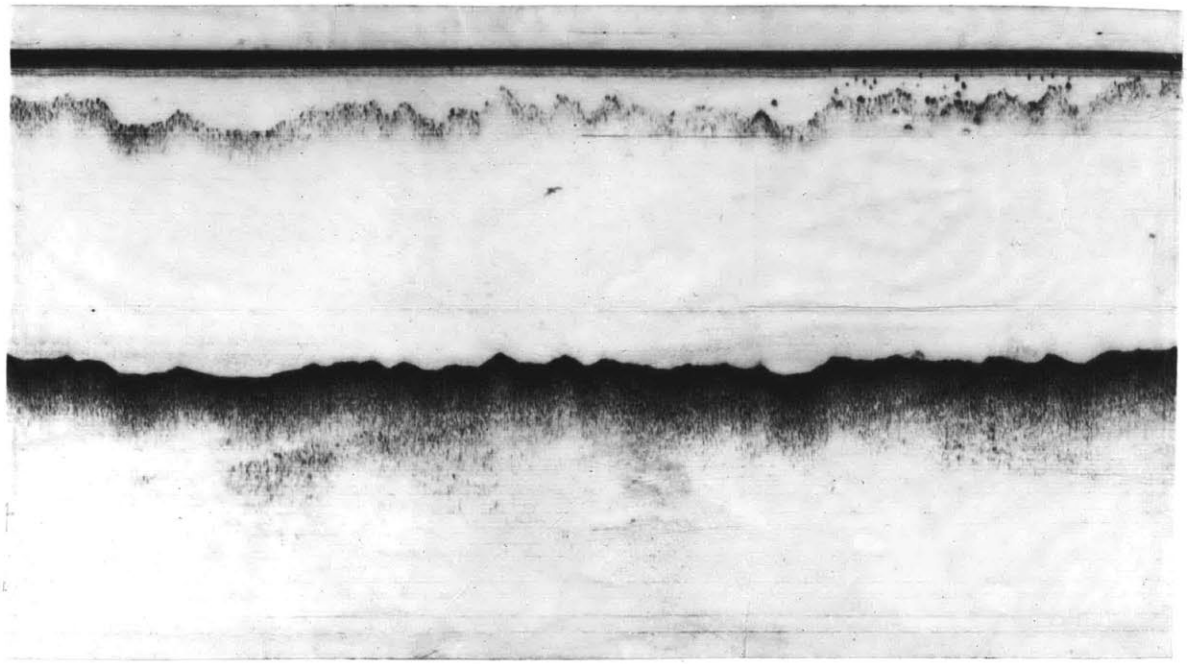


FIG. 5. Irregularities of the sea floor due to sand waves advancing from right to left. Length of section c. 570ft., width of section c.80ft., vert. exag. 1:4.

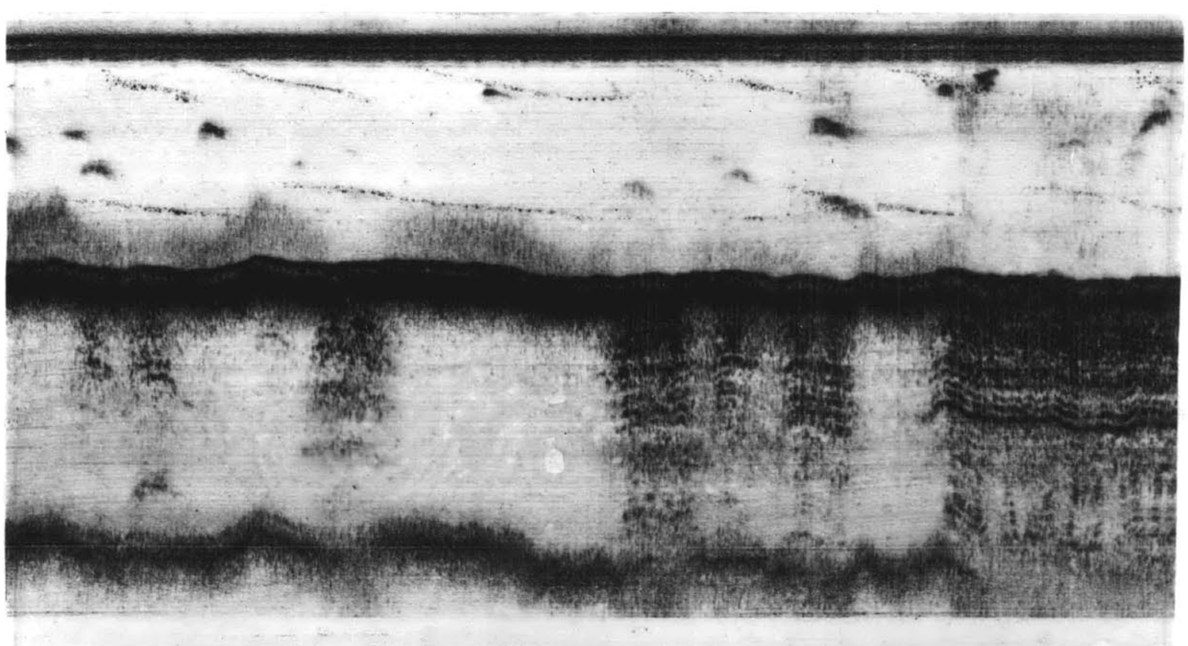


FIG. 6. Rapid variations in the acoustic penetrability of the black mud overlying clay.

of Recent sediment black mud, (c) stratified clay, (d) till and (e) bedrock. The characteristics of each stratigraphic horizon as seen on the records will be considered in turn.

4.1. Bottom Configuration

The harbor bottom is generally smooth and undulating except where interrupted by dredged channels and rocky outcrops. Sinusoidal undulations of the harbor bottom are a feature induced by the up and down motions of the boat due to the waves. Minor bumps and irregularities along the bottom may be a feature of sediment transport. A bumpy bottom may also be caused by rock boulders derived from till from which the finer material has been winnowed by currents. Such a boulder-strewn bottom is a useful indication of underlying till and the possible past presence of a drumlin which has since been eroded away.

Occasionally there are indications of sediment transport in the form of sand waves, rarely more than two or three feet high (fig. 5). The sand waves may be confused with the sinusoidal pattern mentioned above but the sand waves are generally not so smooth or symmetrical and have sharper crests. The sand waves have a slightly steeper slope on the side facing the direction of the movement of the sand wave. It is noticeable that the sand waves tend to be confined to the deeper portions of the harbor.

The correlation of bottom configurations with actual bottom features should prove a rapid means of delineating areas of sediment removal, transport and accumulation.

4.2. Recent Sediments

The Recent black organic mud is virtually ubiquitous in the harbor except where removed by dredging and current scour. On the records it appears as a homogeneous darkening of the record paper, with its lower boundary poorly defined. By decreasing the gain on the S.S.P. slight stratification may be seen in the black mud. The absence of the mud is most evident in the dredged main ship channel where excellent penetration is generally obtained. Elsewhere, the mud may or may not act as an acoustic barrier to the penetration of sound. The acoustic impenetrability of the mud is thought to be due to the presence of considerable amounts of gas in the form of bubbles which absorb and scatter the sound. Abundant gas bubbles are observed to rise from the mud when it is disturbed. As expected, when penetration increases reflection decreases, as indicated by weaker second and third echoes. An unexplainable feature is the local rapid variation of the acoustic penetrability and reflectivity of the mud as illustrated in figure 6.

Peat is found in the upper parts of sections on land around Boston, but the presence of peat beds in or beneath the black mud of the harbor is not evident from the records. Because the harbor is a lower area it was flooded earlier than the surrounding land by the rising sea level following the Pleistocene glaciation, and it is doubtful whether peat was formed then. If it was formed, it has since been removed by marine erosion. Peat may be present in sections around the periphery of the harbor, and if encountered it would prove to be a very effective acoustic barrier.

4.3. Clay.

The clay, because of its stratified nature, is by far the most easily distinguishable stratigraphic horizon displayed on the records. It lies beneath the Recent black mud except when the mud has been removed by dredging. Beneath the clay there is uaually till, though the clay may lie

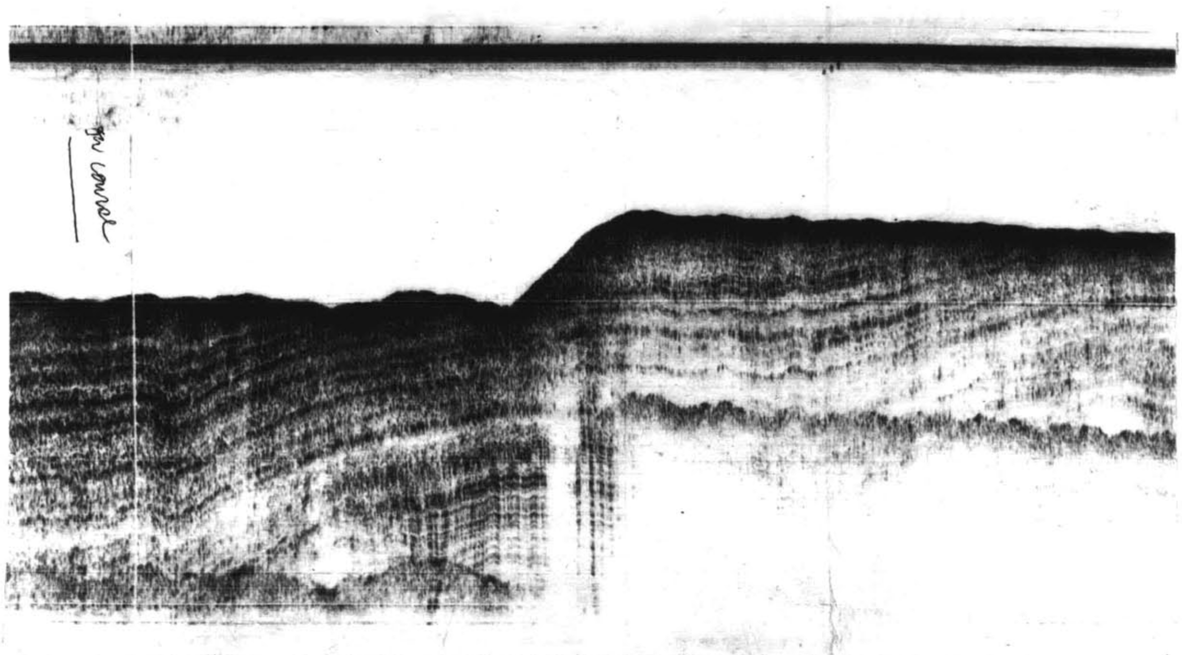


FIG. 7. A clay section showing both coarse and fine stratification. Note also the undulating folds in the clay and the truncation of the beds by the sea floor.

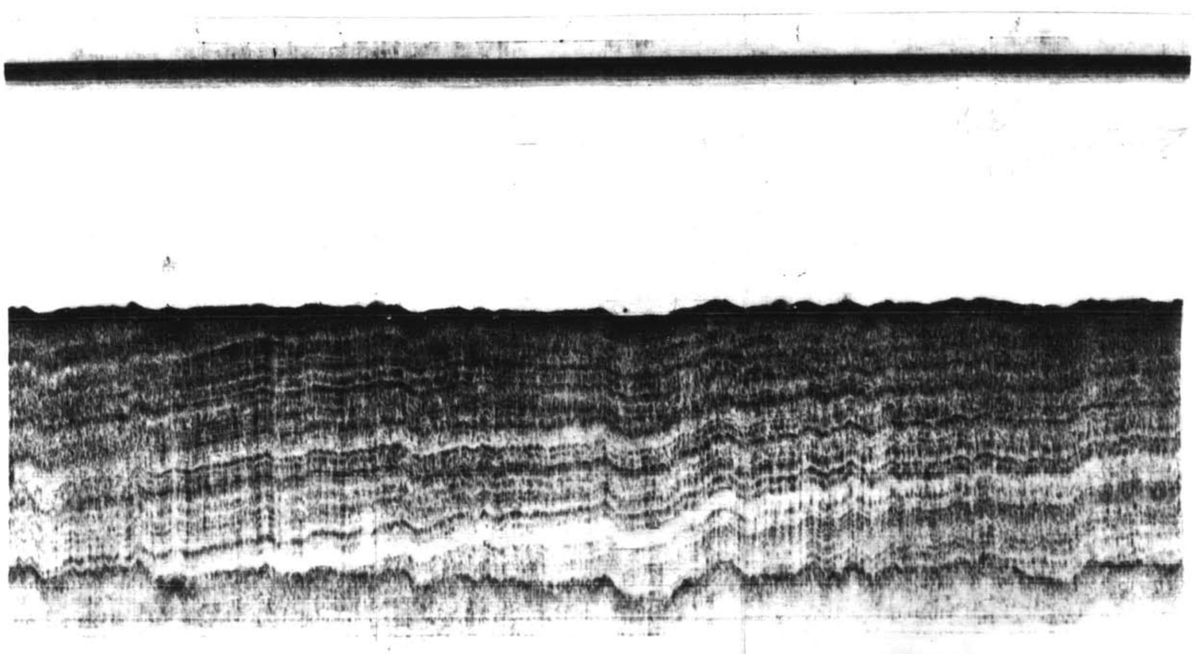


FIG. 8. Pseudo crumpling of the clay stratification due to uneveness in the sea floor. Crumpling in the clay conforms exactly to the sea floor configuration.

directly on bedrock. The clay is a very effective transmitter of sound, and where it is not masked by other sediments it gives excellent penetration. Density variations within the clay due to the interbedded sands and silts show strongly on the records. The thickness of the sandy and silty layers ranges from a few inches to two feet which is comparable to that observed on land. The vertical distribution of the layering is roughly regular, but rapid transitions from coarse to fine layering are frequent (see fig. 7.).

The clay lies horizontally, or in broad undulations which may be a result of differential compaction of the clay over an uneven surface. The approximate 1:4 vertical exaggeration overemphasizes the true slopes on the records. The records frequently show sharp crenulations of the clay stratification (see fig. 8.). These crenulations at first were thought to be due to crumpling of the clay by an overriding ice sheet, but closer examination of the records reveals, however, that the crenulations conform exactly to the bottom configuration and that they increase in amplitude with depth. It is highly improbable that crenulations within the clay would be reflected in the surface sediments and the bottom configuration. Therefore, the apparent deformation is interpreted not as real but either as a feature of the geometry of sound transmission or as a feature of the instrumentation. An increase of sound velocity with depth in the clay would produce the apparent deformation. In the case of the section in figure 8 it has been calculated that at a depth of 35 feet below the top of the clay a sound velocity in the clay three times greater than that in water is required to give the observed increase in amplitude of the crenulations. Such a high sound velocity for this type of sediment does not exist, and on this basis the deformation is believed to be a feature of the

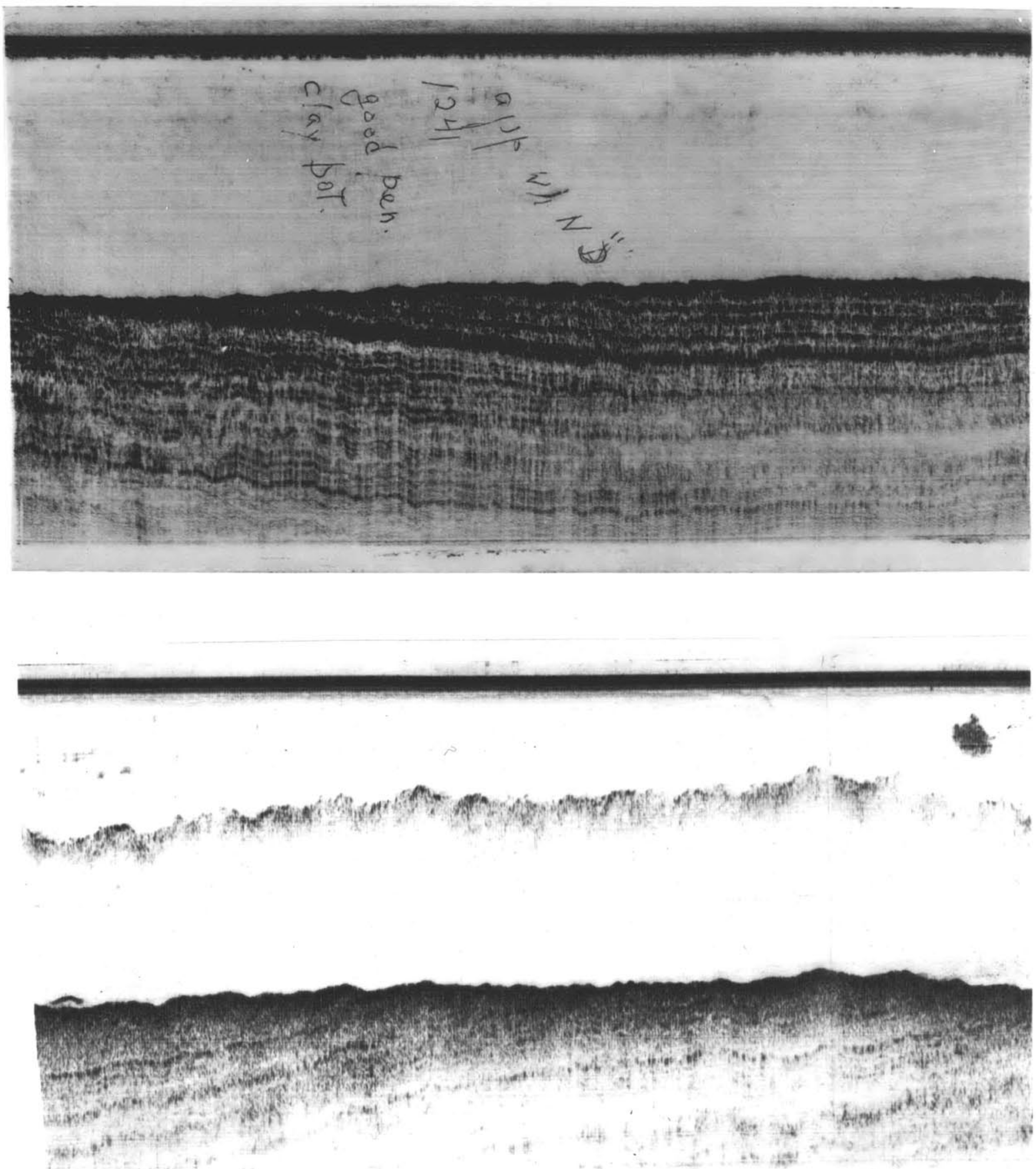


FIG. 9. Gently folded clay beds truncated and unconformably overlain by black mud.

instrument. Fluctuations in the power output of the generator have been observed, and these would produce variations in the frequency output which in turn would result in deformation of the record (J.Yules, personal communication). The conforming of the crenulations in depth with the second echo supports this opinion. In figure 7 is shown a case where the stratification in the clay is unaffected by the bottom configuration.

Figure 12 shows a feature which is either a reverse fault or a coincidental arrangement of the banded pattern. If a fault, it has a throw of approximately 15 feet. The significance of such faulting is difficult to evaluate, particularly as it is an isolated case. However, differential compaction over an uneven surface may conceivably cause overthrusting in the depressed areas. That such compaction may be present is shown by an arching up of the clay over a sub-surface irregularity to the right of the fault.

In many places broad folds in the stratified clay are truncated by the Recent sediments forming a marked unconformity between the two (see fig. 9 .). This is indisputable evidence that the clay has been eroded, though whether it was by subaerial erosion or by bottom scour is not evident from the records.

4.4. <u>Till and Bedrock</u>

In the harbor the till generally lies beneath the clay, but it may also crop out at the surface or be covered by Recent sediments only. The 12 k.c. sound pulses emitted by the S.S.P. are unable to penetrate into the till so that only its surface can be determined. One of the major dilemmas in the interpretation of the records is to distinguish between till surface and bedrock surface. Neither till nor bedrock permits penetration, but the till surface is generally more irregular both in configuration and

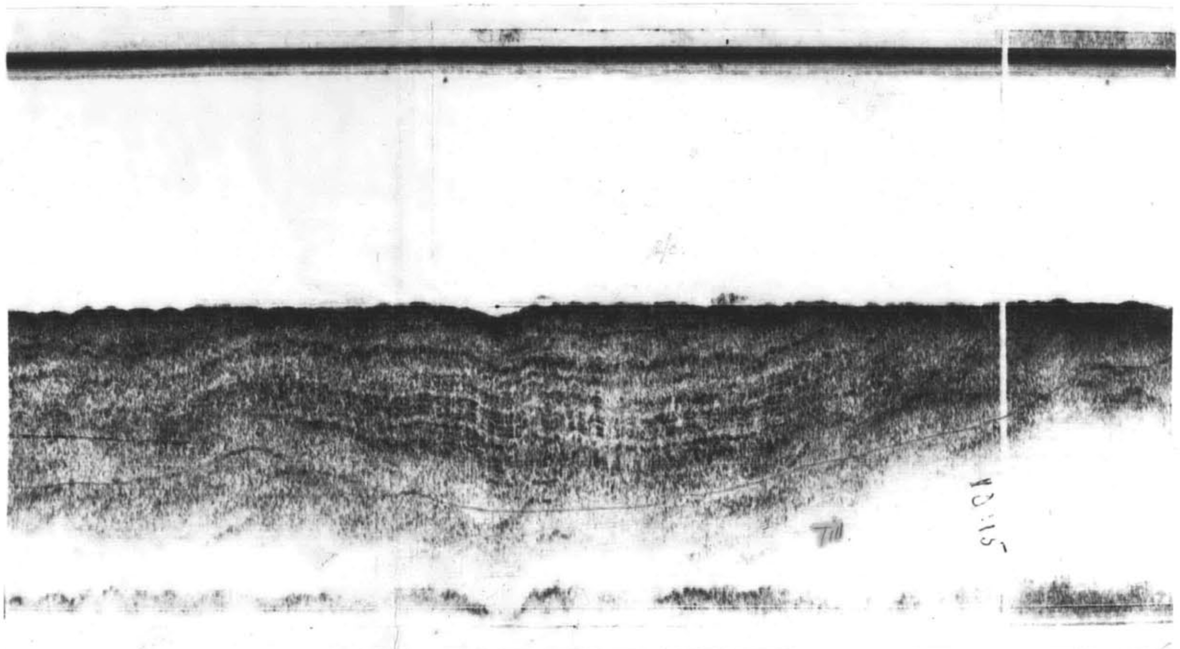


FIG. 10. Uneven and indistinct glacial till subsurface overlain by clay beds.

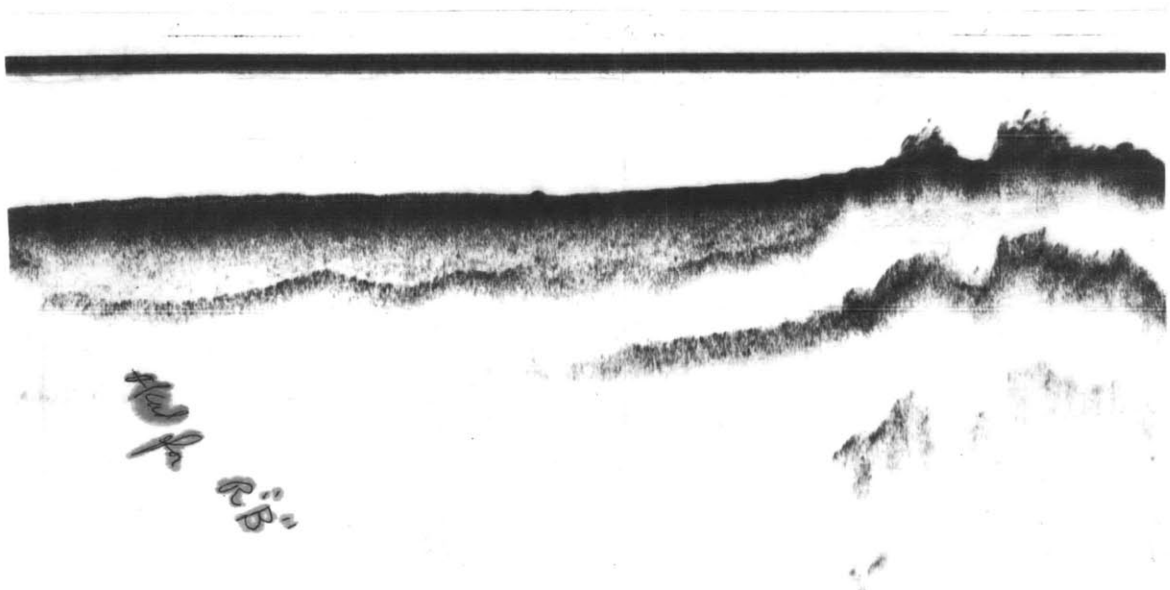


FIG. 11. Sharply defined bedrock subsurface with the bedrock outcropping above the sea floor.

in intensity of return pulse (see fig. 10.). Since the till is acoustically impenetrable to the 12 k.c. sound pulse, a bedrock surface, overlain by a considerable thickness of till, will not be revealed on the S.S.P. records. Supplementary information is very helpful in determining whether a particular sub-surface is till or bedrock.

5. DISCUSSION OF RESULTS

The results from accurately run traverses in Boston Harbor are presented in the form of a fence diagram in figure 14. A facsimile of the records is plotted along the course covered by the traverses, and for accurate location of these traverses with respect to buoys and landmarks, reference should be made to the Boston Harbor Chart. The depth represented by the sections of figure 14 is approximately 80 feet. The sections show the configuration of the harbor bottom below which is plotted an interpretation of the records with respect to the sediment types represented. Where no penetration was obtained, the section is left blank. The clay horizons are easily distinguished on the records and the plotting of the occurrence of the clay can be done with confidence. However, it frequently proves difficult to distinguish between till and bedrock sub-surfaces except where there is good evidence to support the presence of one or the other.

Areas are conspicuous either by their good penetration or by their lack of penetration. Little can be said concerning the areas of no penetration except that they exist and that the black mud is most probably the cause of the lack of penetration. Poor penetration is found along large portions of the traverse.

Continuous good penetration is obtained in an area enclosed by Castle Island, Deer Island Light and Long Island Head. The records east of

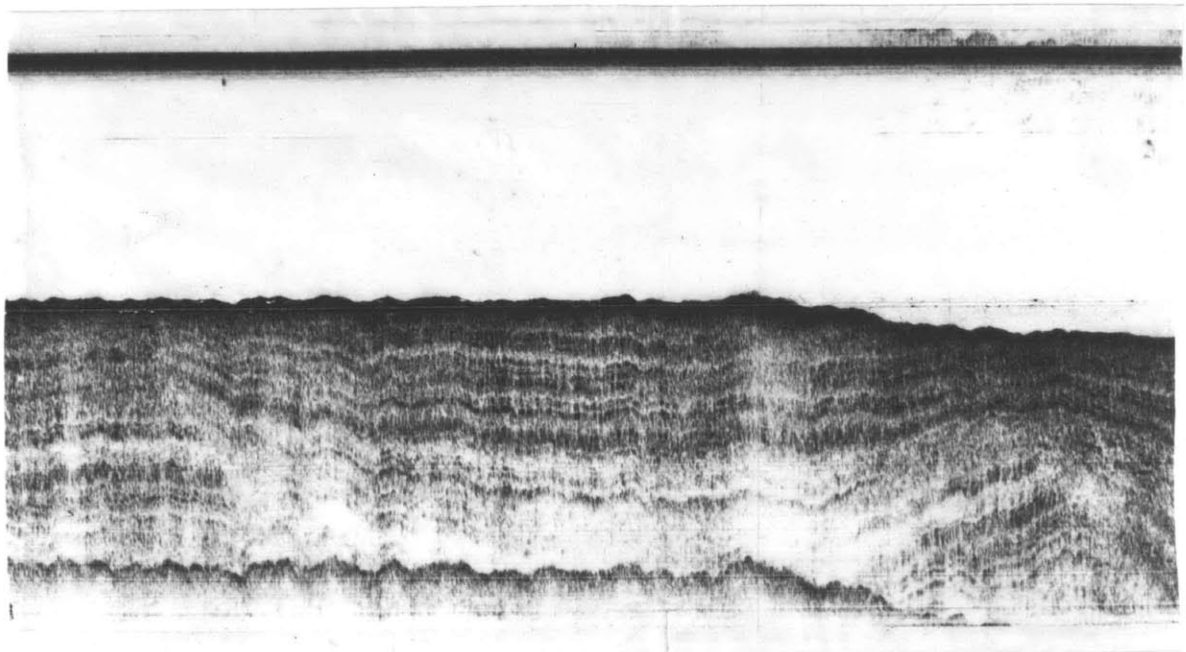


FIG. 12. A possible reverse fault, with overthrusting to the left, in clay beds. Also arching of beds over subsurface irregularity and differential compaction.

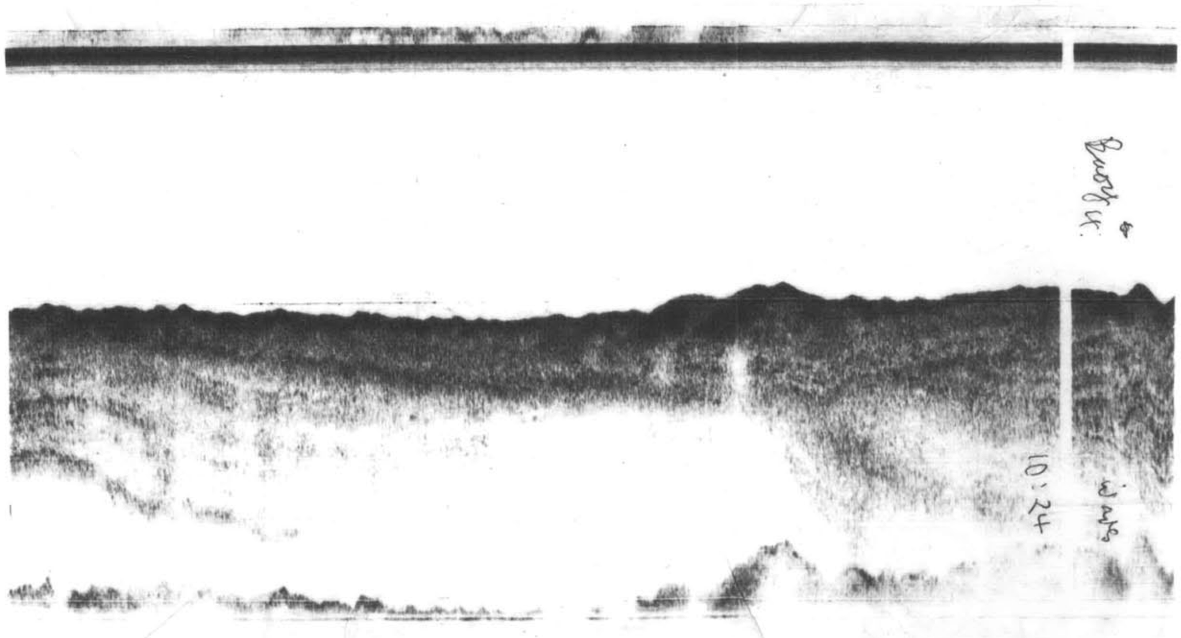


FIG. 13. A depression, in the clay surface, filled with black mud.

Castle Island indicate a subsurface beneath the clay which could be either till or bedrock (see fig.10.). On his bedrock contour map, Crosby (1903) shows bedrock cropping out immediately to the east of Castle Island (fig.2.). This suggests that the subsurface is bedrock but on the records it is characteristic of a till subsurface; i.e. it is indistinct and is not similar to confirmed bedrock surfaces elsewhere. A portion of this feature is shown in figure 11 . This subsurface can be traced on the records for at least a mile east of Castle Island, and has been observed on several traverses over the area.

Only well stratified glacial clays are observed on the records in an area bounded by Deer Island Light, Long Island Head, Spectacle Island, and Governors Island Flats (figs.7,8 and 12.). The horizontal stratification of the clay is interrupted locally by irregularities of the till or bedrock subsurface over which differential compaction of the clay occurs. The irregularities occasionally appear along the base of sections but are usually beneath the range of the S.S.P. when using 5" recording paper. The maximum thickness of the clay remains unknown since it exceeds the penetration of the S.S.P. instrument used. Indications are that the clay has considerable depth in the vicinity of President Roads. This notion may be biased in that good penetration is obtained in this area. Similar clay thicknesses may exist where penetration is poor. The good penetration obtained in President Roads may be due to removal of the black mud by dredging.

The traverse from Deer Island Light and around Gallops Island gives intermittent penetration. The records show clay beneath the sea floor across the main shipping channel from Deer Island Light to Long Island Head.

Between Nixes Mate and Long Island Head the subsurface rises sharply to the sea floor and crops out for a distance of about 400 feet. On the records this surface has characteristics intermediate between till and bedrock, and it is impossible to decide which it is. The location of the subsurface between the drumlins of Long Island Head and Gallops Island indicate that it is a till surface, but this is not conclusive.

Off the eastern end of Gallops Island a bedrock surface rises and reaches the sea floor. A nearby rocky outcrop confirms the nature of this surface. A similar bedrock outcrop occurs between Lovell Island and Nixes Mate on the same traverse. The surface as seen on the records is sharp and distinct and on this basis the surface is attributed to bedrock.

A bedrock ridge extends in a broad arc from Hangmans Island through Sunken Ledge and Quarantine Rocks to Rainsford Island. Two traverses were made over the ridge and the bedrock surface was traced almost continuously for a distance of at least three-quarters of a mile. Bedrock breaks through the sea floor along the axis of the ridge (fig. 11.). Subsequent to the completion of figure 14, several additional traverses in the vicinity of the ridge have yielded excellent bedrock profiles.

In the area between Rainsford Island, Georges Island and Peddocks Island (i.e. Nantasket Roads) there is poor penetration, but intermittent good penetration through clay to bedrock indicates the general vertical sequence. The traverse extending east from Georges Island shows an almost continuous bedrock profile over a distance of more than half a mile. Several indications prove conclusively that this is bedrock; on the record the subsurface is very well defined and outcrops of the subsurface occur as jagged irregularities similar to those in figure 11. The Boston Harbor chart indicates a rocky bottom in this location.

6. CONCLUSIONS AND RECOMMENDATIONS

The Sonar Sediment Probe has produced some excellent results but its incapability to penetrate the black mud prevents the obtaining of maximum information. Good penetration reveals various stratigraphic horizons by their characteristic patterns on the S.S.P. record. Recent sediments show as a homogeneous darkening of the paper. Clay appears as a well banded pattern, while till and bedrock exhibit acoustically impenetrable surfaces. The bedrock surface is more sharply defined than a till surface. Excellent bedrock profiles have been obtained where bedrock outcrops or is near surface.

A depositional history of the Pleistocene deposits of the Boston Basin similar to that suggested by Chute (1959) is proposed. Pleistocene sediments are attributed wholly to the Wisconsin stage of the Pleistocene glaciation. The ice sheet deposited widespread ground moraine, and the retreat of the ice resulted in the local deposition of outwash sands, gravels and clays over the ground moraine. A clay bed, more widespread than, but contemporaneous with the outwash deposits was also laid down during the retreat of the ice. In the Late Wisconsin there was a minor readvance of the ice with the deposition of a sequence similar to the one left by the previous ice advance.

Only one sequence of till, outwash and clay can be recognized in the S.S.P. records from the Boston Harbor. It is thought that this sequence represents sediments deposited by the final readvance of the ice. Although sections through Recent sediments on land show a peat horizon interbedded with black silt, the peat has not been observed on the S.S.P. records taken in the harbor.

To augment the results shown in figure 14, it is recommended:

(i) That a sequence of closely spaced north-south traverses be run over the area of good penetration between Castle Island, Deer Island Light and Long Island Head. Such a survey would enable the drawing of a detailed map showing the distribution of the sub-bottom sediments.

(ii) That a series of closely spaced traverses be run at right angles to the trend of the Hangman Island - Rainsford Island bedrock ridge. This should produce enough information to permit a bedrock contour map of the ridge to be drawn. In addition, this ridge forms a good starting point for the tracing of bedrock under the sediments.

(iii) That cores be taken where the indeterminate subsurfaces mentioned in Section 5 of this thesis intersect the sea floor. Two specific points are recommended for coring. The first is approximately 2000 feet due east of Castle Island and the second approximately 400 feet due west of the southern tip of Nixes Mate.

Large areas of Boston Harbor remain to be traversed with the S.S.P. and there are indications from random traverses that additional areas of good penetration exist. If at all feasible, traverses should be laid out as close to a grid system as possible. This facilitates plotting and gives a systematic coverage of the area.

It is recommended that cores should not be taken until a traverse has been completed. Stopping mid-way through a traverse leads to complications in keeping position which inevitably produces errors in the plotting of courses. Examination of the record of a traverse as soon as it is completed will indicate clearly the best locations for obtaining cores.

The limitations of the S.S.P. in its present form have been evaluated, and it is evident that other techniques will have to be used to penetrate through the areas where the S.S.P. gives poor penetration. Because of the extremely fine resolution given by the S.S.P. it is useful for work involving the clays, but an instrument is required which will reveal the broad sub-bottom surfaces of till and bedrock as well.

For work in areas like President Roads, record paper with a greater width might show penetration to the base of the clay.

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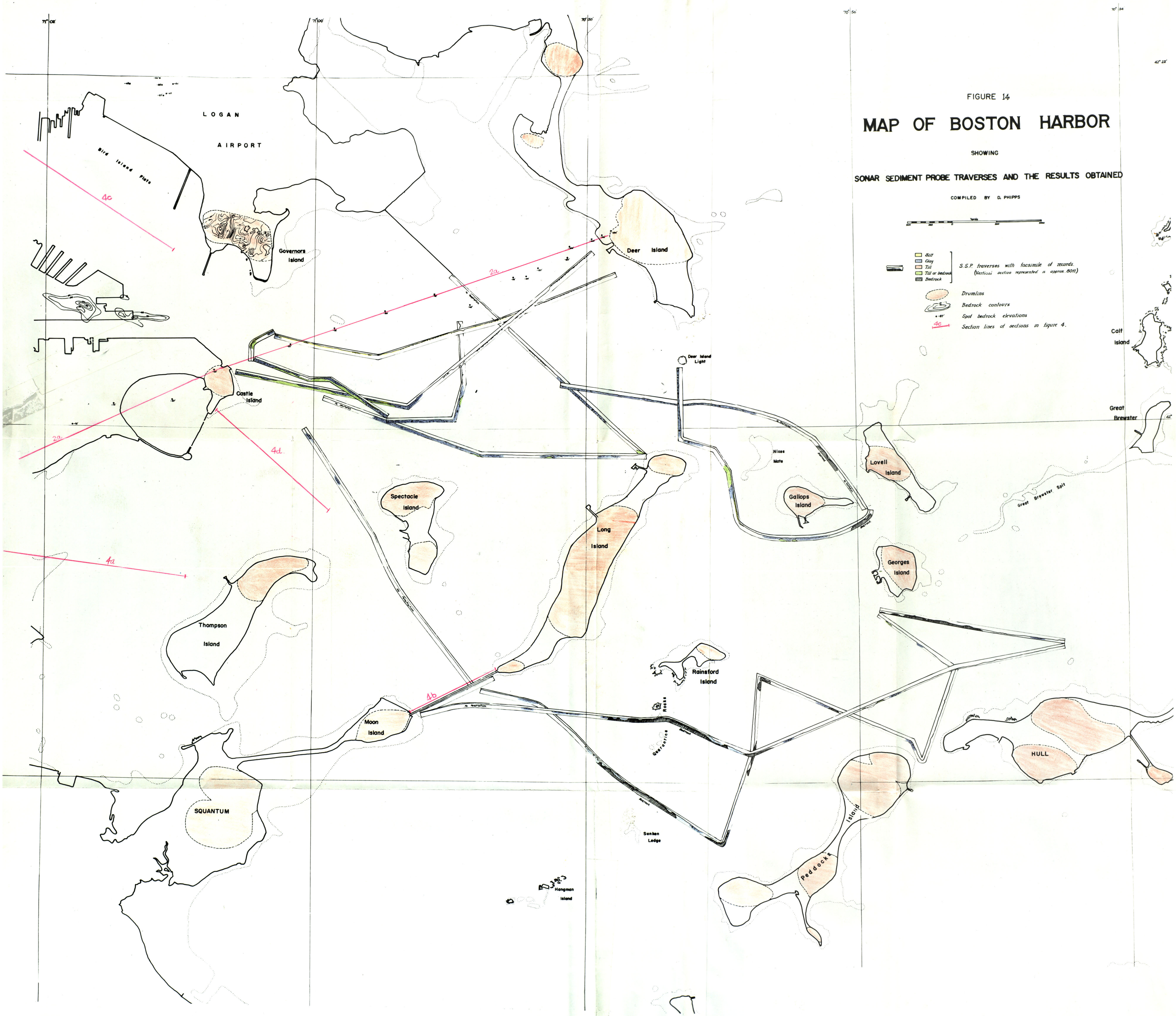

FIGURE 14

MAP OF BOSTON HARBOR

SHOWING

SONAR SEDIMENT PROBE TRAVERSES AND THE RESULTS OBTAINED

COMPILED BY D. PHIPPS