CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
Dominion Observatories

PUBLICATIONS
of the
DOMINION OBSERVATORY
OTTAWA

Volume XXXI • No. 2

THE DEEP BAY CRATER

M. J. S. Innes, W. J. Pearson and J. W. Geuer

Price: $2.00

ROGER DUHAMEL, F.R.S.C.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1964

ERRATA

Publications of the Dominion Observatory
Vol. XXXI, No. 2 "The Deep Bay Crater"

Page 32, right coln., para. 2, line 3, for sussurite read saussurite.

Page 32, right coln., para. 2, line 5, for strains read trains.

Page 34, left coln., line 22, for gnessic read gneissic.

Page 43, left coln., para. 2, line 4, for and about +7 mgals read to about +7 mgals.

Page 43, left coln., para. 4, line 9, for do no suffice read do not suffice.

Page 47, left coln., para. 1, for True depth — 3,210 feet read True depth — 2,310 feet.

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Queen's Printer and Controller of Stationery
Ottawa, Canada
1964

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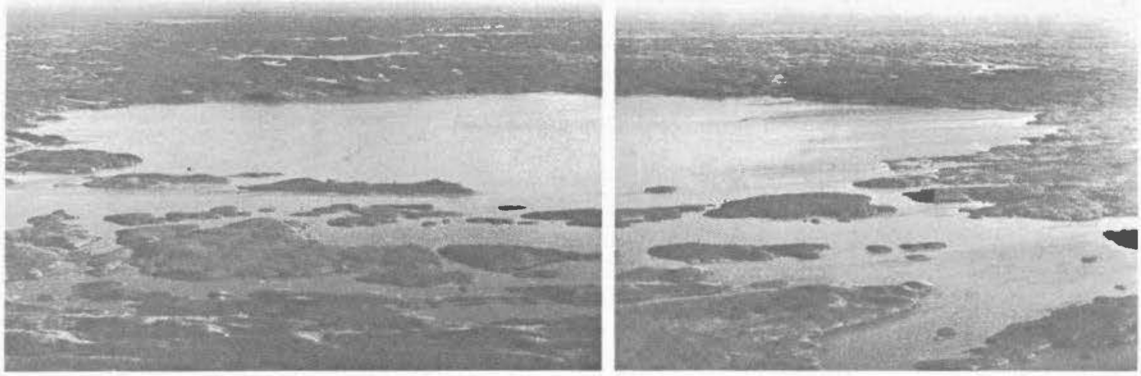
The Deep Bay Crater

M. J. S. INNES, W. J. PEARSON* AND J. W. GEUER



A view looking southeast across Deep Bay from a height of 7,500 feet; island-studded Reindeer Lake appears in the foreground.

ABSTRACT:—Deep Bay forms the southeastern part of Reindeer Lake in northern Saskatchewan. It is a circular, water-filled depression with a diameter of some six and a half miles, a surface elevation of 1,100 feet above mean sea level, and a depth of 720 feet; its centre lies at longitude 102° 59.4′W, latitude 56° 24.4′N. Topographical, geological and geophysical studies, combined with the results of diamond drilling strongly indicate an origin by meteoritic impact, and lend no support to the thesis that the Deep Bay depression is geologically or structurally controlled. The evidence suggests that the crater was formed at least 150 million years ago and had an original rim dimension of almost six miles, a rim height of 890 feet and a true depth of 2,310 feet. Deposition of Mesozoic sediments over the centuries have combined with erosional forces to reduce the crater to its present form.

RÉSUMÉ:—La baie Profonde forme la partie Sud-Est du lac Caribou dans le Nord de la Saskatchewan. C'est une dépression circulaire remplie d'eau de quelque six milles et demi de diamètre, dont la surface est à 1,100 pieds audessus du niveau moyen de la mer et d'une profondeur de 720 pieds. Le centre gît par 102° 59.4′ de long. W. et 56° 24.4′ de lat. N. Des études topographiques, géologiques et géophysiques utilisées avec les résultats obtenus par forage au diamant, indiquent clairement une origine météoritique, et infirment la thèse selon laquelle la dépression de la baie Profonde serait d'ordre géologique ou structural. Il semble que le cratère ait été formé il y a au moins 150 millions d'années, que le diamètre à l'origine ait été de près de six milles, avec un rebord de 890 pieds de hauteur et une profondeur vraie de 2,310 pieds. Des dépôts sédimentaires du mésozoïque au cours des siècles et les forces d'érosion auraient réduit le cratère à sa forme actuelle.

Introduction

Following the discoveries of the New Quebec Crater (Meen, 1950), the Brent Crater (Millman, Liberty, Clark, Willmore and Innes, 1960), and the Holleford Crater (Beals, Ferguson and Landau, 1956; Beals, 1960) attention was drawn to a large circular water-filled depression, known as Deep Bay, which forms the southeastern part of Reindeer Lake in northern Saskatchewan, (*see* above and Figure 1.). Its existence has long been known, but it is only recently that careful scientific investigations have been carried out at Deep Bay and consideration given to the possibility that it may have been formed by the impact and explosion of a large meteorite (Innes, 1957).

Four separate field investigations of the Deep Bay crater have been carried out by the Dominion Observatory. The first investigation was carried out in August 1956 in co-operation with the Department of Mineral Resources of the Province of Saskatchewan; topographical, geophysical and geological observations were made. The topographical observations included the determination of the heights of stations along several traverses, and of prominent topographic features to provide vertical control for the construction of a topographical map (in pocket) of the Deep Bay area. In addition measurements of water depths were made with an echo sounder along several boat traverses to provide in-

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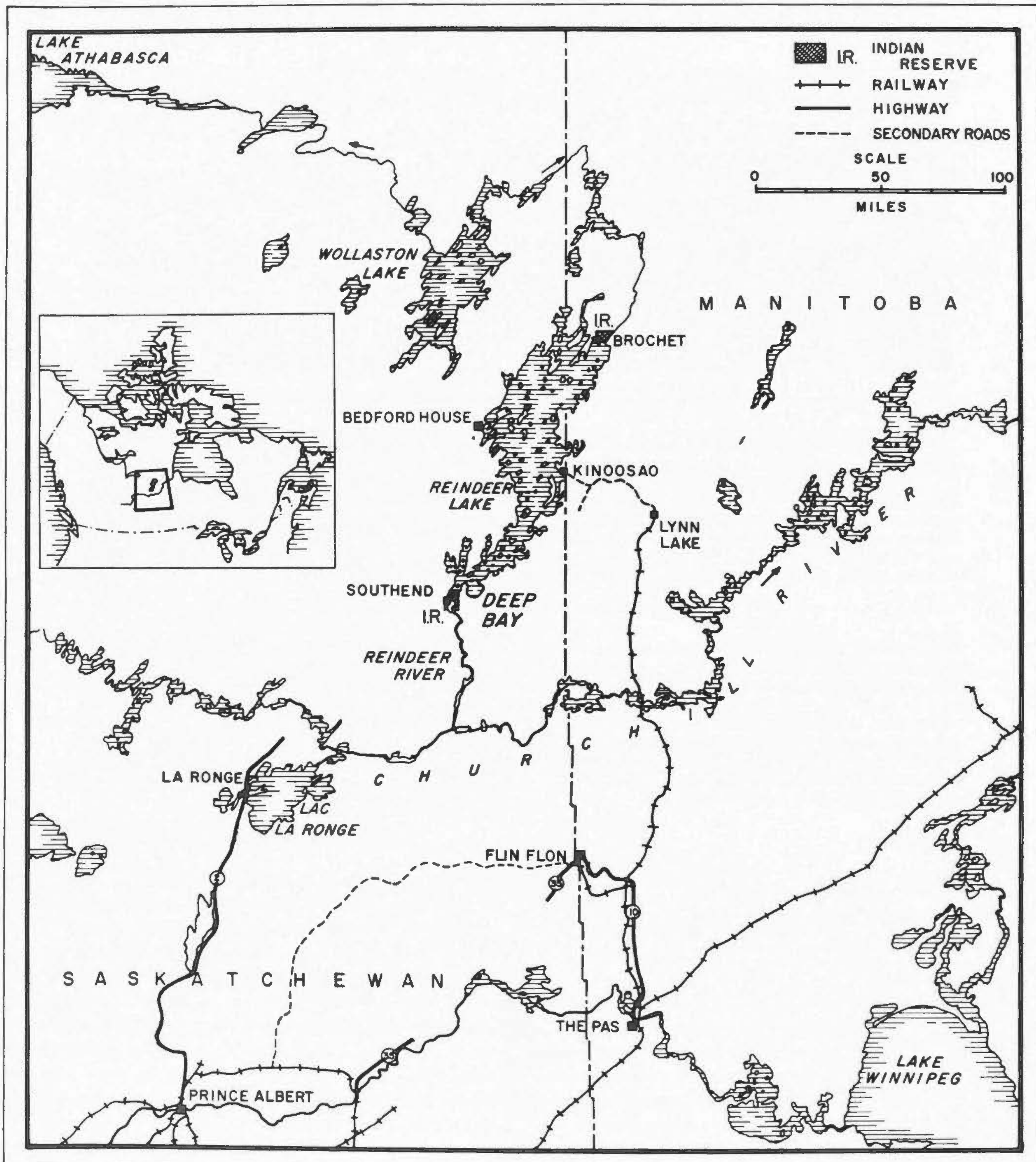

FIGURE 1. Location map.

formation concerning the relief of the present floor of the crater.

The geophysical work consisted of both gravity and magnetic observations. A light aircraft was used for transportation and regional gravity measurements were made on the margins of most lakes suitable for landing within a radius of 15 miles from the centre of Deep Bay. In addition detailed gravity observations were carried out at intervals of about half a mile along the complete shoreline of the bay and along five inland radial traverses for a distance of two to four miles. Observations of the vertical magnetic intensity were carried out during the same period by the Geological Survey of Canada using an airborne magnetometer. Geological mapping was carried out in conjunction with the gravity survey work. Practically all outcrops along the shore of Deep Bay were examined as well as those along the inland traverses and those in the vicinity of the regional gravity stations.

In the winter of 1959 a program for training observers and testing instruments designed for measuring gravity on sea ice in the Canadian Arctic provided an opportunity for further gravity work at Deep Bay. During the last week of February, forty-five gravimeter stations were established on the ice to provide a clear picture of the gravitational field over the bay. Additional gravity measurements were made in July 1960, in conjunction with a Dominion Observatory field program in northern Saskatchewan using helicopters for transportation. It was possible to extend the regional gravity coverage out to a distance of about 30 miles from the crater, and also, to supplement the detailed gravity measurements obtained on previous surveys.

Finally during the winter of 1961–62 a diamond-drilling program was carried out from the ice surface of Deep Bay partly to ascertain the true depth of the crater and partly to investigate the nature of the material filling the crater and underlying its floor.

It is the purpose of this paper to present the combined results of the geological, topographical and geophysical studies and also the findings of the diamond-drilling program. Accounts of the preliminary results of these investigations have been presented elsewhere (Innes, 1957; Innes, 1961; Beals, Innes and Rottenberg, 1963; Innes, 1964).

History and Previous Work

The records show that the first white man to visit Reindeer Lake was the famous explorer David Thompson, who in 1796 succeeded in establishing a new fur trade route from the south to Lake Athabasca via Reindeer Lake. As reported by J. B. Tyrell (1916), Thompson followed and surveyed the western margin of the lake, and although he spent two winters at Bedford House, a trading post he established near the middle of Reindeer Lake, (*see* Figure 1) no mention of Deep Bay appears in the narrative of his report.

The first geological work in the area was carried out nearly one hundred years later by D. B. Dowling (1897) who surveyed the western shoreline of Reindeer Lake. Deep Bay is not specifically mentioned in his report but it is named as such and shown on his geological map as a large bay with indefinite shoreline extending in a southeasterly direction from the main body of Reindeer Lake. The Topographical Survey of Canada made a monumented stadia traverse around the shoreline of Reindeer Lake including Deep Bay during the summers of 1922 and 1925 and good maps showing the topography (not including heights) for the area on a scale of 4 miles to one inch have been available since 1928.

Further geological work was carried out by the Geological Survey of Canada in 1928, with the examination confined almost entirely to the coastline and islands of Reindeer Lake (Stockwell, 1928). The Oliver Lake and Wapus Lake areas including the southern end of Reindeer Lake were studied by F. J. Alcock in 1937, and the results published as G.S.C. Maps Nos. 527A and 528A on a scale of 4 miles to one inch. The Spalding Lake and Reindeer Lake areas immediately to the north were surveyed geologically in 1938 by L. J. Weeks and the results published as G.S.C. Maps Nos. 595A and 596A. In 1950 H.M.S. Rice made a compilation (G.S.C. Map 1016A) on a scale of eight miles to one inch, of geological information for the Reindeer Lake area from published maps of the Geological Survey of Canada and of the Manitoba Department of Mines and Mineral Resources.

As outlined above, Deep Bay is clearly indicated on all but the earliest maps of the area, and it is rather surprising that no mention of its unique character appears in the reports of any of these earlier investigations. As far as can be learned the first published reference that the features of Deep Bay are in marked contrast to the rest of Reindeer Lake appears in a book by P. G. Downes (1943). The author in describing a canoe trip in northern Saskatchewan makes reference to Deep Bay as follows:

> "The southern end of the lake is hemmed in by comparatively high and rugged hills gradually lessening to the north. Here sand-girt islands begin to appear and the whole effect is of a more subdued topography. In the southeast corner is a large and perfectly symmetrical round bay quite devoid of islands and tremendously deep. This huge bay, utterly out of character with the rest of the lake, is a spot usually to be avoided. It is too deep for nets, affords no shelter from the wind, and is supposed to be inhabited by a gigantic fish of miraculous abilities and voracious appetite, inclined occasionally to come up through the ice and select itself a young caribou."

From the information available the first suggestion that Deep Bay may have been formed by a meteorite was made by the late Professor D. S. Rawson, head of the Biological Department of the University of Saskatchewan, in a letter to Mr. A. I. Bereskin, Controller of Surveys for the Department of Natural Resources of the Province of Saskatchewan, as follows:

> Dear Mr. Bereskin:
>
> In view of the recent interest in craters which may have been caused by meteors, you may be interested to know that I found a depth of 660 feet in Deep Bay. This bay is almost circular, and about seven miles in diameter. It is about three times as deep as any other part of the lake, and thus looks to me like a crater of some kind.
>
> Yours very truly,
> D. S. Rawson,
> Head, Biology Department,
> University of Saskatchewan,
> Saskatchewan.
>
> Sept. 19, 1951.

Mr. Bereskin, in turn, passed this information to the Geological Survey of Canada, who discounted the suggestion, but unfortunately did not bring the matter to the attention of the staff of the Dominion Observatory.

The senior author (Innes, 1948; Innes and Thompson 1953) first observed and photographed Deep Bay (*see* Plate I, centre spread) from a light aircraft in 1947 while conducting a regional gravity survey throughout northern Saskatchewan and Manitoba. In 1948 and again in 1951 while carrying out gravity surveys in the Reindeer Lake area, attempts to land in Deep Bay were unsuccessful because of unfavourable winds. The unique character of Deep Bay, tales of tractor trains in winter breaking through the ice at the entrance of the bay, superstitious fears of the local Indians and their unwillingness to cross the bay by canoe, formed the subject of many interesting conversations with the manager of the trading post at Southend. However the suggestion was never made at this time that Deep Bay may have been formed by meteoritic impact and explosion. Only after the Dominion Observatory had carried out investigations of the Brent crater (Millman, Liberty, Clark, Willmore and Innes, 1960) and the Holleford crater (Beals, 1960) and initiated systematic searches for other craters in the Canadian Shield, (Beals, Ferguson and Landau, 1956) was it realized that Deep Bay, too, may have had a similar origin (Innes, 1957).

Description of Deep Bay Area

Location, Accessibility and Inhabitants

Deep Bay, the centre of which has coordinates 102° 59.4′ west longitude, 56° 24.4′ north latitude, elevation 1,106 feet above sea level, is located in the Canadian Shield midway between the great sedimentary basin of the central plains to the southwest and Hudson Bay to the northeast. Although near one of the principal water routes followed by canoes in summer and tractor trains on the ice in winter while freighting supplies to northern outposts, Deep Bay can be reached most easily by aircraft from the small settlement of La Ronge 120 miles to the southwest which is presently the northern limit of the highway system of the province of Saskatchewan.

Reindeer Lake lies immediately south of the tree line that separates the forest area from the tundra and barren lands. The northern end of the lake is sparsely wooded and only small stands of stunted spruce trees are found; on the other hand the country to the south near Deep Bay where it has not been ravaged by forest fires is fairly well wooded with spruce, tamarack, birch and poplar. Reindeer Lake, which may be classed as one of the larger of the many lakes of the Canadian Shield, trends in a direction slightly east of north, is about 150 miles long and some 30 miles wide at its widest point. The lake narrows to the south where for about 70 miles of its length it is only a few miles wide. Its highly irregular and rocky shoreline and its myriads of low rocky islands, both large and small, rising from remarkably clear and transparent water, make Reindeer Lake one of the most beautiful and picturesque lakes of northern Canada (*see* Plates IA and IB).

The region is still sparsely populated and most of the inhabitants are concentrated in the vicinity of the trading posts of Southend and Brochet which have been operated by the Hudson Bay Company for more than 150 years. The native population consists of both Cree and Chipewyan Indians who for the most part live on reservations near the trading posts. In 1961 there were 210 Cree Indians (38 families) living at Southend and 330 Chipewyan Indians (73 families) living on the reservation near Brochet.

Fur trading is the oldest and perhaps still the most important industry of the Reindeer Lake area although commercial fishing and mineral exploration activities have had a stimulating effect on the economy in recent years. A fish packing plant and operational centre of the Saskatchewan Department of Natural Resources is now established at Kinoosao on the east side of the lake midway between Brochet and Southend. A road connecting this community with the mining centre of Lynn Lake, Manitoba, 100 miles to the east on the Canadian National Railroad affords year-round access route to Reindeer Lake and Deep Bay. One result of this new road is that several hunting and fishing lodges have been established and Reindeer Lake is fast becoming a mecca for sportsmen and fishermen.

Topography

Topographically, the Reindeer Lake area is similar to many other places in the Canadian Shield, with flat-topped rock exposures forming hills and ridges above the general level of the lakes, the relief of which seldom exceeds 150 feet. Travelling by canoe, although one might wonder at the wide expanse of Deep Bay (nearly 6½

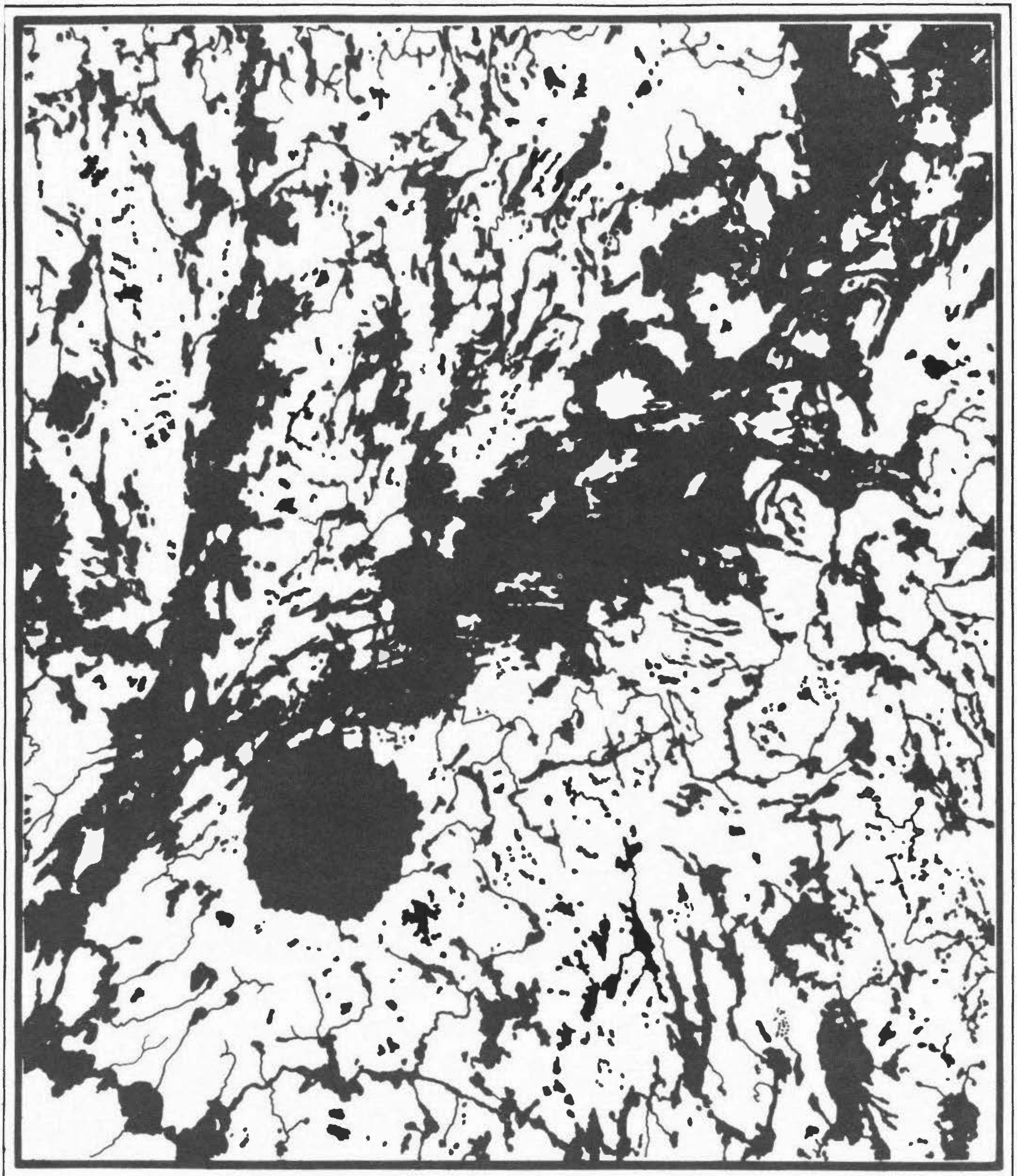

FIGURE 2. A morphological map of Reindeer Lake south. The height of land surrounding Deep Bay is evident from the drainage pattern.

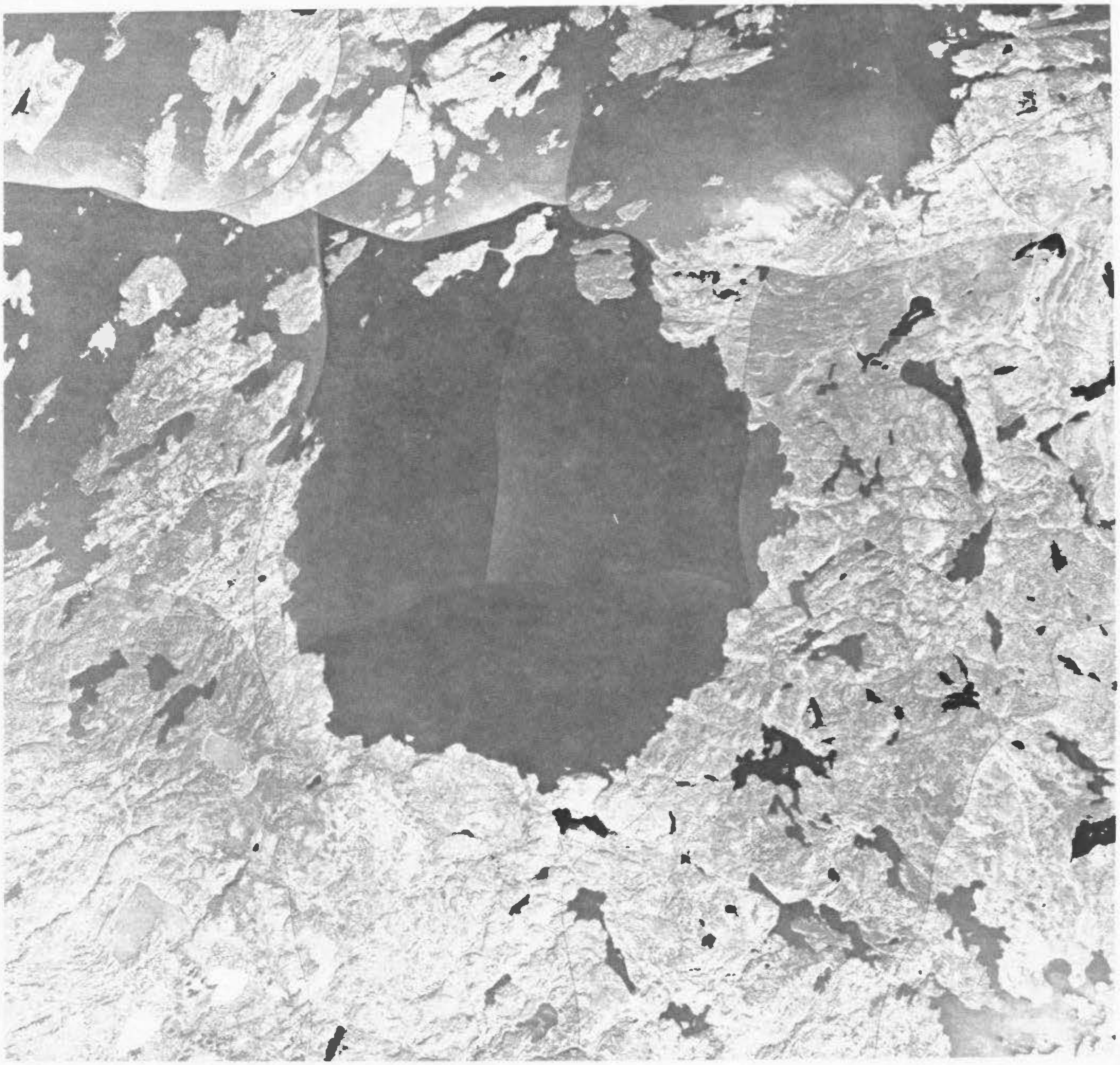

PLATE II. Mosaic of Deep Bay prepared from aerial photographs taken by the RCAF.

miles in diameter), and the complete absence of islands and scarcity of sheltered beaches along its margin, it is unlikely that the near perfect circularity of the bay would be noticed. From an aircraft, flying at a considerable height, these unique features are immediately apparent and stand out in marked contrast to the main body of Reindeer Lake, with its numerous islands and irregular bays and shorelines. The contrast in topographic expression of the Deep Bay region as compared to that of the southern part of Reindeer Lake is clearly illustrated in Figure 2 (*see also* Plate II).

Details of the topography can best be seen from the one mile to one inch map (in pocket) prepared by the Topographical Survey of Canada, which gives elevations and water depths contoured at intervals of 50 feet. The surface elevations, determined photogrammetrically, vary from about 1,106 feet above sea level, the height of Reindeer Lake, to 1,520 feet, the height of the highest point in the map area, which is located about half a mile inland from the eastern shoreline of Deep Bay. Contours of the water depths are based on echo soundings recorded along eleven boat traverses (Figures 3 and 4) of the bay during the summer of 1956 and on results of direct measurements taken through the ice during the winters of 1959 and 1961. Professor D. S. Rawson kindly provided data he collected in a study of Reindeer Lake

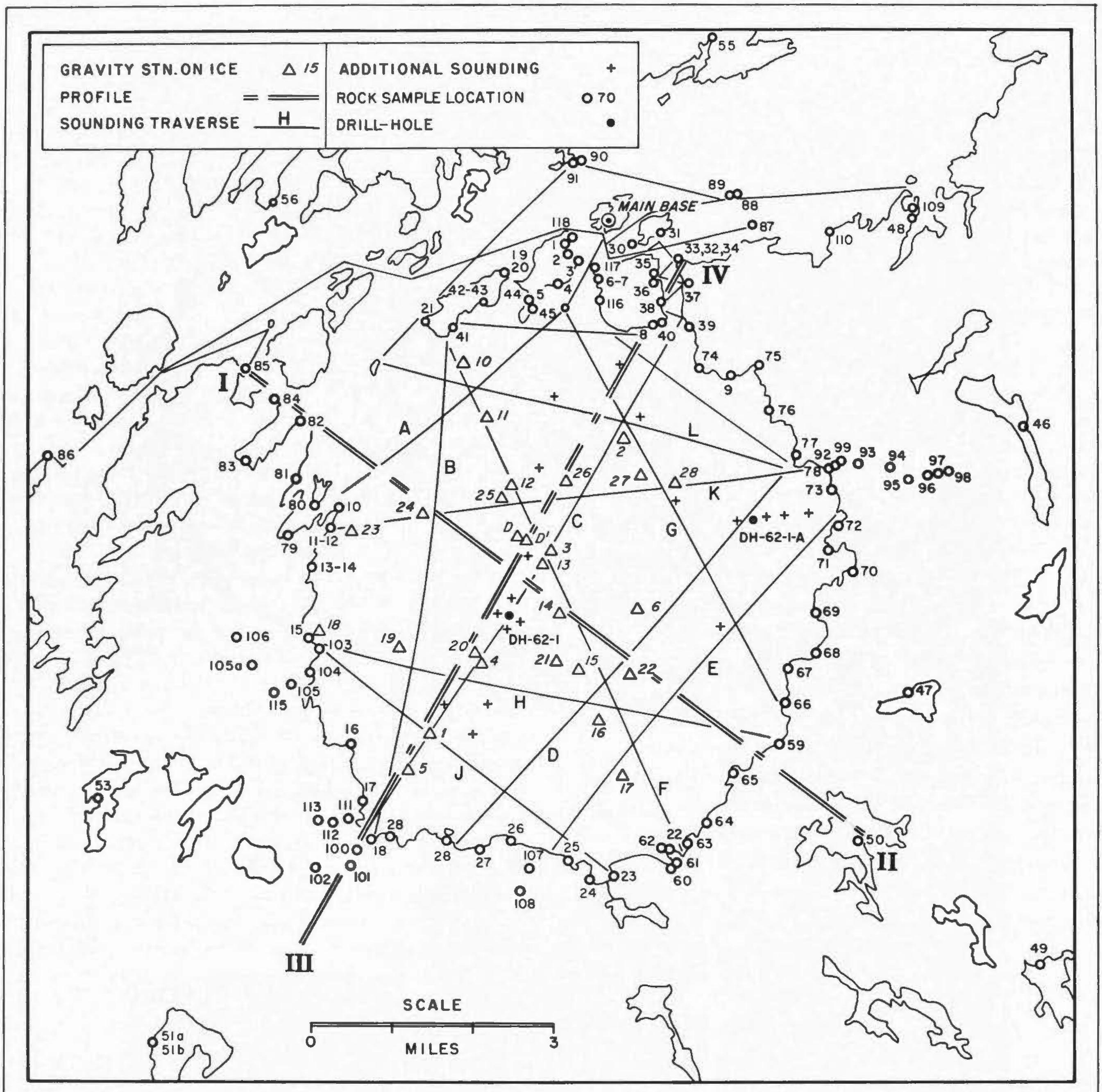

FIGURE 3. Location map of survey operations.

in connection with the fishing industry and these have been used to supplement and verify data obtained by echo sounding.

The soundings show that Deep Bay is a non-symmetrical basin with an average depth of about 500 feet. The deepest part forms an arcuate or kidney-shaped depression about one mile wide and five miles long lying to the east and south of the centre of the bay and reaching a maximum depth of 720 feet. The lowest part of the floor, therefore, has an elevation of 386 feet above sea level and lies approximately 1,130 feet below the highest surface elevation in the vicinity. In striking contrast the main body of Reindeer Lake has few recorded depths greater than 150 feet, and has an average depth of less than 100 feet.

The Effects of Glaciation

The region shows much evidence of having been overridden by huge masses of glacial ice that radiated from the great Keewatin ice centre west of Hudson Bay. The area is made up of irregular hummocky hills and discontinuous ridges, between which the depressions

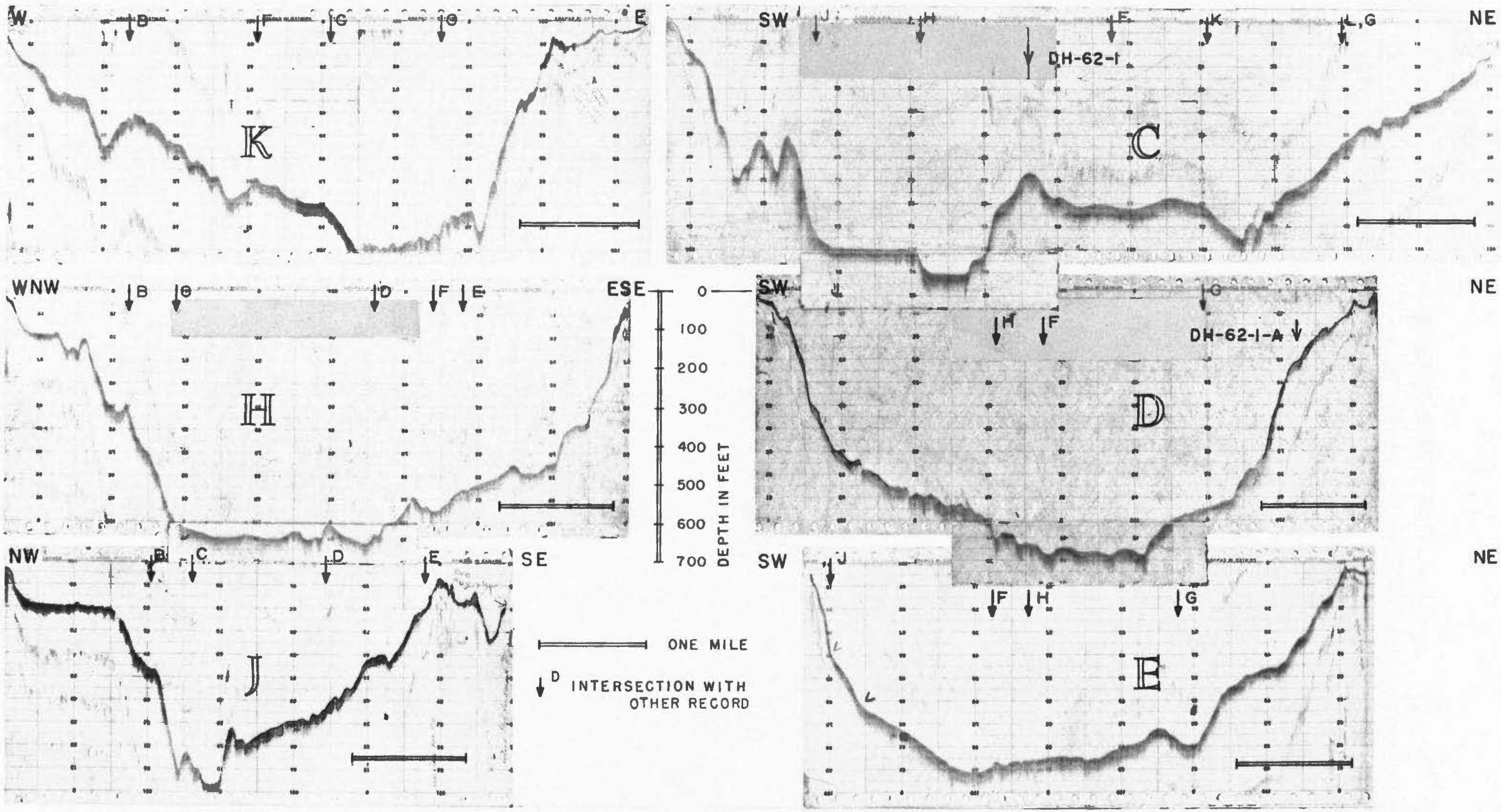

FIGURE 4. Depth recordings for boat traverses C, D, E, H, J and K.

are occupied by lakes varying in size and shape, and by boulder drift and swamp and muskeg. Glacial striae, well preserved in the granitic rocks and indicating that the ice advanced from the northeast, vary from north 15 degrees east to north 30 degrees east near Deep Bay. Erosional and depositional processes of the glacial ice, without doubt, have played the major role in reducing the topography of the Deep Bay crater to its present form. The intense fracturing of the rocks forming the rim, would permit, with the onset of glaciation, penetration and freezing of water along joint planes and fractures. This in turn would promote wedging out of the rock from its normal position, and facilitate erosion. The southwestern rim of the crater would be reduced most rapidly by heavy grinding and scouring as it would present an almost vertical scarp to the advancing ice sheet. On the other hand, the glacier would tend to ride up over the northeastern rim and here plucking probably has been the most effective mechanism of erosion.

Although deeply eroded, much of the bedrock portion of the rim remains and stands on the average about 270 feet above the waters of the bay. The present rim diameter, as marked by the height of land surrounding the bay is about 8½ miles. As with the Brent crater (Millman, Liberty, Clark, Willmore, and Innes, 1960) the drainage pattern of the Deep Bay area is both concentric and radial, and with the exception of three broad channels into Reindeer Lake along the northern side, the drainage is restricted to short intermittent streams no greater than two miles in length. The drainage pattern is clearly illustrated also in Figure 2.

The rim is best preserved along the eastern and southeastern side of the crater, partly because glacial action tends to accentuate the topographic expression of structures that parallel the direction of ice movement but also perhaps because the rocks underlying this area are more resistant. Here the rim stands 400 feet or more above the lake and retains in several places steep and precipitous inner slopes (*see* Plate IIIA centre spread). The original rim diameter has been estimated (Innes, 1961) to have been about 40,000 feet (7.57 miles) on the assumption that the present shoreline of Deep Bay, having a mean diameter of 6½ miles, represents the sectioning of the crater at its original ground level. On this basis Baldwin's (1949) formulae relating crater depths and rim heights with diameter, would place the floor of the Deep Bay crater at a depth of 2,100 feet and the original rim at a height of 1,500 feet with respect to the present surface of the lake. (*see* Figure 5).

Another topographic feature of considerable interest is what appears to be a pre-glacial valley extending in a southwesterly direction from the bay. Another valley which trends northeasterly from a point on the bay diametrically opposite, may prove to be a continuation of the southwesterly one. The approximate locations of these valleys are indicated by the shading in Figure 6, which shows the linear and fracture pattern in considerable detail. The valleys are now occupied by glacial deposits and small lakes and streams.

Wide sand beaches of fine-grained sand occur where these valleys enter Deep Bay. The southwest beach carries both garnet and magnetite sands which have been concentrated by wave action (*see* Plates IIIB, IIIC, centre spread). Along this beach and as far as three miles to the east shale pebbles occur in the sands. The greatest concentration of these pebbles and boulders, which range from one inch or less up to ten inches in diameter, occur on the southwest beach. Eastward from this beach the size and number of pebbles rapidly diminish. Shale pebbles in minor amounts also were noted in the drift in the valley to the southwest.

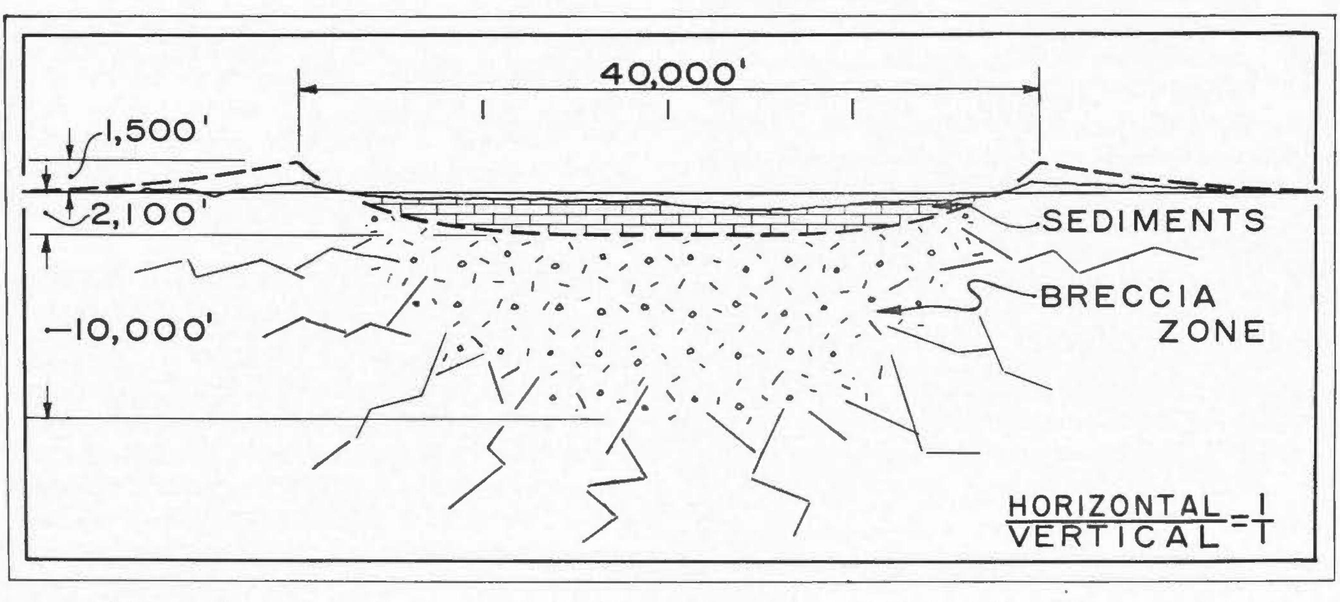

FIGURE 5. Section of typical meteorite crater of the size of Deep Bay, based in part on Baldwin's (1949) depth-diameter relationship.

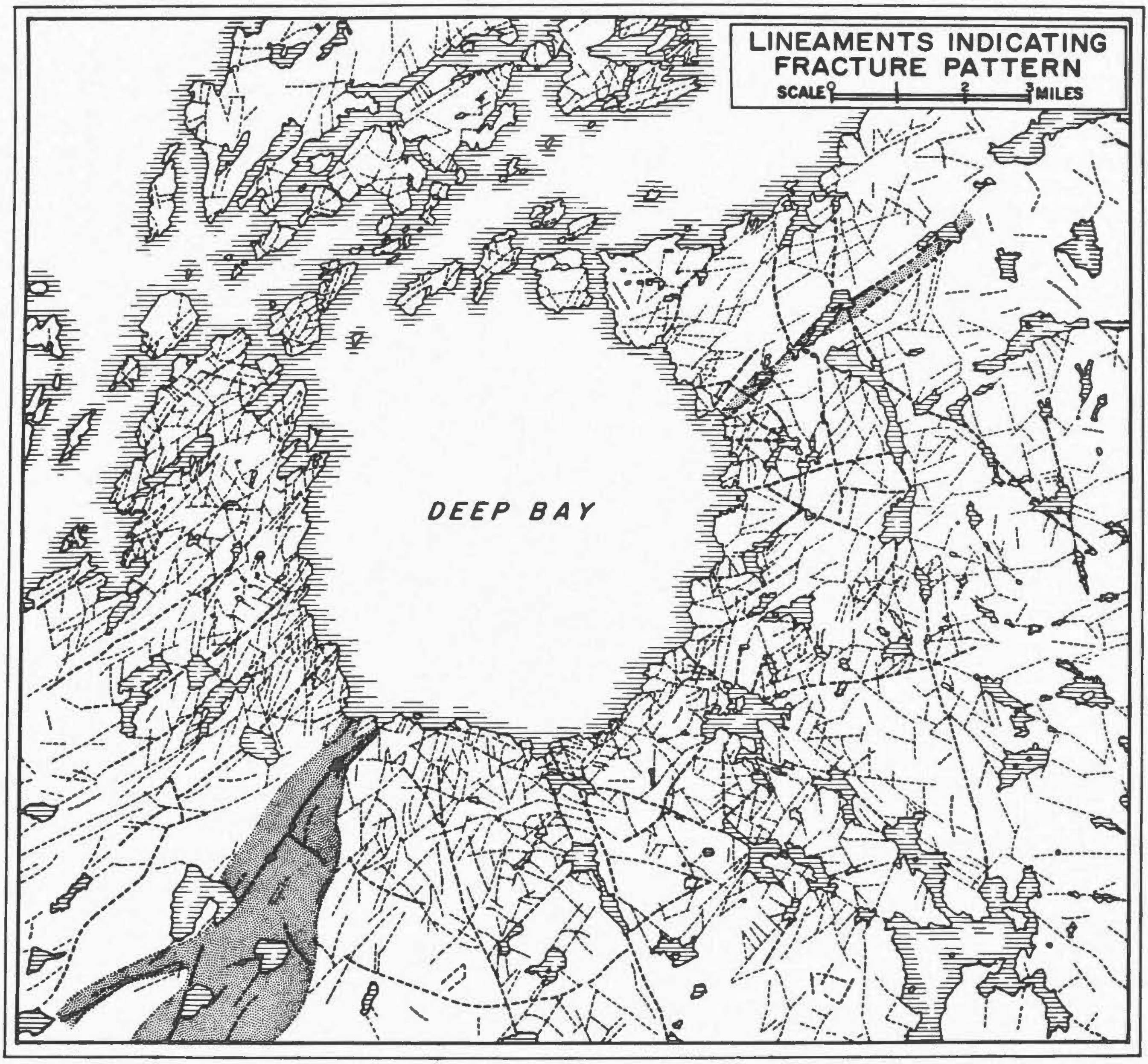

FIGURE 6. Fracture pattern surrounding Deep Bay, on the basis of photo interpretation.

The shale on sectioning was found to carry fossils which appeared to be fish scales, and abundant spores and pollen grains. Presence of the shale posed a problem, for nowhere in the Reindeer Lake area or to the north or northeast has this rock type been observed. Dr. D. J. McLaren of the Geological Survey of Canada kindly had specimens of the shale examined petrographically and for faunal and floral evidence by which the shale could be dated. The conclusions reached are summarized as follows:

1. The rock is a quartzose shale, rich in organic matter and unmetamorphosed.
2. Its age is likely Mesozoic, probably late Jurassic or Cretaceous.
3. It was deposited in a marine environment but presumably not far from shore.

As there are no known occurrences of this rock type within hundreds of miles, the most likely explanation for its presence is that it has been derived from deposits of shale within the bay itself. As will be discussed in a later section the presence of shale in situ near the centre of Deep Bay has been confirmed by drilling but as yet the total thickness of the sedimentary column is not known. The estimate of 2,100 feet for the depth of the crater floor below the original ground level suggests the sedimentary rock underlying the waters of Deep Bay may have a thickness of 1,400 feet.

Gilvarry (1960) noting that the present water depth is considerably less than that predicted for an impact crater the size of Deep Bay, incorrectly concludes that the crater is Pleistocene in age and owes its shallow depth to having been formed in a Pleistocene lake, now largely extinct. He presumes that freezing of the water in the crater has protected it from glacial filling and that its original depth has not changed significantly. In this respect he follows a similar argument used by Harrison (1954) to explain the lack of a great thickness of glacial debris in the New Quebec crater. Harrison's explanation is that with the onset of glaciation the crater lake froze over and formed a firm foundation for the over-riding glacier. However it seems probable that the ice within the crater was not entirely stagnant. Although there is some doubt in regard to the exact nature of the movement of glacial ice, whether by plastic flow or a more complex process of rotational slipping, (Lewis, 1949) the ability of glaciers to scour out basins necessitating movement at the base of the mass of glacial ice has long been recognized. There is indirect evidence (Innes, 1964) that the floor of the New Quebec crater has undergone some glacial scouring.

It is probable that prior to the Pleistocene era the Deep Bay crater was totally filled with sedimentary rock and material, and that it owes its present great depth to glacial scouring. Detailed examination of the depth recordings show that for traverses parallel to the direction of glacial movement, the depth traces are characteristically smooth. On the other hand for traverses opposed to the direction of movement, the traces are more complex indicating irregular grooving of the glacial ice. The U-shaped depression as outlined by the arcuate contours near the middle of the bay is most surely the expression of the main flow of glacial ice having been deflected by the granitic walls of the crater, and a convincing demonstration that movement of ice at the bottom of the bay took place. It is of interest to compare the relief of the floor of Deep Bay with the kidney-shaped lakes occupying the floor of the Brent crater from which an estimated 200 feet of Palaeozoic sediments have been removed by glacial action (Millman, Liberty, Clark, Willmore, and Innes, 1960).

General Geology

General Statement

The rocks of the Deep Bay area are well exposed in the vicinity of the shoreline and rim and are all of Precambrian age, (*see* geological map in pocket and Table 1). The oldest rocks are an assemblage of metamorphic gneisses of sedimentary origin which trend in a northeasterly direction across the northwest half of the area. For purposes of description these have been divided into three main groups—biotite gneisses, hornblende

TABLE 1

TABLE OF GEOLOGICAL FORMATIONS

Cenozoic (Pleistocene and Recent)	Glacial drift	Gravel, sand, boulder clay
Mesozoic	Sedimentary rocks	Unmetamorphosed quartzose shale
		Major unconformity
PRECAMBRIAN	Granitic rocks	Pegmatite, granodiorite, granodiorite gneiss, migmatite
	Migmatite	Migmatite, granitic rocks, pegmatite, augen gneisses, biotite gneiss
		Gradational and intrusive contact
	Metamorphic gneisses	*Calcareous gneisses*—hornblende pyroxene, gneiss, carbonate-pyroxene-hornblende gneiss, calcareous feldspathic quartzite, leucocratic calcareous quartz-feldspar gneiss *Hornblende gneisses*—hornblende-biotite gneiss, hornblende—garnet gneiss. *Biotite gneisses*—biotite-garnet gneiss, biotite gneiss. Feldspathic metasediment

gneisses, and calcareous gneisses. A unit of migmatitic rocks underlies the southeastern half of the area and includes lesser amounts of granitic rocks, pegmatites, augen and biotite gneisses. The geological boundary between the migmatites and gneissic unit to the northwest is gradational in most places. The granitic rocks, including granodiorite, granodiorite gneisses, pegmatites, and migmatite occur along the northwestern and northern sides of the bay. The contact between the granitic unit and gneisses to the southeast is arbitrary. Some of the granitic rocks of this group are definitely intrusive while others appear to be the products of granitization. Both the granodiorite and metamorphic gneisses are cut by pegmatites which may in part be related to the granitic intrusion and in part the result of metamorphic segregation.

For purposes of description the three main groups of metamorphic gneisses have been further subdivided as follows:

(i) *Biotite Gneisses*
  1) Biotite-garnet gneisses
  2) Biotite gneisses

(ii) *Hornblende Gneisses*
  1) Hornblende-garnet gneisses
  2) Hornblende-biotite gneisses

(iii) *Calcareous Gneisses*

1) Hornblende-pyroxene gneiss
2) Carbonate-pyroxene-hornblende gneiss
3) Leucocratic calcareous feldspar-quartz gneiss
4) Calcareous feldspathic quartzite.

The biotite gneisses make up the major part of the metamorphic gneisses with the hornblende-bearing gneisses occurring only as thinner layers interlayered with the biotite variety. For this reason the biotite and hornblende gneisses are mapped as one unit. The calcareous gneisses occur to the north-northeast side of the bay as a well-defined unit.

The feldspathic metasediment was only observed on the north end of an island in Numabin Bay to the west of Deep Bay. This rock type has been intruded by granitic rock which forms the outcrop on the remainder of the island. The metasediment is a fine-grained light buff weathering rock composed essentially of feldspar and quartz. The unit has been strongly sheared and foliated with the foliation striking north 40° east and dipping vertically. Irregular pegmatites cut the metasediment and stringers and lenses of quartz parallel the foliation which appears to be parallel to the original bedding.

The Biotite Gneisses

The presence of garnet is the main distinguishing feature between the biotite-garnet gneiss and the biotite gneiss. The biotite-garnet variety is by far the most abundant and is interlayered with the non-garnetiferous type and the hornblende-bearing gneisses. The biotite-garnet and biotite gneisses vary in grain size from fine to coarse with garnet porphyroblasts attaining a diameter of up to 10 mm. The gneissic structure is generally pronounced, with alternation of biotite-rich layers and ones with abundant quartz and feldspar. Some of the layering is also due to the concentration of garnets in layers up to two inches wide. Commonly the gneissosity is accentuated by the *lit-par-lit* arrangement of narrow stringers and layers of granitic and pegmatitic material. The variation in the amounts of biotite in the different layers gives them different shades of grey ranging from light to dark. Foliation is developed by the parallel orientation of the biotite flakes and is parallel to the gneissosity. Quartz, feldspar, biotite, and garnet are the main constituents. Some non-garnetiferous biotite gneiss layers carry blue quartz. Graphite is present in nearly all these gneisses. A modal analysis of six specimens of the biotite gneisses is given in Table 2.

Microscopically the biotite gneisses have a granoblastic texture in which the quartz and plagioclase generally form a wavy granulitic fabric or a simple mosaic. The biotite nearly always shows pronounced parallel orientation with concentration into definite layers. In some layers the larger grains of quartz and plagioclase are flattened and elongated in the direction of gneissosity and foliation. Grain size ranges from 0.2 to 4 mm with garnets attaining a diameter of 6 mm. The main constituents of the dark layers are quartz, plagioclase and biotite and of the lighter layers quartz and plagioclase. Garnet may be confined to the darker layers, concentrated in definite garnetiferous layers or evenly distributed throughout the rock. The average garnet constituent of the garnetiferous-biotite gneiss is about 9 per cent. Minor amounts of apatite, zircon, and graphite are common to nearly all of these gneisses, while pyrrhotite and pyrite occur in the gneisses in zones of shearing.

TABLE 2.—A MODAL ANALYSIS OF BIOTITE GNEISSES

Slide	P-4R	P-8R	P-9R	P-13R	P-16R	Av.	P-15R
Minerals	%	%	%	%	%	%	%
Quartz	30	38	41	34	33	35	34
Plagioclase	40	29	35	34	48	37	47
Biotite	19	22	20	21	13	19	16
Garnet	10	11	4	1	7	9	
Apatite	×	×	×		×	×	×
Zircon		×	×	×	×	×	
Graphite	1	×	×	×	×	×	3
Magnetite	×					×	
Pyrite	×					×	
Pyrrhotite							×

× = present in minor quantity, $<1\%$
Slides P-4R, −9R, −8R, −13R, −16R—Biotite garnet gneiss
Slide P-15R—Biotite gneiss.

The plagioclase is oligoclase or andesine with anorthite content ranging from An_{28} to An_{40}. The plagioclase is often altered to sericite or sussurite. The quartz is commonly strained and contains microscopic inclusions and bubbles aligned into strings or strains. The biotite is a deep reddish-brown, strongly pleochroic and commonly contains pleochroic halos which surround zircon inclusions. In some cases the biotite shows alteration to penninite and magnetite. Graphite replaces whole lamina in some biotite grains. The garnets generally have a poikiloblastic texture.

The Hornblende Gneisses

The hornblende gneisses form but a small proportion of the unit on the map representing the biotite and hornblende gneisses. There are two main types in the hornblende-bearing group, the hornblende-biotite gneiss, and the hornblende-garnet gneiss.

The hornblende-biotite gneiss is fine to medium grained with alternation of hornblende-rich layers and those of essentially a quartz-feldspar composition. The layers, which vary from grey to dark grey in color depending on the mafic mineral content present, range from 1/10 inch to two inches in thickness. A distinct foliation parallels the layering and the hornblende shows pronounced lineation. Megascopically the gneiss contains hornblende, feldspar, quartz, and minor biotite.

Microscopically, the hornblende-biotite gneiss has a granoblastic texture with the quartz and feldspar forming a simple mosaic and the hornblende and biotite aligned parallel to the gneissosity. There is a wide variation in grain size between the different layers. In the hornblende-biotite layers it ranges from 1 mm to 2 mm while in the quartz-feldspar layers from 2 mm to 4 mm.

Table 3 gives a modal analysis of each of the hornblende gneisses. The hornblende is distinctly pleochroic from green to greenish brown. The plagioclase, which is partly altered to sericite and to a lesser degree to carbonate and muscovite, is oligoclase with an anorthite content of An_{28}. The biotite, which is essentially concentrated in the hornblende-rock layers, is strongly pleochroic from straw yellow to brown. The larger quartz grains show strain and contain strings of microscopic inclusions. The minor constituents include apatite and zircon which occur as euhedral to subhedral grains.

TABLE 3.—A MODAL ANALYSIS OF HORNBLENDE GNEISSES

Rock Type	Hornblende-biotite gneiss	Hornblende-garnet gneiss
Slide	P-49 R	P-113 R
Minerals	%	%
Quartz	32	3
Plagioclase	43	38
Hornblende	17	55
Biotite	7	
Muscovite	×	
Garnet		3
Carbonate	×	×
Apatite	1	
Zircon	×	×
Magnetite		1

× = present in minor amounts, <1%

The hornblende-garnet gneiss is a fine- to medium-grained, well layered gneiss in shades of grey to black. The gneiss has a granular, sugary-looking texture and is quite dense. A foliation parallels the gneissic structure, but lineation of the hornblende in the foliate plane is not pronounced. Megascopically the rock consists essentially of hornblende and feldspar with lesser amounts of quartz and garnet. The size of the garnets average about 1/16 inch in diameter.

Microscopically, the hornblende-garnet gneiss has a granoblastic texture with the feldspar and quartz forming an equigranular mosaic. The hornblende grains have subparallel orientation parallel to gneissosity. Grain size varies from .75 mm to 2.5 mm. In the darker layers hornblende and plagioclase form 93 per cent of the rock with quartz and garnet together with minor constituents —magnetite, zircon and carbonate—forming the remainder.

The hornblende is a brown variety, strongly pleochroic, with pleochroic halos around fine zircon inclusions. The plagioclase, which has an anorthite content of An_{28}, shows minor alteration to sericite and carbonate. The garnets are small and occur as rounded and subhedral forms and they are usually free of inclusions. Magnetite occurs interstitially and replaces both plagioclase and hornblende.

The Calcareous Gneisses

This group of gneisses occurs in an east-northeasterly trending belt on the north-northeast side of the bay and consists of four types, namely:

(i) hornblende-pyroxene gneiss
(ii) carbonate-pyroxene-hornblende gneiss
(iii) leucocratic calcareous feldspar-quartz gneiss
(iv) calcareous feldspathic quartzite.

The carbonate-pyroxene-hornblende gneiss forms the greater portion of these.

The hornblende-pyroxene gneiss occurs interlayered with the carbonate-pyroxene-hornblende variety and is generally fine to medium grained and only moderately gneissic. The layering consists of grey to dark grey layers ranging in thickness from 1/16 inch to one inch and are generally lenticular. Some of the lighter layers or lenses are stained a rusty color. The gneiss consists essentially of hornblende, pyroxene, feldspar, and quartz. In hand specimens the mafic minerals are not easily differentiated. A modal analysis of the different types of calcareous gneisses is given in Table 4.

TABLE 4.—A MODAL ANALYSIS OF CALCAREOUS GNEISSES

Slide	P5-R	P-6R	P-7R	P-48R	P-33R
Minerals	%	%	%	%	%
Quartz	27	1	1	39	57
Plagioclase	42	21	27	45	31
Microcline					7
Biotite	1			1	1
Muscovite					×
Hornblende	19	77	4		7
Pyroxene	10		10		
Carbonate		1	57	2	3
Epidote	1				
Apatite	×			1	
Sphene			1	4	×
Zircon	×			×	
Graphite	×				3
Magnetite		×		×	
Pyrrhotite				×	
Pyrite		×			×

× = present in minor amounts, not estimated.
Slide P5R — Hornblende-pyroxene gneiss
Slide P-6R, P-7R — Carbonate-pyroxene-hornblende gneiss
Slide P-48R — Leucocratic-calcareous-feldspar-quartz gneiss
Slide P-33R — Calcareous feldspathic quartzite.

Microscopically the gneiss is a granoblastic aggregate of plagioclase, quartz, hornblende, pyroxene, and minor biotite with epidote, apatite, zircon, and graphite as minor constituents. The hornblende possesses only a subparallel orientation, while that of the biotite is pronounced. The grain size varies from 0.5 mm to 3 mm. The plagioclase is andesine with an anorthite content of An_{40}. It shows moderate alteration to sericite, chlorite, and carbonate and carries inclusions of hornblende and quartz. The hornblende is of the greenish brown variety, strongly pleochroic and contains pleochroic halos produced by fine zircon inclusions. The quartz shows moderate strain and contains microscopic inclusions commonly found in the quartz of nearly all the gneisses of the area. The biotite is a deep reddish-brown and strongly pleochroic.

The carbonate-pyroxene-hornblende gneiss is fine to medium grained and is well layered. The layering consists of alternating pale greenish grey, dark grey to black, grey-green and pink to buff layers; the thickness of the individual layers ranges from 2/10 inch to three inches. A distinct foliation parallels the gnessic structure and layering in the dark grey and black layers and the lineation of the hornblende is well developed, while that of the grey-green and pink to buff layers is poorly developed.

Microscopically the textures of the different layers is granoblastic with the hornblende in the dark bands showing a linear orientation in the foliate plane. The dark layers consist essentially of hornblende with plagioclase and minor amounts of quartz, epidote, magnetite, and pyrite, while the grey-green layers are composed of plagioclase, pyroxene, carbonate, a small amount of hornblende and minor amounts of quartz and sphene. The pink and buff layers consist mainly of calcite with a minor amount of diopside. The grain size in the grey-green and dark layers ranges from 0.2 mm to 1 mm, while in the pink and buff layers the calcite grains may attain a size of 6 mm. The plagioclase in all the layers is almost entirely altered to saussurite, clinozoisite, sericite, chlorite, and carbonate. It is considered to have a composition of andesine. The hornblende in the black layers is a brown variety, while that in the grey-green is greenish brown and moderately pleochroic. The pyroxene is very pale green to colorless diopside and is partly replaced by hornblende. The sphene when present occurs as rounded to anhedral grains.

The leucocratic calcareous feldspar-quartz gneiss was observed about three miles to the east in a bay off the north shore. It is a medium-grained, light grey to grey, faintly gneissic rock. Megascopically the rock contains feldspar, quartz, hornblende, and carbonate.

Microscopically the gneiss has a granoblastic texture, the quartz and feldspar forming an equigranular mosaic with sutured boundaries between the larger quartz grains. The hornblende has a subparallel orientation and is roughly concentrated into bands. The grain size varies from 1 mm to 3 mm with the larger grains being formed by quartz. The minerals in their order of abundance are plagioclase, quartz, hornblende, sphene, and carbonate. Minor constituents include apatite, zircon, magnetite, pyrite, graphite, and epidote. The oligoclase with an anorthite content of An_{27} is partly altered to sericite, clinozoisite, and carbonate. The hornblende is a green variety with small pleochroic halos. It shows replacement by carbonate, epidote, and vermicular growths of quartz. The carbonate occurs as interstitial grains throughout the slide. The sphene, which is comparatively abundant, is present as subhedral grains up to 1.5 mm in length. The apatite and zircon occur chiefly as small rounded inclusions.

The rock classified as calcareous feldspathic quartzite occurs mainly along the northern side of the calcareous rock unit. The width of the quartzitic layer was not measured but it is estimated that it is at least ten to fifteen feet thick where it outcrops on the northeast point of the mainland opposite the large square shaped island. Original bedding is apparent for it appears that some of the beds were more calcareous than others and have been dissolved out on the weathered surface where it is washed by the waters of the lake, leaving the more siliceous beds standing out in relief. The rock which is fine to medium grained weathers grey to white with rusty staining in places. Macroscopically it consists of quartz, feldspar, and carbonate with lesser amounts of graphite and pyrite.

Microscopically the rock consists of a granoblastic aggregate of quartz and feldspar with graphite and carbonate and minor amounts of biotite, muscovite, sphene, and pyrite. The quartz and feldspar form a wavy mosaic fabric in which the largest quartz grains show elongation parallel to bedding.

The quartz is strained and contains grains of microscopic inclusions. The feldspar consists of oligoclase with an anorthite content of An_{28} and of microcline. The plagioclase is moderately altered to sericite and muscovite. The carbonate is interstitial and the graphite flakes have a subparallel orientation. Biotite, which is present as a minor quantity, is of the reddish-brown variety. The sphene occurs as subhedral grains. Pyrite is interstitial and replaces other minerals.

The Migmatitic Rocks

The unit classified as migmatite consists of biotite gneisses, the greater portion of which has been recrystallized, replaced by, and mixed with quartzofeldspathic material. The rock of this unit varies in grain size from fine to coarse and in color from light to medium grey. The essential minerals are feldspar, quartz, and biotite. The biotite content remains fairly uniform ranging from 17 to 30 per cent. Garnet may or

PLATE IA

PLATE IB

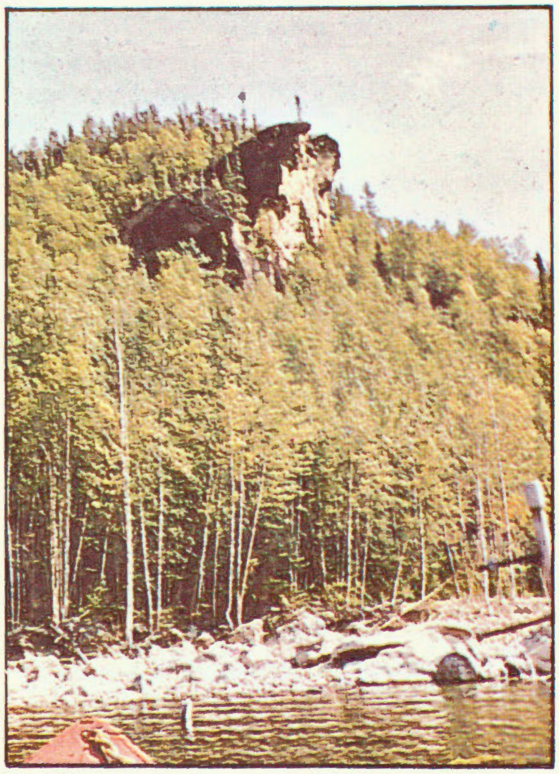

PLATE IIIA

PLATE IIIB

PLATE IIIC

PLATE V

PLATE IA

A view of Reindeer Lake looking southeast; Deep Bay can be seen in the upper right.

PLATE IB

Air photograph of islands near south end of Reindeer Lake.

PLATE IIIA

Vertical rock scarp facing Deep Bay on eastern shoreline.

PLATE IIIB

Wide sand beach along southwest shoreline of Deep Bay.

PLATE IIIC

Concentration of limonite at eastern end of southwest beach.

PLATE V

Vertical scarp forming wall of eastern channel between Deep Bay and Reindeer Lake.

PLATE VIA

Typical shoreline, showing vertical and radial fractures.

PLATE VIB

Rectangular blocks formed by horizontal and vertical jointing along east wall of the crater.

PLATE VIC

Angular blocks, essentially in place fifty feet above lake level, along north shore of the crater.

PLATE VIA

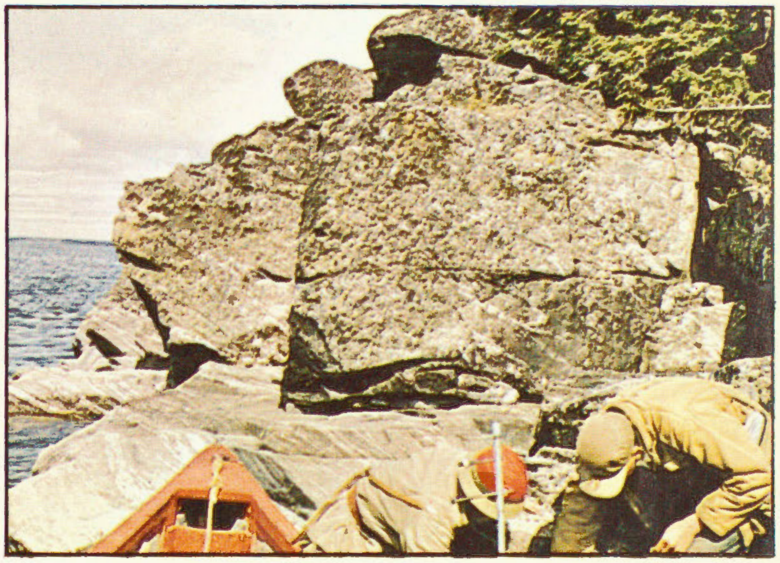

PLATE VIB

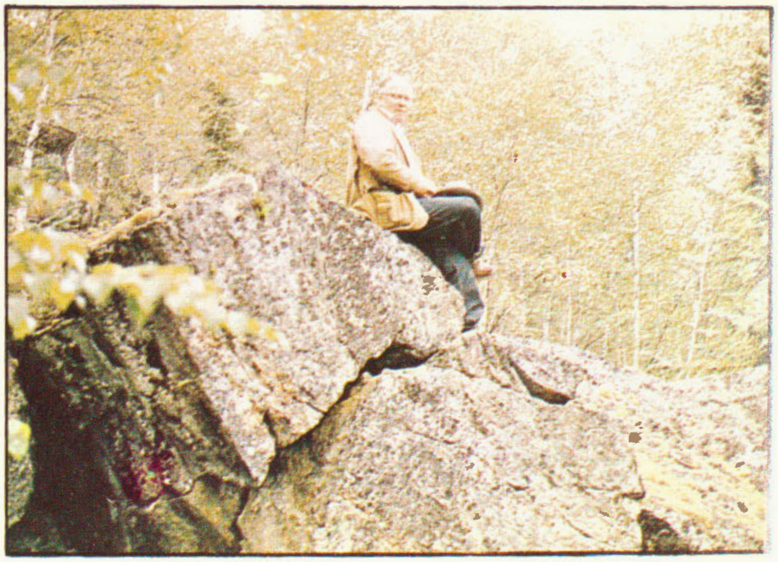

PLATE VIC

may not be present. In the coarser phases of the migmatite porphyroblastic feldspar augen occur, which vary from 1/8 inch to one inch in length. The migmatite generally shows a foliation produced by biotite and a gneissic structure is formed by narrow, elongated layers of the original rock, lenses and layers of recrystallized material and layering produced by metamorphic segregation. Inclusions of the biotite gneisses generally retain an orientation parallel to the regional gneissosity. However, some inclusions may show rotation, indicating mobilization of the introduced material.

TABLE 5.—A MODAL ANALYSIS OF SPECIMENS FROM MIGMATITE ZONE

Slide	P-23R	P-29R	P-63R	P-65R	P-69R	P-73R
Minerals	%	%	%	%	%	%
Quartz	33	28	36	24	35	39
Plagioclase	48	38	32	51	34	41
Microcline				×	6	1
Biotite	17	28	30	18	23	18
Muscovite					1	1
Hornblende				4		
Garnet	2	6				×
Sillimanite	×					
Carbonate	×					×
Epidote				3		
Apatite		×	×	×		×
Sphene				×		×
Zircon	×	×	×		×	
Graphite		×	×		1	×
Magnetite	×	×				

× = present in minor amounts, <1%
P-23R, P-29R—porphyroblastic augen migmatite.

Microscopically the migmatite has a granoblastic texture with quartz and feldspar forming a simple mosaic and the biotite having a subparallel to pronounced foliate arrangement, varying from one area to another within the unit. The variation in grain size is wide, ranging from 1 mm to 5 mm. Table 5 gives the mineral composition of six specimens from the migmatite zone.

Of the six specimens from the migmatite zone all contain oligoclase plagioclase with anorthite contents ranging from An_{25} to An_{30} and three contain microcline. The quartz in general shows strain, contains inclusions and frequently has sutured boundaries. Both the large feldspar and quartz grains contain inclusions of other minerals. The reddish brown variety of biotite is most common, but dark brown and greenish brown varieties are present in some sections. The biotite in nearly all the slides contains pleochroic halos. Muscovite occurs in two sections and hornblende was noted in only one. It was of the green variety and strongly pleochroic. The garnets have a poikiloblastic structure and range in size from $\frac{1}{16}$ to $\frac{1}{2}$ inch in diameter. Section P-23R contains sillimanite which occurs as fine needles associated with quartz. Apatite, zircon, and graphite are common minor constituents while carbonate, sphene, and magnetite are less common. Alteration products include sericite after feldspar, penninite after biotite and epidote after plagioclase and biotite.

The Granitic Rocks

The granitic rock unit lies to the extreme north side of the area mapped. This unit includes granodiorite, granodiorite gneiss, pegmatite, and some migmatite. No true granite was observed in the area. The migmatite occurs more or less in the contact zone of the granodiorite with the biotite gneisses.

The largest masses of granodiorite were observed on two large islands at the north edge of the bay. These are considered to be of intrusive origin for they carry inclusions of biotite gneiss which sometimes show rotation with respect to the gneissosity of the gneisses in the immediate area. To the north and west of the granodiorite the rock is mainly granodiorite gneiss which in part at least is the product of granitization.

The granodiorite is a medium- to coarse-grained pinkish grey rock which in places is massive, exhibiting no or very minor foliation while in other localities it possesses distinct foliation produced by the parallel alignment of the biotite.

The granodiorite gneisses designated in the geological map are generally medium grained and vary from faintly gneissic to distinctly layered, the layering being produced by the concentration of biotite into definite layers. The major constituents of both the granodiorite and gneisses are quartz, feldspar, and biotite.

TABLE 6.—A MODAL ANALYSIS OF SPECIMENS FROM GRANITIC UNIT

Rock Type	Granodiorite	Granodiorite gneiss
Slide	P-2R	P-90R
Minerals	%	%
Quartz	31	18
Plagioclase	35	23
Microcline	29	24
Biotite	5	33
Muscovite		×
Carbonate	×	
Apatite	×	×
Zircon	×	×
Magnetite	×	2

×—present in minor quantity

Microscopically the granodiorite and gneisses contain quartz, plagioclase, and microcline in a granoblastic mosaic. The orientation of the biotite is random to subparallel in the granodiorite while in the gneisses it is more pronounced. Table 6 gives the modal analysis of two specimens of the granitic rocks.

The main difference between the granodiorite and granodiorite gneiss is the proportion of feldspar and quartz in the grandiorite and the greater amount of biotite in the gneiss where it is more distinctly confined to definite layers. The plagioclase is oligoclase with an anorthite content ranging from An_{20} to An_{29}. Albite, pericline, and carlsbad twinning is common. The microcline exhibits the typical grid twinning. The plagioclase shows considerable alteration to sericite and saussurite in the granodiorite while in some of the gneisses there is alteration to carbonate and muscovite as well. Sericitization of the microcline has taken place to a minor degree. The quartz, which is generally interstitial to the feldspar, shows slight to moderate strain in the granodiorite but in some of the gneisses it is much more pronounced. Strings of microscopic inclusions are commonly present in the quartz of both the grandiorite and granodiorite gneiss. The biotite in the granodiorite is of the reddish brown variety, strongly pleochroic from pale yellow to reddish brown while in the gneisses it may be either dark brown or reddish brown. Pleochroic halos are common. Biotite shows alteration to penninite associated with magnetite. Accessory minerals include apatite and magnetite.

Economic Geology

There are no known mineral deposits of economic importance in the immediate area but there are graphite, pyrite and pyrrhotite occurrences. Graphite is a common minor constituent of most of the gneisses, but it occurs as a major constituent in some layers of gneiss within the synclinal structure on the west side of the bay. Here some layers and lenses are estimated to contain as much as 25 per cent graphite. Outcrops carrying these layers weather a yellowish brown to yellow and are easily observed from the air. The gneisses carrying graphite in this structure are highly sheared and foliated. The graphite occurs as flakes lying in the foliate or shear plane. Disseminated pyrite and pyrrhotite are associated with the graphite.

Finely disseminated pyrite and pyrrhotite with some graphite occur in shear zones up to 15 feet wide in a number of zones around the bay. These zones weather a reddish brown to yellowish brown and are conspicuous even at a distance. Areas of mineralization are indicated on the geological map.

Structure

Careful examination of the structural relationships between these various rock types in no way suggests a geological origin for Deep Bay. In the geological investigation, particular attention was paid to mapping structure, to determine if the bay and surrounding rim could have resulted from some form of structural control. As only a reconnaissance geological study has been carried out so far, liberal use of aerial photographs has been made to determine structural and regional trends, lineaments and fracture patterns.

Both foliation and gneissosity are well developed in the gneisses and generally parallel one another, but in certain localities a second foliation has been superimposed. Some of the layering in the gneisses is regarded as being due to the recrystallization of the original sedimentary beds, thus the foliation and gneissosity in all the rock units generally strike in a northeasterly direction and dip from 85 to 40 degrees to the northwest. The general trend (*see* geological map in pocket) is approximately the same on both sides of the bay.

The regional structural trend (Figure 7) is also northeasterly, striking across the bay, thus indicating that the depression forming Deep Bay is not structurally controlled. A prominent structural feature on the west side is a shallow synclinal structure that is abruptly terminated at the shoreline. To the south and east the structural trends indicate complicated folding which bears no relationship to the shape of Deep Bay.

That Deep Bay is the result of a tremendous explosion is clearly indicated by the intense fracturing and shattering of the granitic rocks which is most pronounced in the vicinity of the shoreline. Large-scale fracture zones and fault zones of various widths, now partially obscured by glacial action and deposition, cut radially and obliquely across the rim and persist for several miles from the margin of the bay. Although these are quite difficult to trace from ground observation they stand out quite clearly when seen from an aircraft or from aerial photographs. Deciduous trees, chiefly birch and poplar characteristically tend to flourish in the depressed fracture zones, while coniferous varieties, mainly spruce seem to prefer the ridges and higher terrain.

The most prominent lineaments are shown in Figure 6. Various phenomena such as fractures, faults, bedding planes, schistosity, glaciation and others all have a bearing on their organization and contribute to their pattern. Although the lineaments have a somewhat random arrangement, there are prominent sets which extend for great distances and are more or less radial to the shoreline. These may be attributed to the crater-forming event. One such set of lineaments corresponds to the main channels of the northeast and southwest trending valleys described in the topography. Although it has been suggested that these are preglacial valleys, there is evidence that both valleys may be controlled by large radial faults formed by the explosion and later accentuated by glacial action. Plate IV shows an almost vertical scarp of a fault that parallels the northeastern valley on its northwestern side. Further, in the vicinity of the small lake (*see* topographical map in pocket) about three miles southwest of the bay, a trail follows the southwest valley between two prominent parallel ridges which

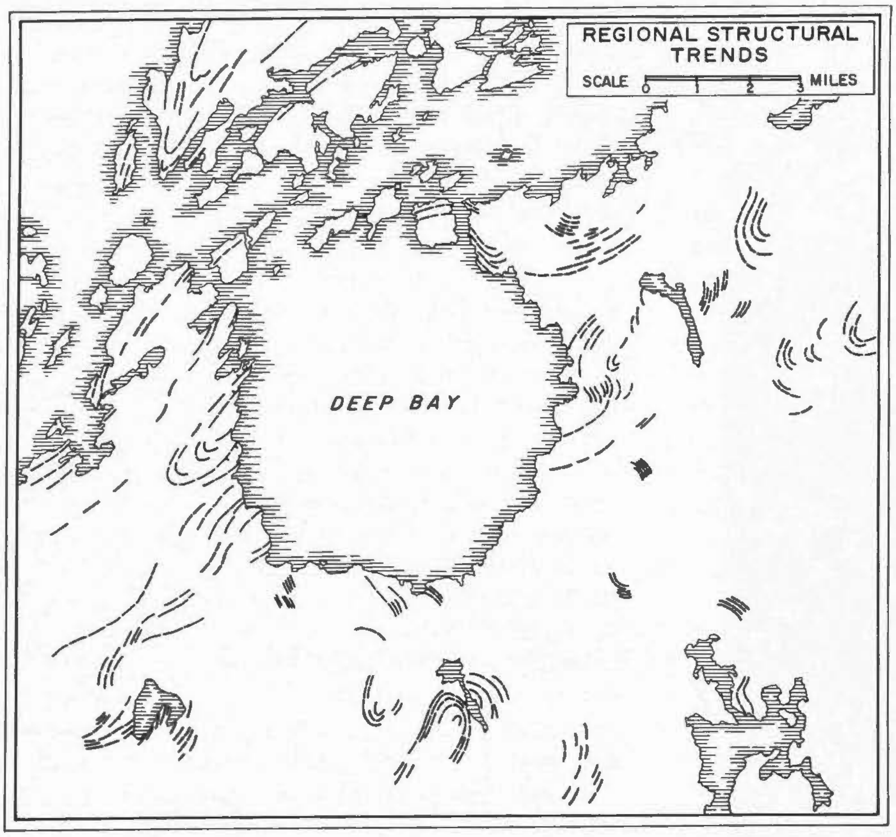

FIGURE 7
Regional structure trends.

rise 100 to 175 feet above the valley floor and which in places are less than one-tenth of a mile apart. A heavy mantle of fine sand drapes both ridges forming slopes varying from about 30 to 45 degrees, the angle of repose for sand. This and the straightness of the depression strongly suggest that these sand ridges are bedrock controlled and that the course of the southwest valley is in fact controlled by a radial fault zone. It seems likely that the channels connecting Deep Bay with the main body of Reindeer Lake to the north also may prove to be the expression of radial faulting. Evidence for such faulting is provided from the abruptly rising rock walls and from water soundings, which, show (*see* topographical map) that the channels, particularly the two eastern ones, are extraordinarily deep. Plate V is a view of the scarp which forms the eastern wall of the eastern channel.

The rocks forming the shoreline of Deep Bay show signs of major shattering and fragmentation (*see* Plates VIA, VIB, VIC, centre spread). A close-set pattern of jointing has been observed in many rock exposures but generally the jointing has resulted in the formation of huge rectangular blocks which decrease in number as the jointing decreases in intensity with increasing distance from the bay. Figure 6 shows the lineaments and the fracture pattern in considerable detail.

A system of concentric fractures is also well developed particularly in that area less than three miles from the shoreline. Perhaps the most prominent feature that may be the expression of such fracturing is a narrow arcuate lake three miles long, located about three miles east of the crater. There is some evidence from the drainage pattern and from the dissected topography that this depressed zone is much longer and circumscribes the whole crater and has a diameter of about 12 miles. Within this area lie the rocks that form the now deeply eroded rim of the crater, with the general appearance of having been shattered into huge blocks by a process involving little or no horizontal movement.

Implications of Structure Data

Nearly 30 years ago, Boon and Albritten (1936) in an attempt to explain generally the salient features of the underlying structure of meteorite craters suggested a concentric pattern of ring synclines and anticlines as one outstanding characteristic of impact structures. The circular fracture zone surrounding the rim of the Deep Bay crater may indeed be identified as a ring syncline in the sense that it is generally a depressed zone, but by no stretch of the imagination is it possible to identify topographical irregularities at larger distances, as outer concentric anticlines and synclines. Without doubt this circular break occurred in response to compressional and tensional stresses set up in the violent action of the crater's formation. It has a diameter of 12 miles, nearly twice the diameter of the present crater at ground level, and roughly marks the outer limit of intense fracturing

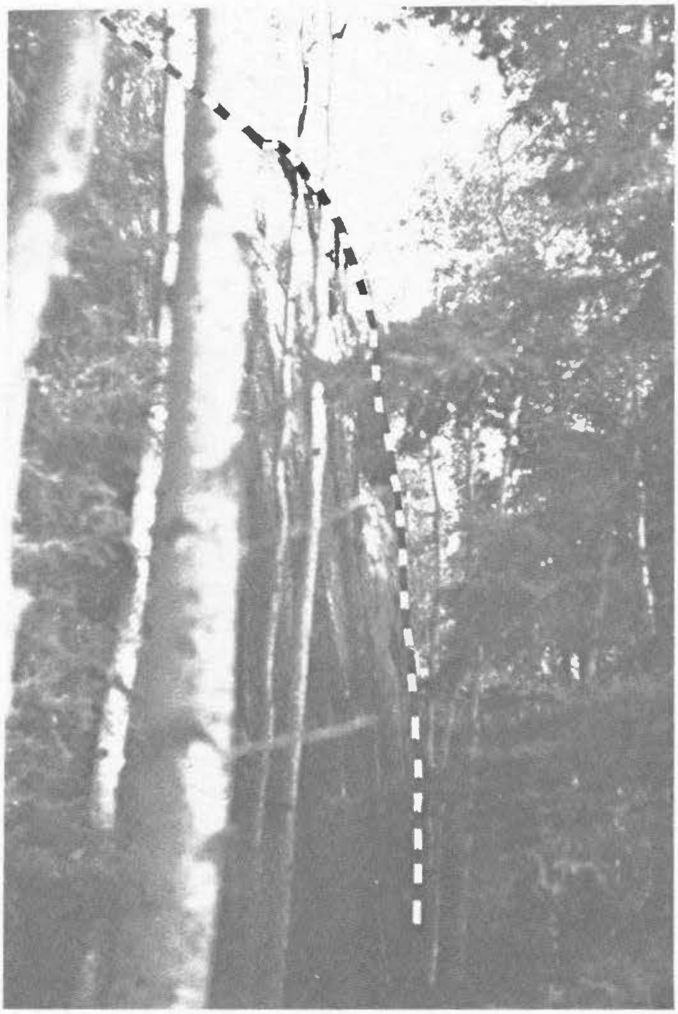

PLATE IV A
Radial fault scarp that parallels northeastern valley.

PLATE IV B
Close-set pattern of rock-fracturing along north shore.

and jointing accompanying uplift of the crustal rocks in the formation of the rim. The fracture zone surrounding the Brent crater (Millman, Liberty, Clark, Willmore and Innes, 1960) is in a much more advanced stage of erosion but nevertheless careful stereoscopic examination of the aerial photographs reveals, particularly on the northeast side of the crater, a partial 'ghost' ring or halo having an indefinite diameter of about 20,000 feet. This is also about twice the accepted crater diameter.

The circular fracture surrounding Deep Bay may be analagous to the markings surrounding the lunar maria although these have diameters (150 to 670 km) on a scale much grander than that of Deep Bay. Hartman and Kuiper (1963) interpret the concentric structures surrounding the lunar basins as ring-faults formed at the times of the impacts which formed the basins. Their table which gives the diameters of the lunar concentric systems, indicates that for the smaller basins, the ratio of the diameters of the outer rings to the diameters of the basins vary from 1.9 to 2.2. Interestingly enough the same ratio is found if the dimensions of extremely small impact craters are examined. For example, in experiments to investigate the mechanism and conditions under which shatter cones may be formed by shock from high-speed impact, Shoemaker and Gault (1962) describe a tiny crater, 5 cm in diameter and 1.3 cm deep formed by impact of a spherical aluminum pellet into dolomite. Of interest to this discussion is the fact that the impact also formed an almost completely circular fracture zone having a diameter of 11 cm or 2.2 times larger than this small crater's diameter.

Although it is obvious that circular fracturing must be a consequence of and accompany all cratering by impact, the true nature of the process is not clearly understood. Ring fractures have not been observed at the more recently formed Arizona and New Quebec craters, perhaps largely because of being obscured by overlying drift and unconsolidated material. In view of the interesting comparisons made above and the more advanced stage of erosion at Deep Bay, which permits a view of the rock deformation to a considerable depth, the fracture zone surrounding Deep Bay warrants further careful field examination and possibly diamond drilling.

Geophysical Investigations

The topographical, geological and structural investigations that have been outlined, strongly support the hypothesis that Deep Bay has been formed by meteoritic impact and explosion. If so, the great amount of energy expended in its formation would result in marked changes in the physical properties of the country rock, not only at the point of impact but in the area surrounding the crater. Accordingly geophysical investigations employing magnetic, gravity and seismic methods were carried out in the expectation that they might provide important evidence to test the validity of an explosive origin.

Magnetic Investigations

The total-intensity magnetic map of the Deep Bay area (in pocket) is based upon an aeromagnetic survey carried out by the Geological Survey of Canada. Because of the rugged topography the observations were carried out at a flight altitude of 1,000 feet above general ground level, almost twice the height usually flown in conducting detailed aeromagnetic surveys in the Canadian Shield areas. Nevertheless, the results are equally definitive and in qualitative agreement with the magnetic results obtained at other fossil craters (Millman, Liberty, Clark, Willmore, and Innes, 1960).

It is generally known that granitic gneisses of the Canadian Shield produce highly variable magnetic fields, largely due to concentrations of magnetite crystals in contact zones and along bedding planes. Apparently these crystals become polarized under the influence of the earth's magnetic field during the processes of thermal and dynamic metamorphism in which the rocks were transformed into gneisses. Contours of variations in the magnetic field, therefore, tend to follow the outlined major structural features.

The magnetic field in the Deep Bay area is highly irregular with local disturbances giving rise to steep gradients of as much as 600 gammas per mile, the anomaly contours tending to follow the prominent structural trends of the gneisses. The variation in intensity appears related to the amount of granitic material within the gneisses. Peak anomaly values and also the steepest gradients are produced by the paragneisses that underlie the northwestern half of the crater area; on the other hand the intensities are much lower and uniform over the injection gneisses to the south and east. The most significant feature of the magnetic map is the small and uniform variation in intensity over the central portion of the crater when compared with the anomalies for the surrounding area. Over the bay, the total variation does not exceed 190 gammas with uniform gradients no larger than 50 gammas/mile.

Several factors, all of which are consistent with the hypothesis of an explosive origin, may be mentioned to explain satisfactorily the low magnetic relief associated with the central part of the crater. First of all the aeromagnetic data are influenced by variations in the distance between the magnetic source and the magnetometer. These results are typical of those in areas of deep sedimentation, the widely spaced contours and low gradients being an indication of a considerable depth to the boundaries between rocks of contrasting magnetic properties. While the great thickness of sedimentary material now filling the crater would contribute considerably to the

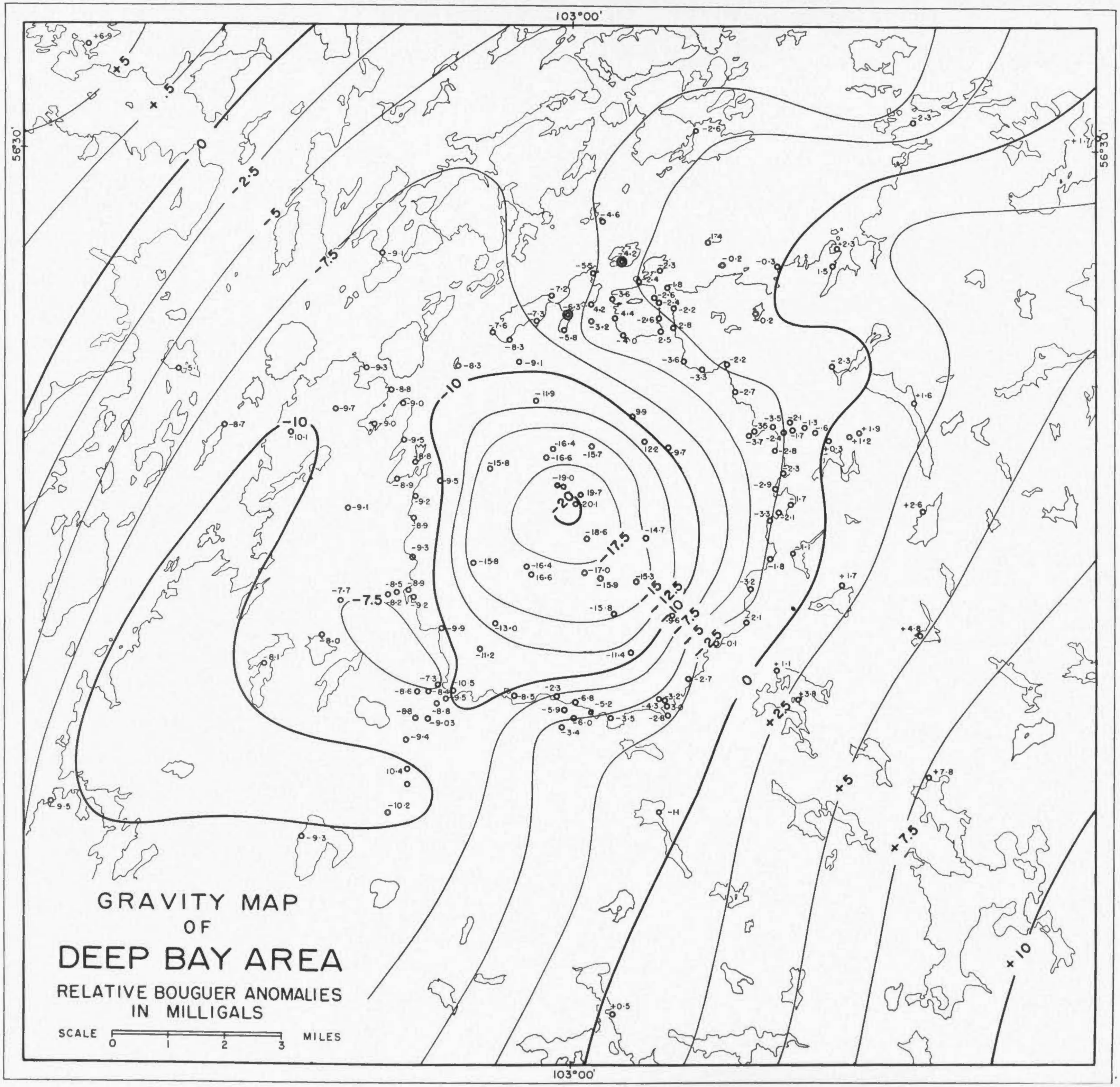

FIGURE 8. Bouguer gravity anomaly map contoured at intervals of 2.5 mgals.

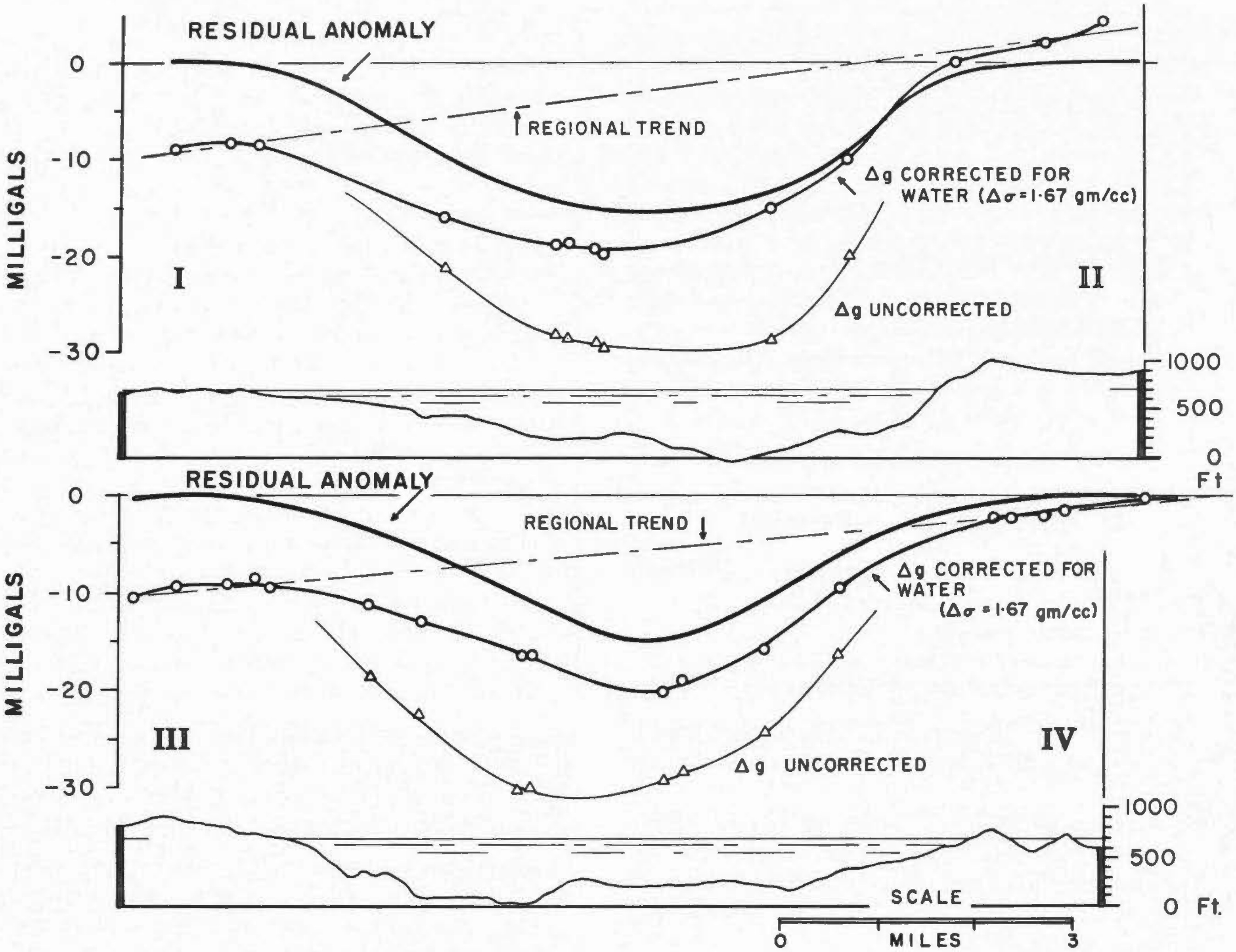

FIGURE 9. Gravity and topographical profiles I—II, and III—IV across Deep Bay.

decrease in magnetic intensity because of its lower and more uniform susceptibility compared to the surrounding gneisses, the great volume of fragmental rock and breccia underlying the sediments most likely is responsible for the major effect. Impact and explosion would disrupt the systematic alignment of the magnetic materials within the gneisses to form a random distribution of poles within the brecciated zone, thus resulting in a general decrease in the magnetic field intensity.

There is evidence that the crater-forming event also disrupted the magnetic pattern beyond the shoreline of Deep Bay. It will be noticed that the low magnetic relief extends about three miles to the southeast of the shoreline of Deep Bay and also northwest to the edge of the map area. The area is underlain by paragneisses that, although disturbed, have suffered very little or no horizontal movement. While no straightforward explanation can be offered without further investigation, it seems possible that the apparent abnormal polarization may be a magneto-mechanical phenomenon, whereby the magnetization of these rocks has been altered as the result of shock. It also seems possible that heat generated by the impact may have been sufficiently high for the rocks to lose their magnetism.

Gravity Results

The gravity anomaly map (Figure 8) and two diametrical gravity profiles (Figure 9) give the important results of the gravity investigation. The rugged terrain and dense vegetation surrounding the crater made the gravimeter operations very difficult and the usual practice of establishing a rectangular array of stations could not be followed. However the gravimeter observations totalling 122 land stations and 27 ice stations seem plentiful enough to provide a clear picture of the main variations in the gravitational field over the crater and vicinity. While conventional gravimeters were used to observe the land stations, a thermostatically controlled Worden gravimeter with greater than usual damping characteristics and a specially constructed eyepiece for averaging the readings was employed for the measurements during the winter from the ice surface of the Bay.

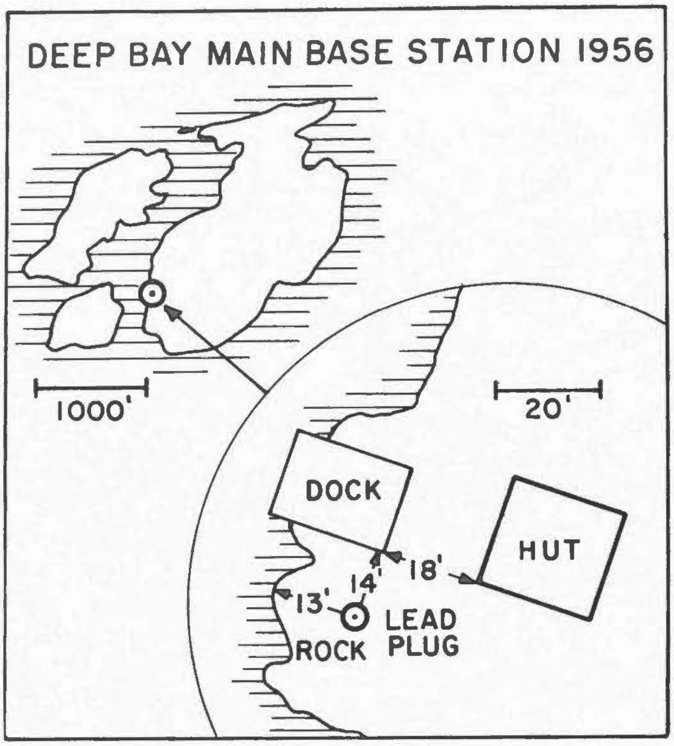

FIGURE 10
Site of main gravity base station.

Repeat observations at selected stations indicated that the gravity measurements have uncertainties of 0.2 mgal or less.

The Bouguer anomaly values are all relative to an arbitrarily selected main base station located to the north of Deep Bay on a small island in Reindeer Lake and identified by a lead marker in a rock outcrop (Figure 10). This station has coordinates;

Latitude: 56° 28′.2 N.
Longitude: 102° 58′.8 W.
Height: 1,110 feet above mean sea level.

The value of gravity for this station is 2.8 mgals higher than Dominion Observatory base station no. 9185-60 and has an absolute value of 981.5321 cm/sec^2, relative to the national base station in Ottawa. From this it may be deduced that the relative gravity anomaly of -4.21 mgals adopted for the main base station corresponds to an absolute Bouguer anomaly of -39.60 mgals and that all anomaly values in Figure 8 may be converted to absolute Bouguer anomalies by subtracting 35.39 mgals.

In preliminary reports of this work (Innes, 1957, 1961, and Beals, Innes, and Rottenberg, 1963) the Bouguer anomaly values were calculated in the usual way using a surface density of 2.67 gms/cc, arbitrarily adopted before density data were available from rock sampling. More recently the densities of 153 samples of granitic rocks from the area have been found to have a mean value of 2.77 gms/cc. The distribution of the rock sampling is shown in Figure 3; the location number, description, and density of each specimen are collected in a table in Appendix A; while the mean density for each of the four main groups of granitic rocks recognized in the area are given in Table 7. Use of 2.67 gms/cc in-

TABLE 7.—TABLE OF ROCK MEAN DENSITIES AND GRAVITY ANOMALIES

Rock Unit	Rock Density (gms/cc)			Gravity Anomalies (mgals)		
	No. of Samples	Range in Density	Density	No. of Stations	Range	Mean
Granodiorite and granodiorite gneiss	28	2.60–3.07	2.72	19	− 9.3 to −1.4	−6.09
Biotite garnet and hornblende paragneisses	47	2.47–3.05	2.78	36	− 9.9 to +1.6	−5.6
Calcareous gneisses	17	2.66–3.02	2.85	11	− 6.3 to +2.3	−2.38
Migmatites	61	2.63–3.06	2.75	48	−10.2 to +7.8	−3.67
Mean	153		2.765	114		−2.96

stead of 2.77 gms/cc in the reductions, produces errors as great as 0.2 mgal for the land stations of higher elevation, and 0.9 mgal for ice stations where water depths are the greatest. Because of the present uncertainty of the variation of density with depth within the crater, only a qualitative interpretation of the gravity anomalies is attempted here, and such reduction errors may be deemed negligible. However to facilitate further study and detailed analysis of the gravity field when better control is available the principal facts for the 27 gravity measurements made on the ice surface of Deep Bay are collected in Appendix B.

The gravity map shows relative Bouguer anomalies contoured at intervals of 2.5 mgals. The anomalies have a total range of 27 mgals, from -20 mgals near the middle of Deep Bay and about $+7$ mgals in each of the northwest and southeast quadrants of the map area. The trends of the contours are northeasterly conforming with the general direction of the geological structure. In Table 7 the range and mean value of the gravity anomalies are tabulated for each of the units of granitic rocks. Although both density and anomaly values are quite variable for each unit their mean values nevertheless show some direct correlation.

As found over other circular features of suspected meteoritic origin the gravitational field associated with Deep Bay is negative with contours of equal anomaly forming a circular pattern concentric with the shoreline. The amplitude of the gravity variation is much larger than found associated with other structures, reaching a minimum value after corrections for water depths, of about 20 mgals near the centre of the Bay. After making a further correction for regional gradients of about 0.9 and 1.3 mgals per mile to the northeast and southeast respectively the maximum residual anomaly (Figure 9) is about -15 mgals.

With little doubt the relatively lower gravity values over Deep Bay must arise from the low-density sedimentary rocks within the basin and the underlying broken and fragmental granitic rocks. As gravity provides a measure of the total rock deformation suffered during the crater's formation (Innes, 1961) it is important to distinguish the relative amounts of these two low-density materials. Unfortunately the gravity anomalies by themselves do no suffice for this and a direct answer must await the results of a successful diamond drilling program. The results of a seismic survey of Deep Bay (Sanders, Overton and Bataille, 1964) using refraction techniques, are consistent with the gravity measurements and show a disturbed zone under the crater in which the velocity of propagation of the seismic waves is approximately 25 per cent less than the normal background value of 20,000 ft/sec for Precambrian terrain. As the observations were made on ice, which has a seismic velocity of 10,000 ft/sec, definitive values for the propagation velocity of the sedimentary rock could not be obtained. However the results suggest that the sedimentary sequence may extend to depths of 1,800 to 2,500 feet below the level of the lake. More definitive seismic information should be obtainable from a summer survey.

Erratics of Cretaceous shale discovered on the south beach were found to have densities which vary from 2.00 to 2.64 gms/cc with a mean value of 2.53 gms/cc. If the sedimentary material now lying above the crater floor consists of shale having the same mean density, its contribution to the negative gravity field for the thicknesses estimated above would vary from 3 to 6 mgals, leaving from 9 to 12 mgals to be explained by the underlying fragmental rocks.

Diamond Drilling Results

The Drilling Program

A diamond-drilling program was undertaken from the ice surface of Deep Bay during the winter of 1961–62 in order (1) to determine the depth from the surface of the lake to the floor of the original crater, and the nature of the material lying above and below the crater floor; (2) to test generally the structural interpretations based upon geophysical and geological observations. Two holes 62–1 and 62–1A were put down at the sites indicated in Figure 3. It would be expected that the most valuable information could be obtained by drilling at the exact centre of the crater where the water depth is about 575 feet. However because of the limited experience Canadian companies have had in drilling in deep water, it was necessary to restrict the operations to sites where depths are 400 feet or less. The site for the first hole, 62-1 therefore, was located about three quarters of a mile west of the centre of the crater, where, over a small area of about 20 acres, the present floor rises so that the water depth is slightly less than 400 feet (*see* topographical map in pocket). The hole was put down to a total depth of 591 feet below the surface of the lake. After penetrating 400 feet of water and about 100 feet of fine silty clay including one granite boulder three feet thick, poorly compacted shale was encountered. The shale was more indurated with depth, which permitted fair core recovery from a depth of 507 feet to the bottom of the hole.

At a depth of 591 feet the drill rods became stuck and it became necessary to abandon the hole before reaching the full objective. Inability to provide adequate support for the outer casing and to maintain it in a vertical attitude presented grave difficulties. As great lengths of casing and several strings of drilling rods had already been lost through failure and buckling of the outer casing and as very little time remained before spring breakup of the ice , it was deemed advisable to complete the operation by drilling in much shallower water.

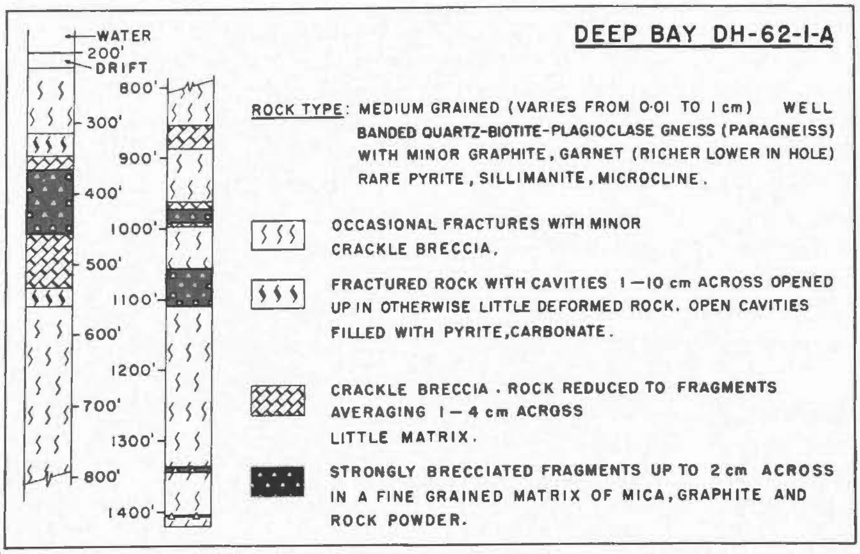

FIGURE 11
Log of drilling and vertical section for drill hole 62-1A.

Accordingly the drill rig was moved to a site about one mile from the eastern shoreline of the bay where the water is only about 200 feet deep. Although considerable difficulty was also experienced here in penetrating the unconsolidated material and glacial drift, this 62-1A hole was finally collared into bedrock at a depth of 240 feet, and put down to a total depth of 1,420 feet.

Logs of Drill Hole 62 1-A

A log and vertical section showing the rock types encountered in hole 62-1A are illustrated in Figure 11. Specimens of core are shown in Plate VII. The rock types lie entirely within the biotite-garnet gneiss unit recognized in the general field geology of the region. The main variety is a well-layered, medium-grained, quartz-oligoclase-biotite gneiss with a number of associated minerals in varying proportions. From near-surface down to 1,125 feet graphite is conspicuous, making up as much as 10 per cent of the rock in some bands. Garnet is abundant below 582 feet rising to as much as 35 per cent of the mode at 1,125 feet. Sillimanite was identified in a biotite-granite gneiss from 395 feet. Common accessories include apatite, pyrite, microcline, monazite, and zircon. Diopside occurs with the sillimanite-bearing gneiss but amphibole was not recognized in any thin section.

A minor assemblage of coarser quartz-microcline-muscovite rocks forms thin irregular horizons within the biotite-garnet gneisses and may be genetically associated with the nearby migmatite unit. Minor oligoclase and biotite with this assemblage are strongly altered to sericite and chlorite respectively.

The granoblastic, post-kinematic texture which is typical of this gneiss group has been overprinted by an intense deformation leading to the development of zones of fracturing, crushing, and brecciation. At its most intense, the deformation yields a breccia of wall rock fragments up to several centimetres across in a matrix of finely crushed minerals also derived from the wall rock. Introduced carbonate with or without pyrite cements the breccia matrix in some cases. The same minerals line cavities that have been opened up in the closely fractured rocks flanking the breccia zones. Alteration of feldspars and mafic minerals to sericite and chlorite respectively is conspicuous where this mineralization has taken place. However there is no sign of secondary quartz. Primary quartz in some cases shows intense undulous extinction which may be connected with the brecciation.

There is no evidence of strong lithologic control over the localization of deformation as all rock types are brecciated in similar manner. The absence of secondary quartz raises hopes that high-pressure polymorphs such as coesite, if formed, may still survive.

Discussion of Drilling Results

The drilling results suggest that the original crater diameter was considerably less than 40,000 feet as first estimated. Although the drill core from hole 62-1A shows evidence of intense deformation with the development of extensive zones of breccia, there are nevertheless long sections of core, up to 400 feet long in which only occasional fractures are evident. These slightly fractured sections grade into zones of crackle or mosaic (Norton, W. M., 1917) breccia, which is rock reduced to fragments containing little or no matrix. The zones of crackle breccia in turn grade into the zones of most intense deformation in which the strongly brecciated fragments

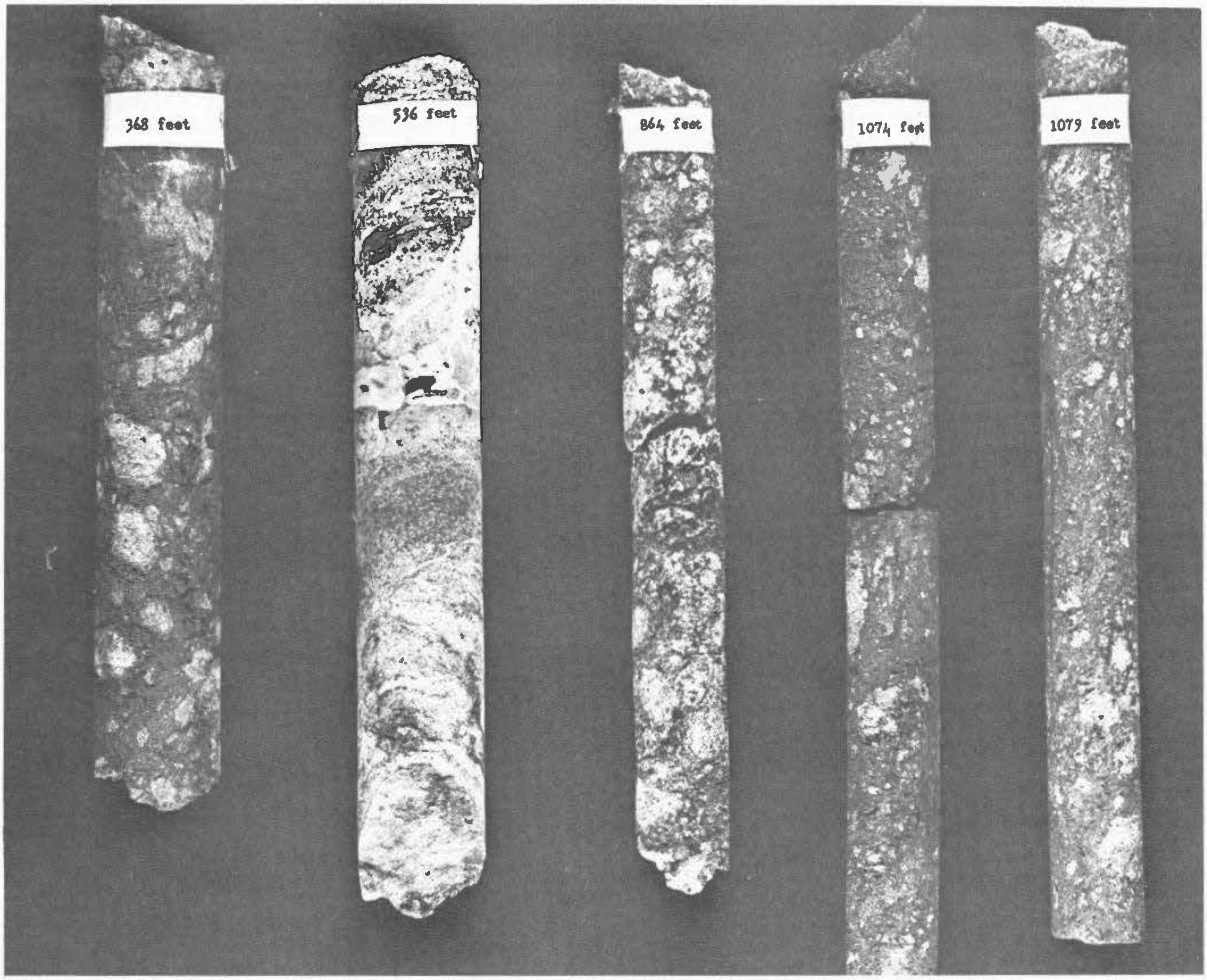

PLATE VII. Specimens of drill core from drill hole 62-1A.

are bound in a fine-grained matrix of mica, graphite and rock powder. The general nature of the deformation in which there is little or no evidence of mixing strongly suggests that hole 62-1A is situated very close to the outer limit of the zone of complete rupture but does not lie within it.

The estimate of an original rim diameter of 40,000 feet for Deep Bay is based upon the assumption that the present shoreline, which has a diameter of about $6\frac{1}{2}$ miles (34,300 feet) represents the sectioning of the true crater at the average level of the surrounding terrain at the time the crater was formed. If this estimate is correct one would expect that in drilling offshore at the site of hole 62 1A it would be necessary to penetrate at least 500 feet of overburden and/or consolidated sedimentary material before reaching the breccia zone. The fact that the drilling intersected granite gneiss that is essentially in place at a depth of 240 feet below the surface of the lake is, therefore, further evidence that the original crater diameter was considerably less than 40,000 feet.

This conclusion and the fact that the upper surface of the sedimentary rock (shale) was found to lie at a depth of 500 feet near the centre of the lake led to a re-examination of the depth recordings to see if it were possible to make a better estimate of the configuration of the true crater, its centre, and the horizontal distribution of the sedimentary rock within it. The results of this investigation are illustrated in Figure 12. It was found that the character of the depth profiles tends to vary with their orientation, whereby those profiles, or portions thereof that parallel the direction of glacial ice movement, are distinctly less irregular than those that are opposed. This may be seen from careful analysis of depth records reproduced in Figure 4.

The topographically featureless areas of the crater floor are believed to be the expression of flat-lying sedi-

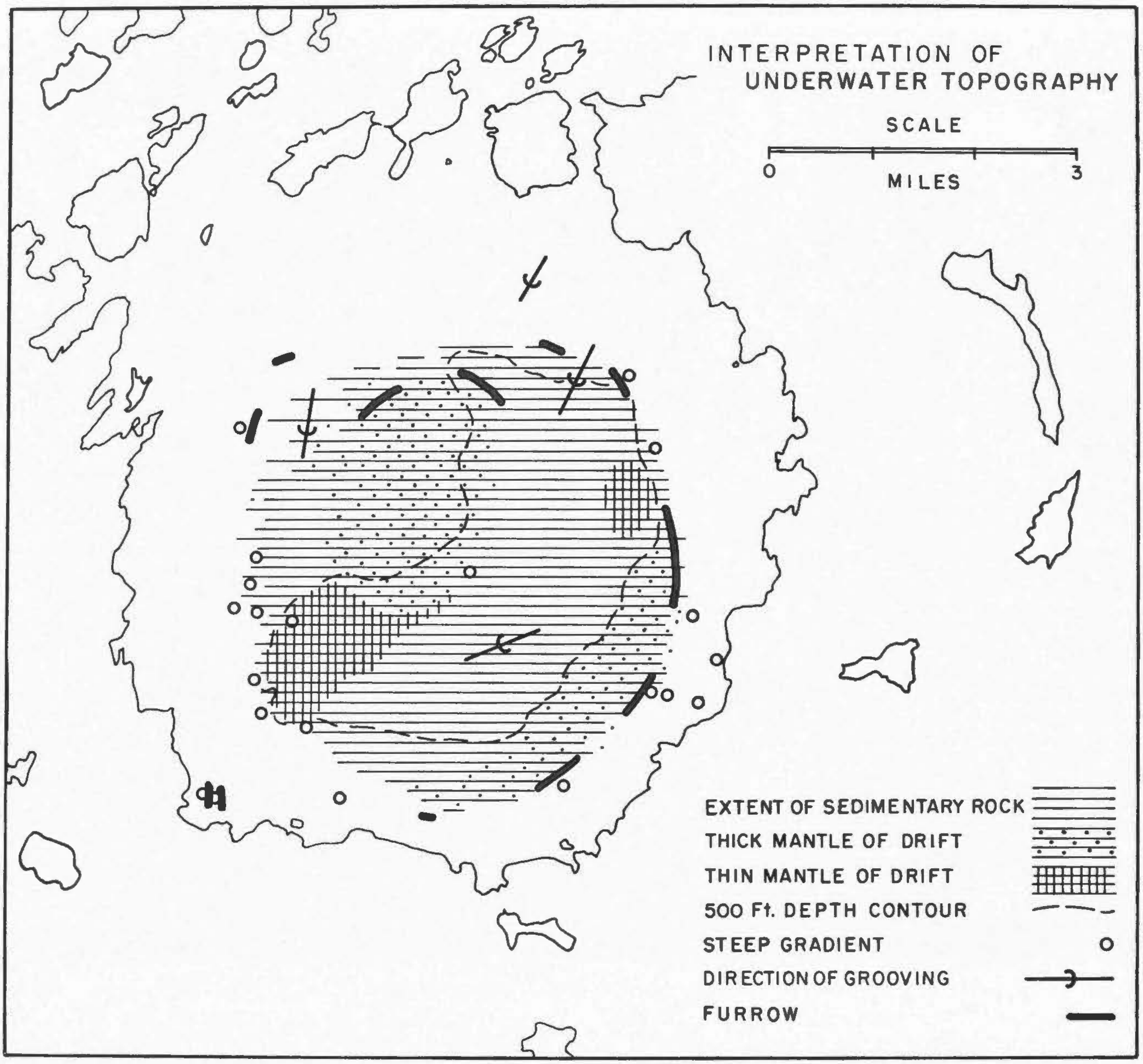

FIGURE 12. Geological interpretation of the underwater topography of Deep Bay.

mentary rock above which the mantle of glacial drift and unconsolidated material is thin. It is significant that all these areas lie at depths of about 500 feet or greater; in contrast, irregularities in the relief of the crater floor in other areas are believed largely due to varying thicknesses of the glacial deposits. Quantitative analyses show that the gradients of the depth profiles across the inner slopes of the crater vary from about 5 to 20 degrees but in several places, notably to the south and east, the gradients reach maximum values of about 35 degrees. Abrupt changes in the gradient that are clearly indicated on all records, are believed to mark the outer limit of complete rupture. The arcuate furrows or depressions near this outer limit are believed to be the expression of the contact between the sedimentary rock and the gneisses forming the crater's inner wall. Projection down-slope from the points where these discontinuities occur, to a depth of 500 feet, has been used to define the outer limit of the bay underlain by sedimentary rock as illustrated in Figure 12. The configuration of this area is nearly circular with a diameter of about 4.5 miles or 23,760 feet.

The conclusion then, that this hole lies within the fracture zone, and the fact that no sedimentary rock was encountered suggests that the original crater diameter was considerably less than 40,000 feet as was first estimated. The revised crater model consistent with this new information and based upon Baldwin's (1963) depth-diameter relationships, is illustrated in Figure 13. The revised crater dimensions are as follows:

Original rim diameter	—	31,000 feet
Apparent crater depth	—	3,200 feet
Rim height	—	890 feet
True depth	—	3,210 feet

These dimensions suggest that at least 450 feet of the crater's original rim has been eroded, and that the sedimentary rocks now lying within the crater have a minimum thickness of about 1,600 feet.

The most important result from the drilling operation has been confirmation of the interpretation given the geophysical data, namely that the negative anomaly fields reflect deformation of rock underlying the waters of Deep Bay in the form of intense fracturing and fragmentation. Although it may now be predicted more confidently that crater-filling breccia underlies the sedimentary rocks within the bay, it is extremely important to follow up this work by successfully putting down a drill hole at the centre of the crater.

Age of the Deep Bay Crater

From the evidence on hand it is possible to fix the age of the Deep Bay crater only within very wide limits. It is clear from the foregoing that it has been formed in granite gneiss of the Churchill province of the Canadian Shield and is therefore younger than the Hudsonian orogeny (Stockwell, 1962) or 1,700 million years. Diamond drilling has revealed the existence of at least 100 feet of undisturbed Mesozoic strata near the centre of the bay. On the basis of fossil evidence these strata are considered to be of Upper Jurassic or Lower Cretaceous age, formed about 150 million years ago. This also may be taken as a minimum age of the crater, but of course does not preclude the possibility of older strata at depth. Although it is dangerous to estimate geological age upon the amount of erosion, the fact that the deeply eroded rim is sufficiently high to control the drainage in the area, suggests that the Deep Bay crater is perhaps not much older than the sedimentary rock within and this may be taken as a fair estimate of the age of the Deep Bay crater.

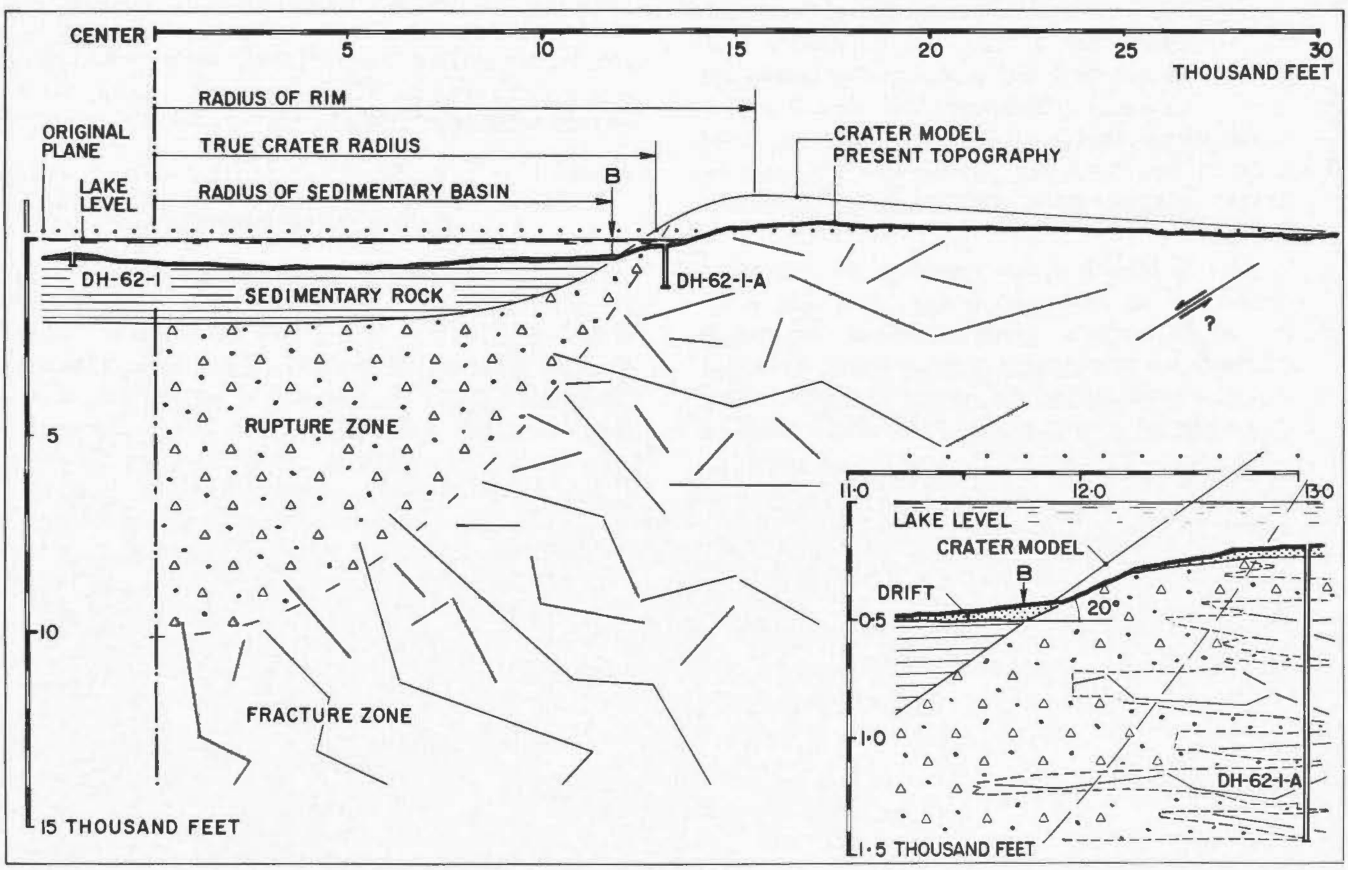

FIGURE 13. Structural section of Deep Bay based on topographical, geophysical and drilling results. The dimensions of the crater model are based on Baldwin's (1963) depth-diameter relationship.

Summary and Future Investigations

In presenting this account of the investigation, the suggestion that Deep Bay is of meteoritic origin is accepted even though positive identification such as the discovery of meteoritic material is lacking. All evidence topographical, geological, and geophysical indicate a crater structurally similar to the well-authenticated Barringer meteorite crater in Arizona. This is clearly recognized even though Deep Bay is many times larger, has been formed in a terrain underlain by much harder rock, is aeons older and is deeply eroded, so much so, that only a portion of its original superstructure remains. No evidence has been uncovered to support the possibility that Deep Bay may have been formed from internal forces. The fact that the crater's walls cut abruptly across pre-existing structures eliminates the possibility that Deep Bay is geologically controlled. There is no evidence to suggest that the crater is an erosion basin formed by certain rock types eroding more quickly than others; nor is there evidence that the crater has been formed by subsidence, controlled by faulting or by systems of intersecting faults. Deep Bay lies near the centre of the Canadian Shield and remote from areas in which there is evidence that volcanic activity has occurred since the end of Precambrian time. It should finally be mentioned that of the Canadian craters that have been studied and identified as of probably meteoritic origin (Beals, Innes and Rottenberg, 1960; Halliday and Griffin, 1963; Dence, Innes, and Beals, 1964; Dence, 1964; Innes, 1964) all have a random distribution and show no preference of location in respect to major or minor geological structures.

Although the results of the foregoing investigations have the merit of appearing to explain Deep Bay as of meteoritic origin, definite confirmation of the events that produced this outstanding feature can be achieved only by further investigation and study. A complete and thorough geological investigation of the area should be carried out, with particular attention being given to structural details, including statistical studies of rock deformation and fracturing for a distance of at least one diameter from the shoreline of Deep Bay. At the same time a systematic rock sampling program is required to provide oriented specimens for laboratory studies of rock deformation, as well as for the determination of the density and the magnetic and other physical properties of the country rock. Further geophysical work should include (a) more complete gravity mapping both in the vicinity of the crater and over the bay itself; (b) careful seismic work during the summer months to map the configuration of the true crater floor; (c) long-term heat-flow measurements from the deepest part of the bay.

Most important of all is the need to carry out a diamond-drilling program from the ice surface of the bay in winter. Drill cores from holes successfully put down offshore and near the middle of the bay will provide information for a wide variety of basic studies related to crater formation. First of all they will provide information concerning the character of the material underlying the crater's floor from which it should be possible to distinguish with confidence between the rock deformation resulting from comparatively slow tectonic events and the more complete crushing and fragmentation characteristic of impact breccia. Basic studies should include careful petrographic examination of the drill cores for shock-induced effects, including changes in the physical properties of the rocks and the determination of the nature and amount of shock-melted materials. Diamond drilling of the crater will enable a better estimate to be made of the crater parameters, its true depth, width, the extent of the lens of breccia postulated to underlie the crater floor and the age of the crater. Finally because of the restricted environment offered by the Deep Bay crater, the sedimentary rock lying within it should provide a splendid record of all marine transgressions and withdrawals for this area of the Shield, since the craters formation. Clearly the scientific study of the Deep Bay crater has only begun.

Acknowledgements

Many individuals contributed to the research program reported here. The authors are indebted to A. I. Bereskin, Comptroller of Surveys, Department of Natural Resources of the province of Saskatchewan and other members of his department for their support and cooperation during the early stages of the field investigation, to the late Professor D. S. Rawson of the University of Saskatchewan for bathymetric data, to Dr. D. J. McLaren of the Geological Survey of Canada for examining specimens of shale and identifying the fossils they contain, to M. R. Dence of the Gravity Division for logging the diamond drill cores and assisting in their interpretation. Finally we are indebted to Dr. C. S. Beals, Director of the Dominion Observatory for his interest in this project and many stimulating discussions.

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APPENDIX A

Table of Rock Densities

Specimen Number	Rock Description	Density
1	Biotite-quartz-feldspar-garnet gneiss	2.76
2	Granite (intruding No. 1)	2.68
2	“ “ “	2.63
3	Biotite-quartz-feldspar-garnet gneiss	2.78
4	Biotite-quartz-feldspar-garnet gneiss	2.84
5	Hornblende-biotite-quartz-feldspar-garnet gneiss	2.88
6	Hornblende gneiss	3.01
6	Hornblende-calcareous-quartzitic gneiss	3.02
7	Calcareous banded gneiss (quartzitic)	2.86
7	“ “ “ “	2.81
7	“ “ “ “	2.82
8	Garnet-biotite-quartz-feldspar gneiss	2.88
9	Biotite-quartz-feldspar-garnet gneiss with granitic injection	2.72
9	Quartz-feldspar-biotite-garnet gneiss	
10	Quartz-feldspar-biotite-garnet gneiss	2.71
11	Mineralized-quartz-feldspar-biotite gneiss	2.47
12	Biotite-quartz-feldspar-garnet gneiss	2.65
12	Biotite-quartz-feldspar-garnet gneiss	2.76
12	“ “ “ “ “	2.78
13	Garnet-biotite-quartz-feldspar gneiss	2.81
14	Pegmatite carrying chrome mica	2.56
14	“ “ “ “	2.51
15	Quartz-biotite-garnet gneiss	2.72
16	Biotite-quartz-feldspar-garnet gneiss	2.74
16	“ “ “ “ “	2.70
16	“ “ “ “ “	2.68
17	Biotite-quartz-feldspar-garnet-injection gneiss	2.74
18	Unmetamorphosed quartzose shale (drift only)	2.10
19	Feldspar augen-biotite-quartz-feldspar-garnet gneiss	2.70
20	“ “ “ “ “	2.61
21	Biotite-quartz-feldspar gneiss with granite injection	2.71
21	“ “ “ “ “	2.62
21	“ “ “ “ “	2.68
21	“ “ “ “ “	2.60
22	Biotite-hornblende-quartz-feldspar gneiss	2.71
23a	Feldspar augen-injection gneiss	2.71
23b	Feldspar augen-biotite-quartz-feldspar gneiss	2.73
24	Feldspar augen-injection gneiss	2.80
24	“ “ “ “	2.77
25	Biotite-quartz-feldspar-garnet injection gneiss	2.70
25	Feldspar augen-injection gneiss	2.72
25	“ “ “ “	2.64
25	“ “ “ “	2.74
26	Feldspar augen biotite-quartz-feldspar-garnet gneiss	2.76
26	Feldspar augen-injection gneiss	2.70
26	“ “ “	2.66
27	Feldspar augen-injection gneiss	2.69
28	Feldspar augen-injection gneiss	2.74
29a	Biotite-quartz-feldspar-garnet gneiss	2.77
29b	“ “ “ “ feldspar augen gneiss	2.76
30	Biotite-quartz-feldspar gneiss	2.89
30	“ “ “	2.78
30	“ “ “	2.61
30	“ “ “	2.78
31	Biotite-quartz-feldspar gneiss	2.80
32	“ “ “	2.76
32	“ “ “	2.74
33	Calcareous-quartzitic gneiss	2.66
33	“ “ “	2.94
34	Graphite mineralization in gneiss	2.68
35a	Hornblende gneiss	2.96
35b	Garnet-hornblende gneiss	2.90
35c	Calcareous-quartzitic gneiss	2.86
35d	Hornblende-quartz-feldspar gneiss	2.82
35	“ “ “ “	2.71
37	Calcareous-quartzitic gneiss	2.78
37	“ “ “	2.81
38	Hornblende-biotite-quartz-feldspar gneiss	2.85
38	“ “ “ “ “	2.84
38	“ “ “ “ “	2.87
39	Hornblende-biotite-quartz-feldspar-garnet gneiss	2.82
39	“ “ “ “ “ “	2.89
40	Biotite-quartz-feldspar-garnet gneiss	2.82
40	“ “ “ “ “	2.95
40	“ “ “ “ “	2.79
41	Biotite-quartz-feldspar-garnet gneiss	2.73
41	“ “ “ “ “	2.73
42	Quartz-feldspar-biotite gneiss	2.74
42	“ “ “ “	2.73

Specimen Number	Rock Description	Density
43	Granite	2.59
43	“	2.68
43	“	2.64
43	“	2.60
44	Quartz-feldspar-biotite-garnet gneiss	2.76
45	“ “ “ “	2.89
46	Biotite-quartz-feldspar gneiss (graphite mineralization)	2.74
47	Feldspar augen-biotite-quartz-feldspar gneiss	2.77
48	Quartz-feldspar-hornblende gneiss	2.72
49	Hornblende-quartz-feldspar gneiss	2.81
50	Hornblende-biotite-quartz-feldspar-garnet gneiss	2.96
51a	Biotite-quartz-feldspar-garnet gneiss	2.79
51b	Biotite-quartz-feldspar-garnet injection gneiss	2.75
52	Biotite-quartz-feldspar-garnet gneiss	2.83
53	Biotite-quartz-feldspar-garnet gneiss	2.79
53	“ “ “ “ “	2.75
54	Hornblende gneiss	3.04
54	“ “	3.04
55	Quartz-feldspar-biotite injection gneiss	2.77
55	“ “ “ “ “	2.74
56	Quartz-feldspar-biotite-garnet gneiss	2.69
56	“ “ “ “ “	2.62
57	Quartz-feldspar-hornblende gneiss	2.77
58	Biotite-quartz-feldspar-garnet gneiss	2.79
59	Feldspar augen injection gneiss	2.66
60	Biotite-quartz-feldspar-garnet gneiss	2.78
61	Graphitic granite	2.63
62	Pegmatite carrying magnetite	2.96
62	“ “ “	2.74
63	Biotite-hornblende-quartz-feldspar gneiss	2.74
64	Biotite-quartz-feldspar injection gneiss	2.77
65	Quartz-feldspar-biotite-hornblende gneiss	2.74
65	“ “ “ “ “	2.72
66	Feldspar augen injection gneiss	2.67
66	“ “ “ “	2.67
66	“ “ “ “	2.68
67	Mineralized gneiss	2.66
67	“ “	2.88
68	Feldspar augen injection gneiss	2.72
68	“ “ “ “	2.76
69	Feldspar augen gneiss	2.70
69		2.72
70	Feldspar augen gneiss	2.75
71	Quartz-feldspar-biotite-garnet injection gneiss	2.79
71	“ “ “ “ “	2.77
71	“ “ “ “ “	2.79
72	Garnetiferous-feldspar augen gneiss	2.81
73	Feldspar augen gneiss	2.73
75	Biotite-quartz-feldspar-garnet injection gneiss	2.84
75	“ “ “ “ “ “	2.84
76a	Biotite-quartz-feldspar-garnet injection gneiss	2.76
76b	“ “ “ “ “ “	3.05
77	Quartz-feldspar-biotite-garnet gneiss	2.78
78	Feldspar augen biotite-quartz-feldspar-garnet gneiss	2.75
79	Biotite-quartz-feldspar-garnet gneiss	2.74
80	Biotite-quartz-feldspar-garnet gneiss	2.73
81	Biotite-quartz-feldspar-garnet gneiss	2.74
81	“ “ “ “ “	2.77
81	“ “ “ “ “	2.76
82a	Granite	
82b	Feldspar augen biotite-quartz-feldspar-garnet gneiss	2.76
82	“ “ “ “ “	2.64
83	Biotite-hornblende-quartz-feldspar gneiss	2.77
83	“ “ “ “ “	2.79
84	Biotite-granitic gneiss	2.70
85	“ “ “	2.69
85	“ “ “	2.68
86	Arkose	2.70
86	“	2.68
86	“	2.68
86	“	2.66
87	Biotite-quartz-feldspar gneiss	2.79
88	“ “ “ “	2.73
88	“ “ “ “	2.78
89	Granite (coarse grains)	2.60
90	Banded biotite-quartz-feldspar gneiss (granitic)	2.71
90	“ “ “ “ “ “	2.70
91	Amphibolite	3.07
92	Feldspar augen biotite-quartz-feldspar gneiss	2.73
93	Feldspar augen injection gneiss	
94	“ “ “ “	
95	Biotite-quartz-feldspar-garnet gneiss	

APPENDIX A—*Concluded*

Specimen Number	Rock Description	Density	Specimen Number	Rock Description	Density
96	Feldspar augen injection gneiss		105	Mineralized graphite and sulphide biotite-quartz-feldspar-garnet gneiss	
97	Injection gneiss	2.70	107	Garnetiferous feldspar augen gneiss	2.75
98	Biotite-quartz-feldspar-garnet gneiss (medium grained)	2.74	108	Biotite-quartz-feldspar injection gneiss	2.74
98	Biotite-quartz-feldspar-garnet gneiss (coarse grained)	2.70	108	" " " "	2.80
98	Biotite-quartz-feldspar-garnet gneiss	2.72	109a	Calcareous gneiss	
99	Feldspar augen injection gneiss	2.75	109b	Biotite-quartz-feldspar (associated with [a])	2.90
100	Injection gneiss	2.70	110	Quartz-feldspar-biotite gneiss	2.77
101	Biotite-quartz-feldspar gneiss	2.76	110	" " " "	2.76
102	" " " injection gneiss	2.81	111	Biotite-quartz-feldspar gneiss	2.76
103a	Mineralized graphite quartz-feldspar-biotite gneiss etc.		112	Hornblende gneiss (2 varieties)	2.74
103b	Biotite-quartz-feldspar gneiss		112	" "	2.88
104	Biotite-quartz-feldspar-garnet gneiss		113	" "	3.06
			116	Biotite-quartz-feldspar-garnet gneiss	2.75
			117	" " " " "	2.75
			118a	Granite	2.60
			118b	Biotite-quartz-feldspar-garnet gneiss	2.78

APPENDIX B

Principal Facts for Ice Stations

Station No.*	Water Depth (ft)	Δg from main Base (mgals)	Latitude Correction (mgals)	Relative Bouguer Anomaly		
				$\sigma=2.0$ gm/cm³ (mgals)	$\sigma=2.67$ gm/cm³ (mgals)	$\sigma=2.77$ gm/cm³ (mgals)
T-1	450	−25.7	+3.1	−16.9	−13.0	−12.4
T-2	420	−17.6	−1.3	−13.5	− 9.9	− 9.4
T-3	450	−29.7	+0.4	−23.6	−19.7	−19.1
T-4	650	−32.4	+2.0	−22.1	−16.6	−15.7
T-5	350	−22.3	+3.6	−14.2	−11.2	−10.8
T-6	710	−31.0	+1.2	−20.7	−14.7	−13.8
T-7(D)	460	−29.1	+0.2	−23.0	−19.1	−18.5
T-8(D')	450	−28.8	+0.2	−22.9	−19.0	−18.4
T-10	100	− 8.8	−2.4	−10.0	− 9.1	− 8.6
T-11	230	−15.3	−1.5	−13.9	−11.9	−11.6
T-12	360	−23.6	−0.5	−19.5	−16.4	−16.0
T-13	450	−30.4	+0.7	−24.0	−20.1	−19.5
T-14	510	−30.7	+1.3	−22.9	−18.6	−17.9
T-15	675	−32.5	+2.2	−21.7	−15.9	−15.0
T-16	540	−30.3	+3.0	−20.4	−15.8	−15.1
T-17	420	−24.2	+3.8	−15.0	−11.4	−10.9
T-18	0	−11.1	+1.6	− 9.5	− 9.5	− 9.5
T-19	290	−23.8	+1.8	−18.3	−15.8	−15.4
T-20	650	−32.2	+2.0	−21.9	−16.4	15.5
T-21	660	−33.1	+2.1	−22.6	−17.0	−16.1
T-22	650	−31.3	+2.2	−20.8	−15.3	−14.4
T-23	140	−13.4	+0.1	−11.4	−10.3	−10.1
T-24	250	−21.2	−0.2	−18.2	−16.1	−15.7
T-25	400	−24.5	−0.3	−19.7	−16.6	−15.8
T-26	475	−25.1	−0.6	−19.6	−15.7	−15.0
T-27	510	−22.3	−0.6	−16.4	−12.1	−11.4
T-28	540	−21.2	−0.5	−14.8	− 9.7	− 9.5
T-29	450	−23.1	+2.9	−14.5	−10.6	−10.0

*For location of stations see Figure 3.