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THE BRENT CRATER

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The Brent Crater

PART I

General Considerations

BY

Peter M. Millman

ABSTRACT.—The feature known as Brent Crater, located in Algonquin park, Ontario, was first observed on aerial photographs as a circular depression approximately 2 miles in diameter. Geological investigations indicated that the circular area was underlain by Palaeozoic sediments while the surrounding country rock was mainly granite gneiss. Magnetic investigations led to the conclusion that the crater was filled with material of lower magnetic susceptibility than the surrounding rock. Seismic observations indicated that the crater contained up to 1,000 feet of fairly soft rocks, and perhaps 3,000 feet of other material in which seismic waves travelled more slowly than in the surrounding gneiss. Gravity observations showed that the crater was filled with material of relatively low density to a depth of from 1,500 to 4,000 feet depending upon assumptions concerning the average density contrast. A diamond drill hole near the centre penetrated to a depth of 570 feet of Palaeozoic sediments while a second hole near the edge revealed the presence of large quantities of rock breccia. It was concluded that the crater was formed by the impact of a meteorite, *possibly* in late Precambrian time and that its present state was a consequence of subsequent erosion and the deposition within it of Palaeozoic sediments.

RÉSUMÉ.—L'accident géographique connu sous le nom de cratère Brent et situé dans le parc Algonquin (Ontario) a été observé pour la première fois sur des photos aériennes révélant l'existence d'une dépression circulaire d'un diamètre d'environ deux milles. Il découle d'études géologiques faites sur place que cette cuvette repose sur une assise de roches sédimentaires paléozoïques, alors que le gneiss granitique prédomine dans la région environnante. Des observations magnétiques ont démontré que ce cratère est rempli de matière rocheuse dont la sensibilité magnétique est plus faible que celle de la roche environnante. A l'aide d'appareils sismiques, on a établi que ce cratère contient une couche de quelque mille pieds d'épaisseur de roches plutôt tendres, et peut-être 3,000 pieds d'autres matériaux au travers desquels les ondes sismiques se propagent plus lentement qu'à travers le gneiss encaissant. Des observations gravimétriques ont démontré que la densité des matériaux rassemblés dans ce cratère est relativement faible jusqu'à une profondeur de 1,500 à 4,000 pieds, et varie suivant les hypothèses relatives au contraste de densité moyenne. Un trou percé à l'aide d'une foreuse à diamant près du centre a traversé 570 pieds des sédiments paléozoïques, mais un second trou percé près du bord du cratère a révélé la présence de fortes quantités de roche bréchoïde. On en a conclu qu'il s'agit d'un cratère météorique, causé par la chute et l'explosion d'une météorite, à la fin du précambrien *peut-être*, et que son état actuel est l'effet de l'érosion subséquente des sédiments qui s'y sont déposés au cours du paléozoïque.

In 1951 John A. Roberts, President of Spartan Air Services Ltd., Ottawa, was looking over some of the high altitude vertical air photographs of Ontario taken by his company for the Government of Canada. In an area on the north border of Algonquin provincial park near Brent, Ontario, he noticed the outline of a nearly perfect circle superimposed on a terrain of thick woods and numerous small lakes, (*see* Figure 1). The 1950 expedition from the Royal Ontario Museum, led by Dr. V. B. Meen to study a large crater in the north of Ungava Peninsula (Meen, 1950), had highlighted the possible connection between circular markings on the Canadian Shield and ancient meteorite falls. Spartan Air Services got in touch with the Dominion Astronomer, Dr. C. S. Beals, and showed him the Brent photograph. After discussions with the Geological Survey of Canada it was decided that during the summer of 1951 the Dept. of Mines and Technical Surveys would send a small exploratory expedition to study the area from the ground and to decide whether a more extensive geophysical investigation was warranted.

The centre of the circle apparent on the air photographs is at lat. 46° 04′ 31″ N, long. 78° 29′ 00″ W. In the discussions which follow, this feature will be termed the "Brent Crater" for convenience in reference.

The personnel of the exploratory expedition were Dr. H. M. A. Rice, Geological Survey of Canada, A. A. Onhauser and W. E. T. Smith, Geomagnetic Division of the Dominion Observatory, and the writer, at that time with the Stellar Physics Division of the Dominion Observatory. The investigation was carried out between July 4 and July 9, 1951. There was no access by road to the area but access

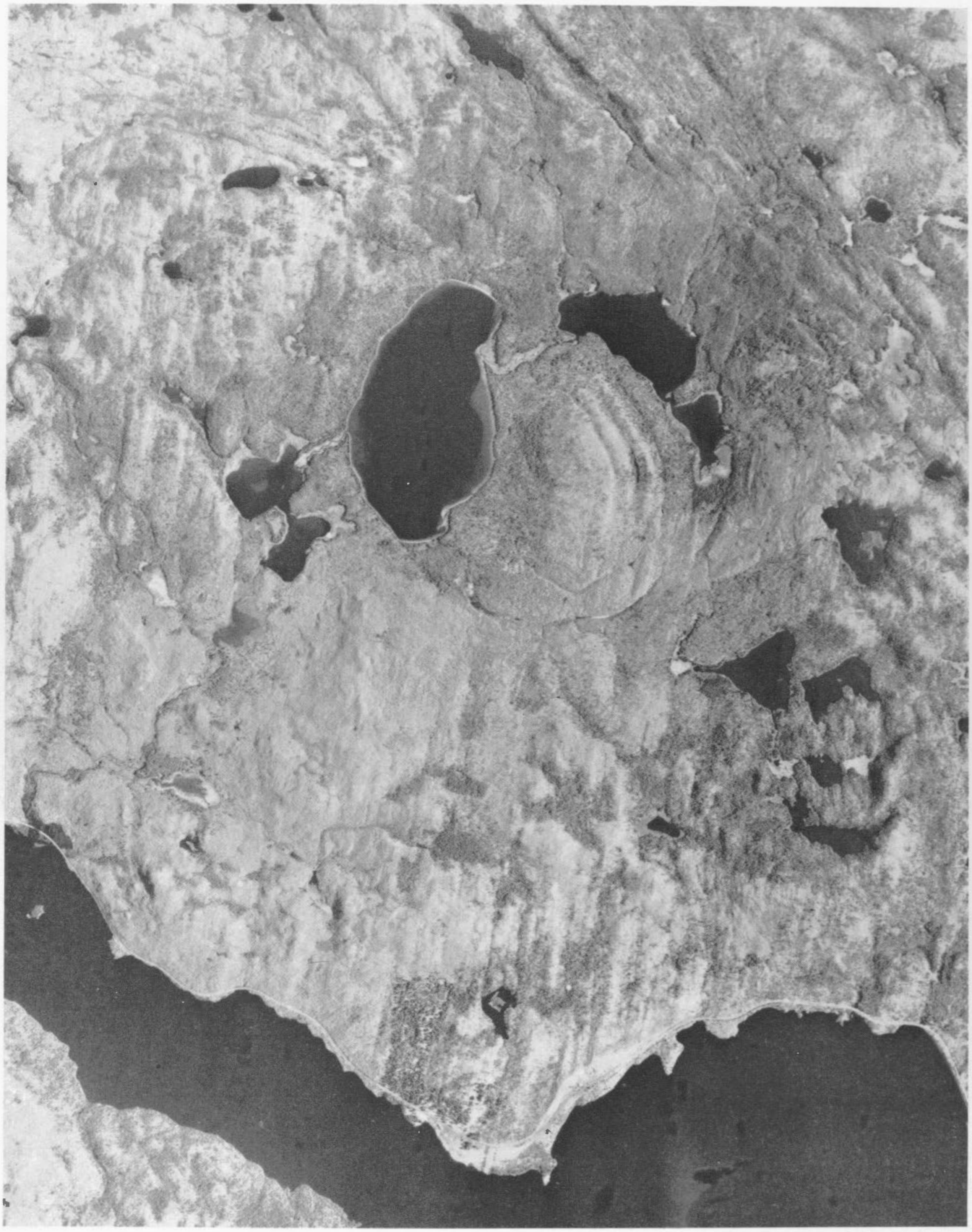

Figure 1. Vertical air photograph of the Brent feature. (Spartan Air Services photo)

by rail was relatively easy. The village of Brent, with a population under 100, is a divisional point on the transcontinental line of the Canadian National Railways (*see* Figure 2). From here old logging trails lead some 3 miles to the shore of Gilmour Lake, the largest lake inside the crater.

On this first expedition (*Sky and Telescope*, 1951; *Science News Letter*, 1951) the general nature of the topography and geology of the crater and its surroundings were noted. A Paulin altimeter was used to determine approximate elevations in relation to Cedar Lake at Brent, which was adopted as a standard. Soundings were taken on Gilmour Lake and a number of standard magnetic stations were established, using a saturated core type electronic magnetometer. Brent lies within the boundaries of Algonquin provincial park. The personnel of the expedition were hospitably accommodated by

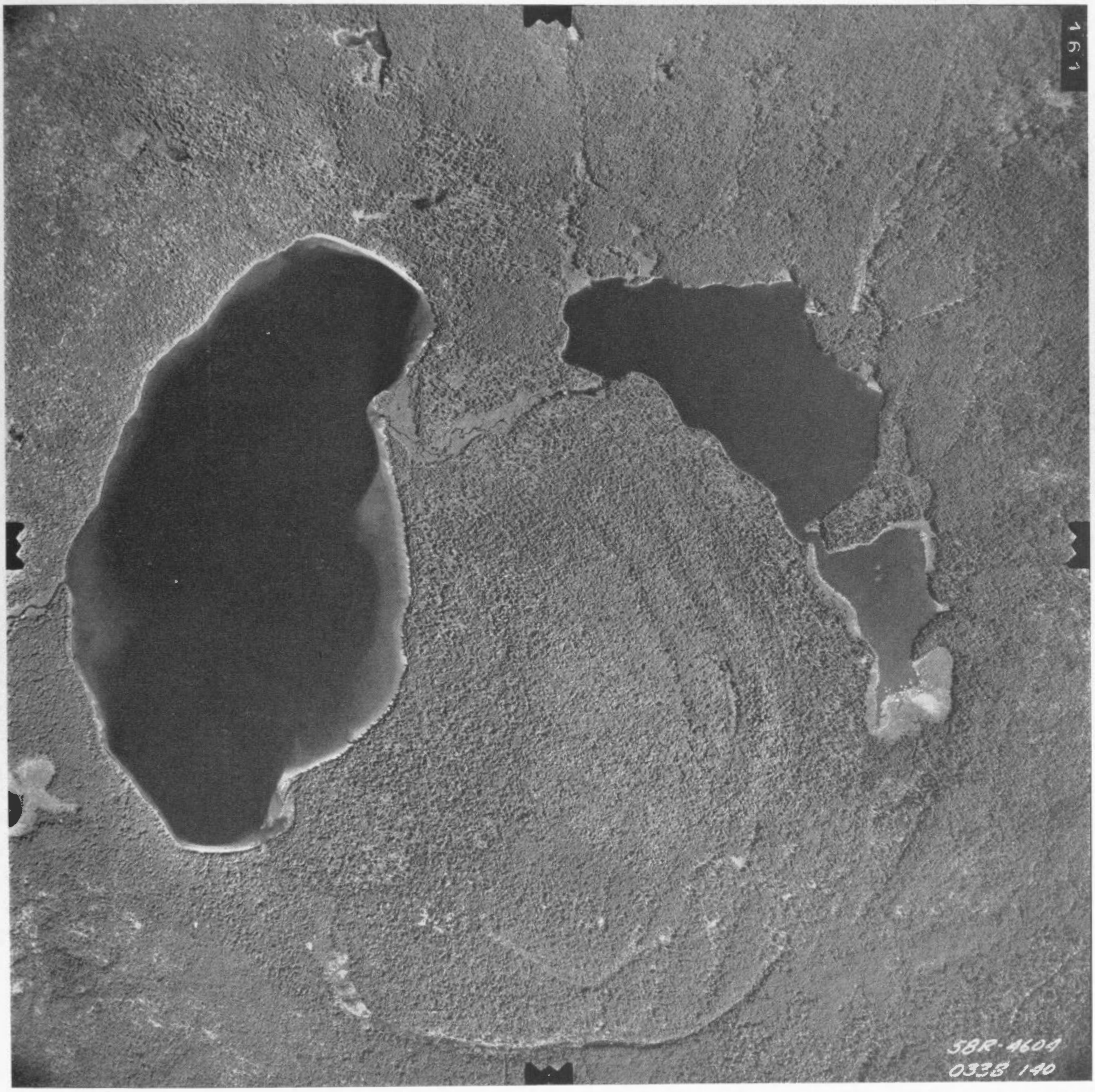

Figure 1a. Low-level vertical air photograph of the Brent feature, supplied by Ontario Department of Lands and Forests, showing the densely wooded terrain.

Deputy Ranger William Christie and his staff at the Brent headquarters of the Ontario Department of Lands and Forests.

The circle which called attention to this region, and which circumscribes the outer shores of both Gilmour Lake and Tecumseh Lake, has a diameter

Figure 1b. View of the beach at the south end of Gilmour Lake. The centre of the crater is to the right. Dr. Millman, (left) and Mr. Barringer are wading toward the aircraft.

of 9,500 ft. (*see* Figure 3). It is formed by the slopes on the lake shores and by discontinuities of general level in the woods, often marked by small stream beds. The topography rises gradually in a direction outward from the circumference of this circle, except on the east where Gilmour Lake drains into Brant Lake. However, there is no marked crater-like depression and to an observer on the ground there is no indication that the feature exists. In all probability it would never have been discovered without the assistance of high altitude air photography. The writer has flown over the area at 10,000 feet and from this elevation the outline of the circle is very distinct to anyone on the lookout for it.

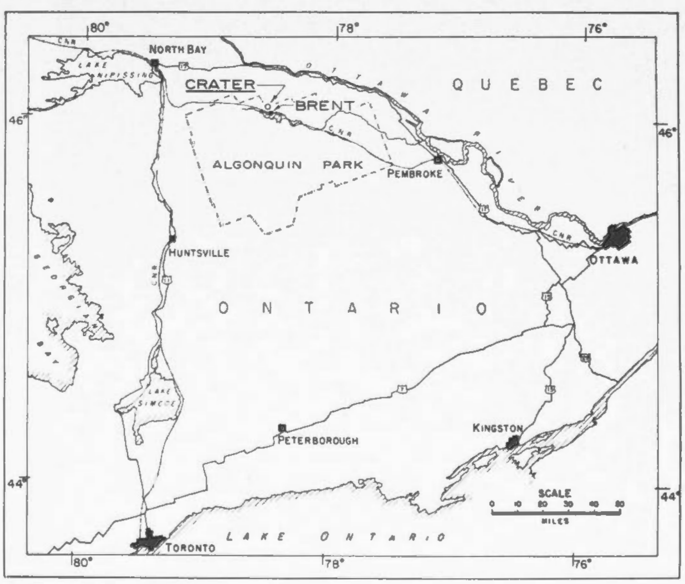

Figure 2. Location map.

Soundings were made at 28 positions on Gilmour Lake. These have been indicated as W-1 to W-28

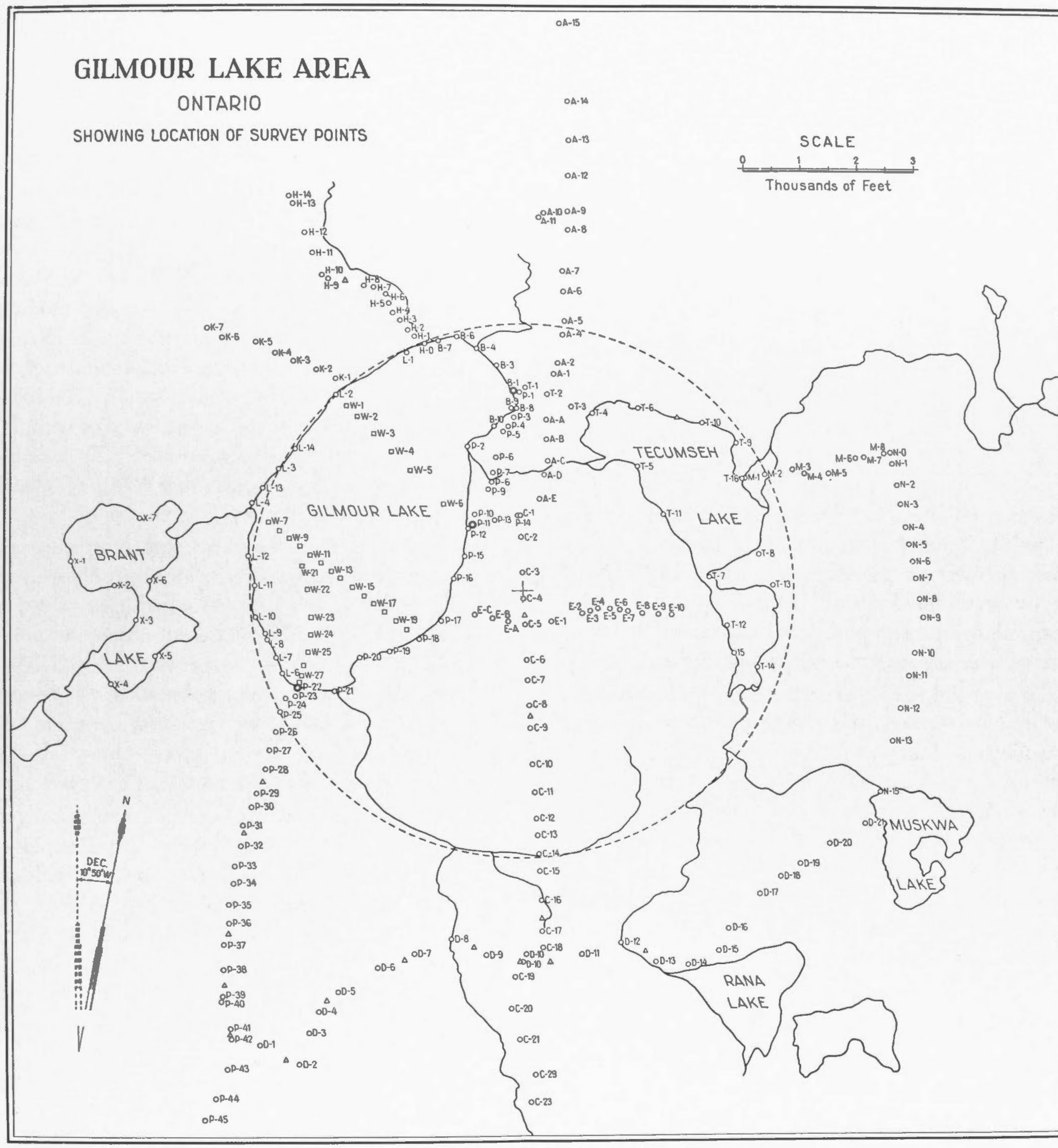

Figure 3. Location of survey points.

in Figure 3. The values of the depth of water found on July 7, 1951, are listed in Table I. Weather conditions made it difficult to carry out a more complete sounding program at this time but it seems unlikely that the lake reaches a depth greater than 85 to 90 feet. From its size and the appearance of its shores it is almost certain that Tecumseh Lake is shallower.

During the 1951 expedition there was only time to make a preliminary and incomplete survey of the land elevations in and around Brent crater. Later, in 1953, Dr. M. J. S. Innes of the Gravity Division of the

TABLE I

Water depths, Gilmour Lake, July 7, 1951

Position	Depth (feet)	Position	Depth (feet)
W–1	18	W–15	40
W–2	40	W–16	30
W–3	60	W–17	14
W–4	82	W–18	8
W–5	51	W–19	8
W–6	4	W–20	6
W–7	4	W–21	41
W–8	8	W–22	40
W–9	17	W–23	36
W–10	32	W–24	28
W–11	40	W–25	31
W–12	40	W–26	31
W–13	43	W–27	30
W–14	44	W–28	24

Dominion Observatory determined the ground control points lettered from A to P in Figure 3. Using these and the air photographs, the Topographical Survey constructed a contour map of the area. This is reproduced in Figure 4. The position of the circle referred to above stands out quite clearly on this map.

To give the reader a better idea of this feature, two profiles through the center of the crater have been plotted in Figure 5. The vertical scale used is five times the horizontal. The lines chosen are at right angles to each other and avoid the west side of the circle through which the area drains into Brant Lake. The extreme range in ground elevation is 400 feet for one profile and almost 600 feet for the other. To record the average effective profile, elevations were measured along eight equally spaced radii (N, NE, E, SE, S, SW, W, NW) and mean values calculated. These mean values are also plotted in Figure 5, and exhibit a range in elevation of approximately 275 feet. Baldwin (1949) has given two formulae which apply to the normal explosion crater. These are:—

$$D = 0.1083\, d^2 + 0.6917\, d + 0.75 \qquad (1)$$

$$E = -0.097\, D^2 + 1.542\, D - 1.841 \qquad (2)$$

where D is log rim diameter in feet;

d is log depth in feet;

E is log rim height in feet.

If, for purposes of discussion, it is assumed that the 9,500-foot circle seen on the air photographs represents the sectioning of an ancient explosion crater at the original ground level, then the original rim diameter would have been close to 11,500 feet. Inserting this value in equations (1) and (2), a total depth of 1,555 feet results, and a rim height of 662 feet, hence a depth below original ground level of about 900 feet. It is evident that, from the standpoint of size, this crater is almost an exact twin of the New Quebec crater (Millman, 1956). It is also evident that, if the Brent crater is a true explosion crater, its original form has been greatly modified and in fact almost obliterated by subsequent changes on the earth's surface. A simplified standard crater profile, with parameters which satisfy Baldwin's equations, has been plotted in Figure 5 for comparison with the existing Brent profiles. The levelling influence of glacial action and other forces are clearly present at Brent.

The Brent crater lies in an area of granite and granitic gneisses of the Grenville subprovince of the Canadian Shield. On the first expedition, outcrops of bedrock in situ were found at numerous points outside the crater circle. None were located inside this circle, however. At some points near the circumference of the circle a few outcrops of fragmental rock were noted. These had somewhat the appearance of consolidated explosion breccia.

Circular features on the earth's surface may be produced in various ways. Apart from explosion impact craters, referred to above, there are volcanic craters and cones, volcanic necks and caldera, and modified forms of these. Other circular markings include cryptovolcanic structures, basic plugs or stocks, laccoliths, ring dykes, erosion basins, coral island atolls, salt domes and features produced by frost action.

The evidence obtained on the first exploratory expedition seemed to indicate a greater probability for the explosion origin of the Brent crater than for any of the other possible hypotheses. Hence, it was desirable to carry out a more complete study of the feature.

On July 13, 1951, the area was covered with the airborne total force magnetometer of the Geological Survey of Canada and a map of the magnetic contours was produced, (*see* Figure 7). In the summer of 1953, additional field work in and around the crater was carried out on the ground. A gravity and magnetic study was made during the period June 7 to June 26, 1953 by the Dominion Observatory, and a combined seismic and gravity investigation, also by the Dominion Observatory, was carried out from September 10 to October 1, of the same year. In

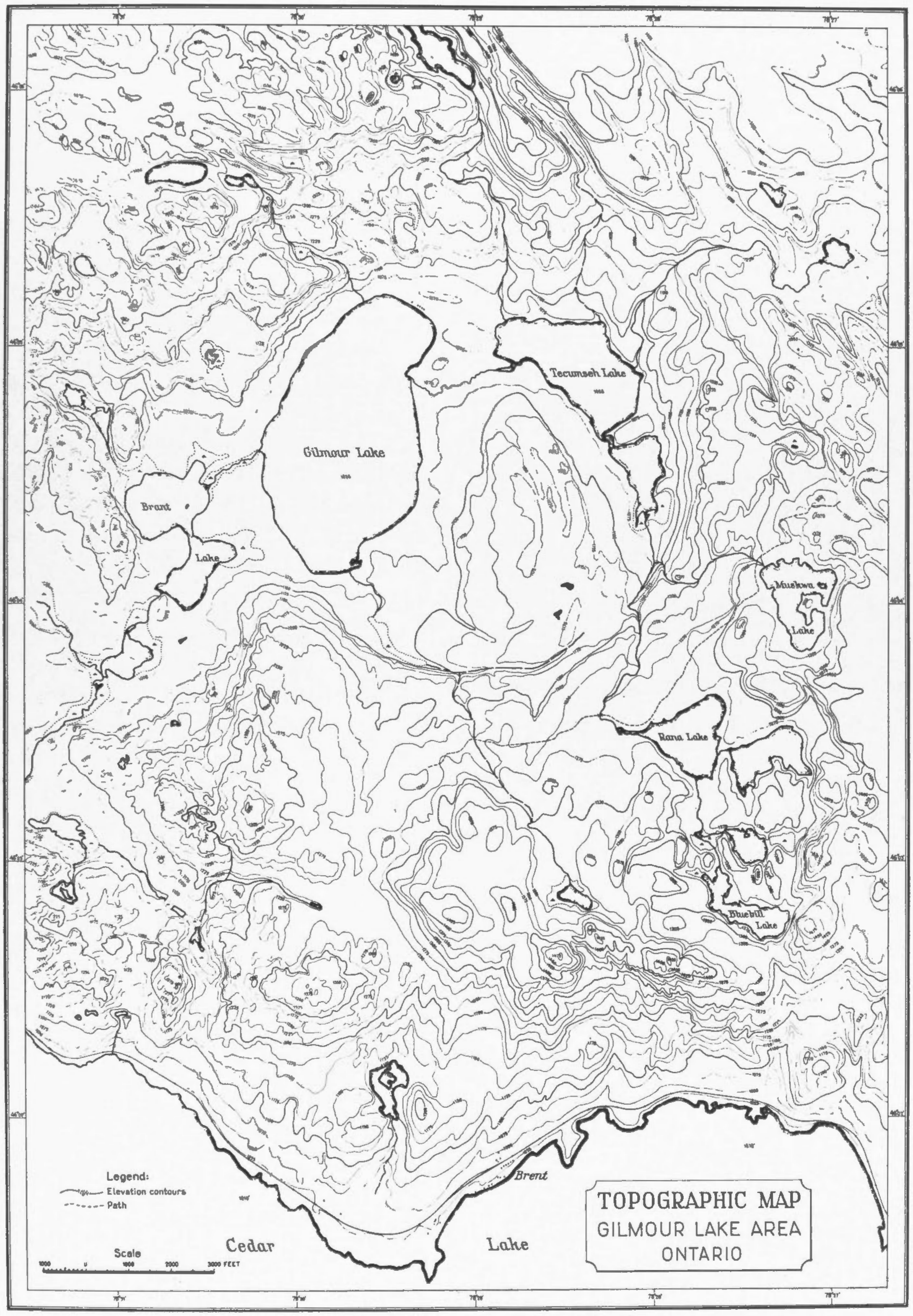

Figure 4. Topographic map, Gilmour Lake area.

1954, the Geological Survey carried out a study of the geology of the area from August 24 to September 1. In 1955, from February 21 to March 30, drilling operations were carried out by the Dominion Observatory. The results of these various expeditions are reported in this combined report.

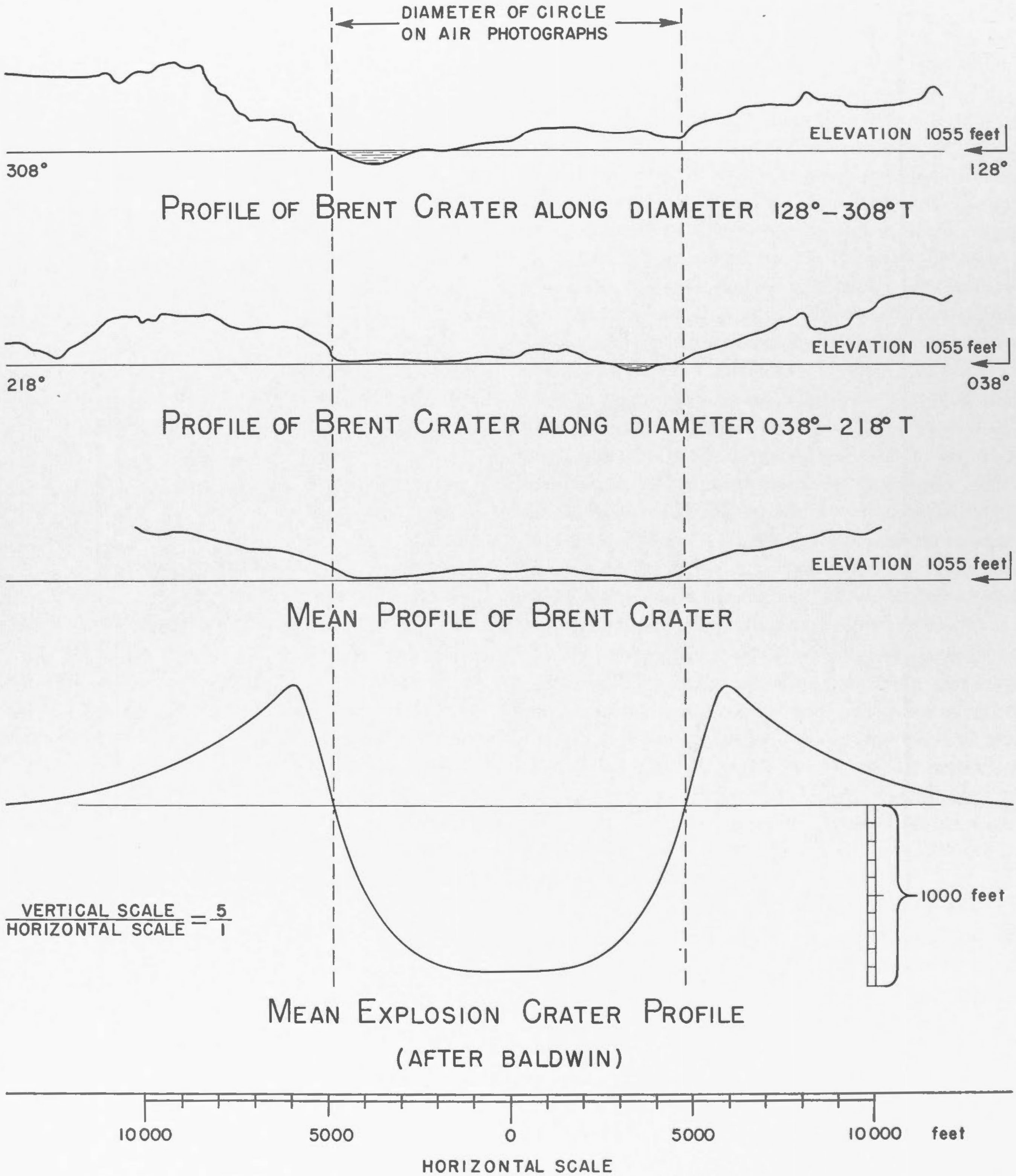

Figure 5. Topographic profiles across centre of crater.

PART II

The Age of the Brent Feature from Geological Observations*

BY

B.A. Liberty

The Brent topographic feature lies within the Grenville subprovince of the Canadian Shield. Notwithstanding the glacial cover, it is clear that the Brent feature consists of a nearly circular depression in granite gneiss now partly filled with limestone of Ordovician age. Diamond drilling has revealed the existence of 546 feet of undisturbed strata near the centre of the feature. Their age is considered to be Middle or Lower Ordovician on the basis of fossil evidence in the upper part and the apparently continuous sedimentation throughout. Rock types are predominantly: grey, fine-grained and lithographic limestone with minor red and green argillaceous limestone and shale; grey, fine-grained sandstone with minor shale; and alternating grey, calcareous shale with siltstone and sandstone.

The time of formation of the Brent feature is considered to be of some importance. That it existed prior to Middle Ordovician time is illustrated by the presence in it of strata of this age. However, in view of the fact that the drill holes did not completely penetrate the Palaeozoic sedimentary rocks, the possibility of older strata being present is realized. The lowest rock is tentatively dated as Lower Ordovician, but some of it might be Cambrian with possibly more Cambrian lying below. Thus the depression is younger than the Grenville and older than Middle Ordovician and may possibly be dated Cambrian. Although the feature might have originated at any time between formation of the Grenville and deposition of the first Palaeozoic sediments in eastern Ontario, it most probably formed during the latter part of this interval. As it is such a small feature, geologically, the period of erosion before it was covered by the protective Palaeozoic strata could not have been very long or the feature would have been obliterated. The youngest Grenville is tentatively dated at about 800 million years and the base of the Cambrian about 500 million years.

At the time of writing there is insufficient geological evidence known to prove or disprove the meteorite crater origin of the Brent depression. Positive evidence, such as meteorite fragments and radial scars, was not observed but this would in all probability have disappeared in the immense time that has elapsed since the feature was formed. Geological evidence does, however, indicate within the limits stated above the time of formation of the depression.

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PART III

A Magnetic Study of the Brent Crater

BY

J.F. CLARK

In 1951 a preliminary survey was carried out by the Magnetic Division of the Dominion Observatory in the Brent area. The purpose was to determine whether there were large anomalies near Gilmour Lake. Six magnetic stations were established between Brent and Gilmour Lake by A. A. Onhauser and W. E. T. Smith of the Dominion Observatory and absolute values of vertical force computed. In June 1953, these stations served as reference points for a much more extensive vertical force magnetometer survey, which was conducted over the whole area of the feature. The 1953 survey provided additional information concerning the magnetic properties of the feature and distribution of magnetic matter in the area, to aid in structural interpretation.

The location of magnetic stations is indicated in the chart of Figure 6. Several lines of observation points were laid out and they are indicated by letters such as H, L, C, D, P, M, N, etc. The value of vertical force is indicated for each station and for the contour lines constructed from them.

The datum used for identifying contour lines is 56,500 gammas, i.e. the values placed on each contour line on the chart (Figure 6) are to be added to this datum to give the total vertical intensity in gammas. The magnetic vertical intensity at the base camp (B-1) was measured at 57,086 gammas. Further observations were taken in June 1953 at the 123 stations shown in the diagram. Two magnetic instruments were used; a Sharpe vertical force variometer and an Askania, variation type, field magnetometer. Magnetograms recorded by Agincourt Magnetic Observatory and the Dominion Observatory magnetic laboratory in Ottawa served to control these field station measurements. Individual readings at each station were corrected for disturbances and diurnal variation.

The contours of the anomalies indicate a very low gradient in vertical force over the circular portion of the feature inside the rim. Large anomalies occur outside the rim of the crater particularly in a small region along the M-line. The total range of vertical force over the whole region was found to be 720 gammas, most of which occurs along the eastern rim of the crater. The greater variation in the vertical intensity might be expected here as all stations are underlain by granite gneiss which characteristically produces variable anomaly fields.

In addition to the Dominion Observatory observations the Geological Survey as part of their program in 1951 obtained airborne magnetometer profiles over the crater and surrounding districts. The ground survey data were used in conjunction with the contour lines derived from these airborne magnetometer results. Several flights were carried out at an elevation of about 500 feet above ground level. The flightlines and total force anomalies are shown in Figure 7.

Agreement of the airborne results with the ground survey is quite good over the central portion. Outside the rim the range in vertical force on the ground is greater by about 300 gammas than that indicated by the airborne instrument. Therefore, the pattern obtained over the centre must result from magnetic attraction at depth; outside the rim, the pattern corresponds to that which would result from local and near-surface attraction.

If the depth of the crater is 1,500 feet, the magnetic force detected by an instrument on the ground i.e., 1,500 feet from the basement rock, compared to the magnetic force detected by an airborne magnetometer in an aircraft traversing the area at 500 feet, i.e., 2,000 feet from consolidated rock, will be in the ratio of

$$\frac{1}{(1500)^3} = \frac{1}{(2000)^3} \text{ or } 2.37 \text{ to } 1.00.$$

the response being approximately one-half as great

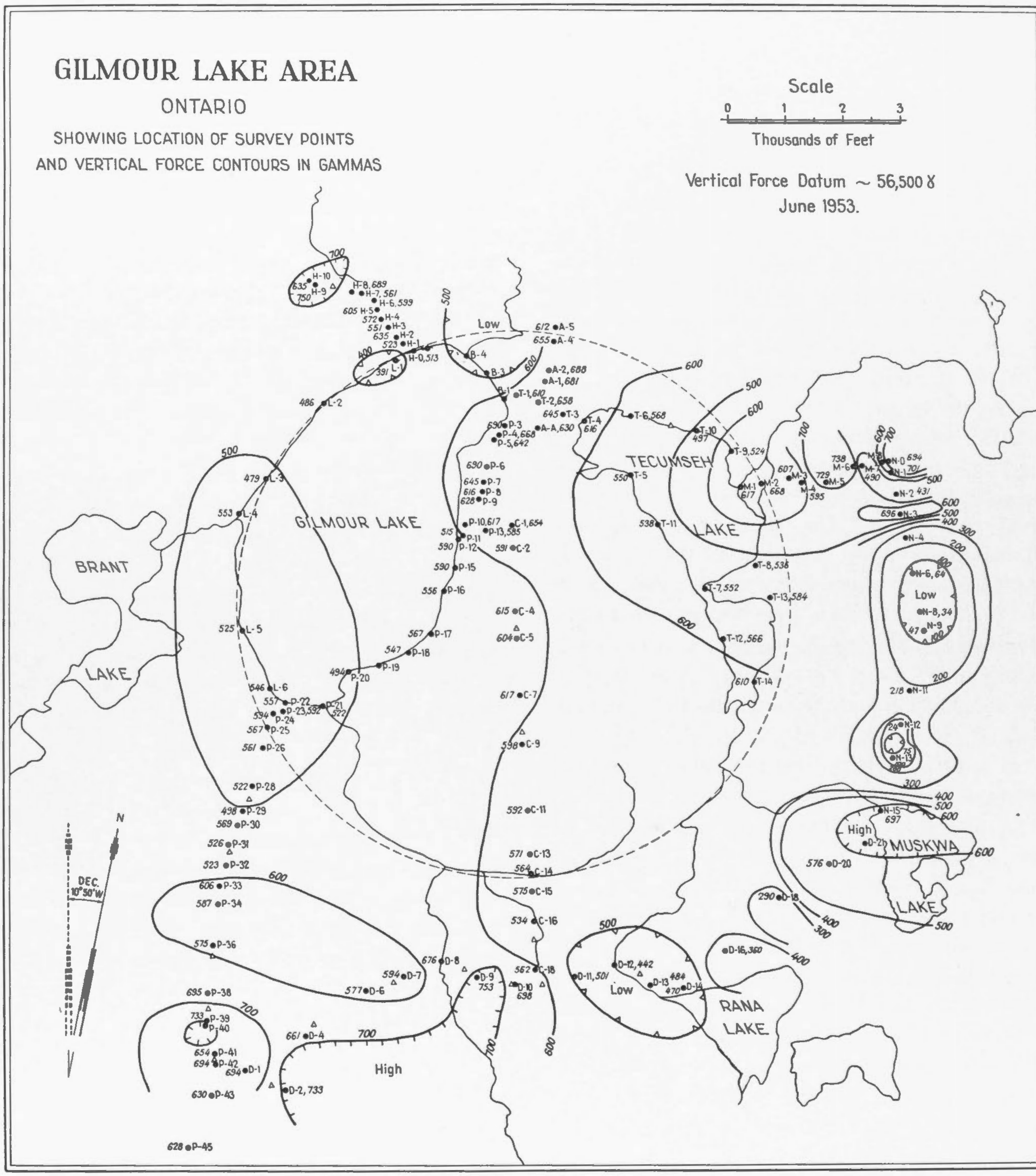

Figure 6. Anomalies of vertical magnetic intensity.

in the air as on the ground, since the magnetic field falls off as the cube of the distance.

Across the central portion of the feature the variations observed were:

Airborne	70 gammas
Ground	125 gammas

This is a ratio of 1:1.8, close to the predicted value. It should be pointed out that a greater number of

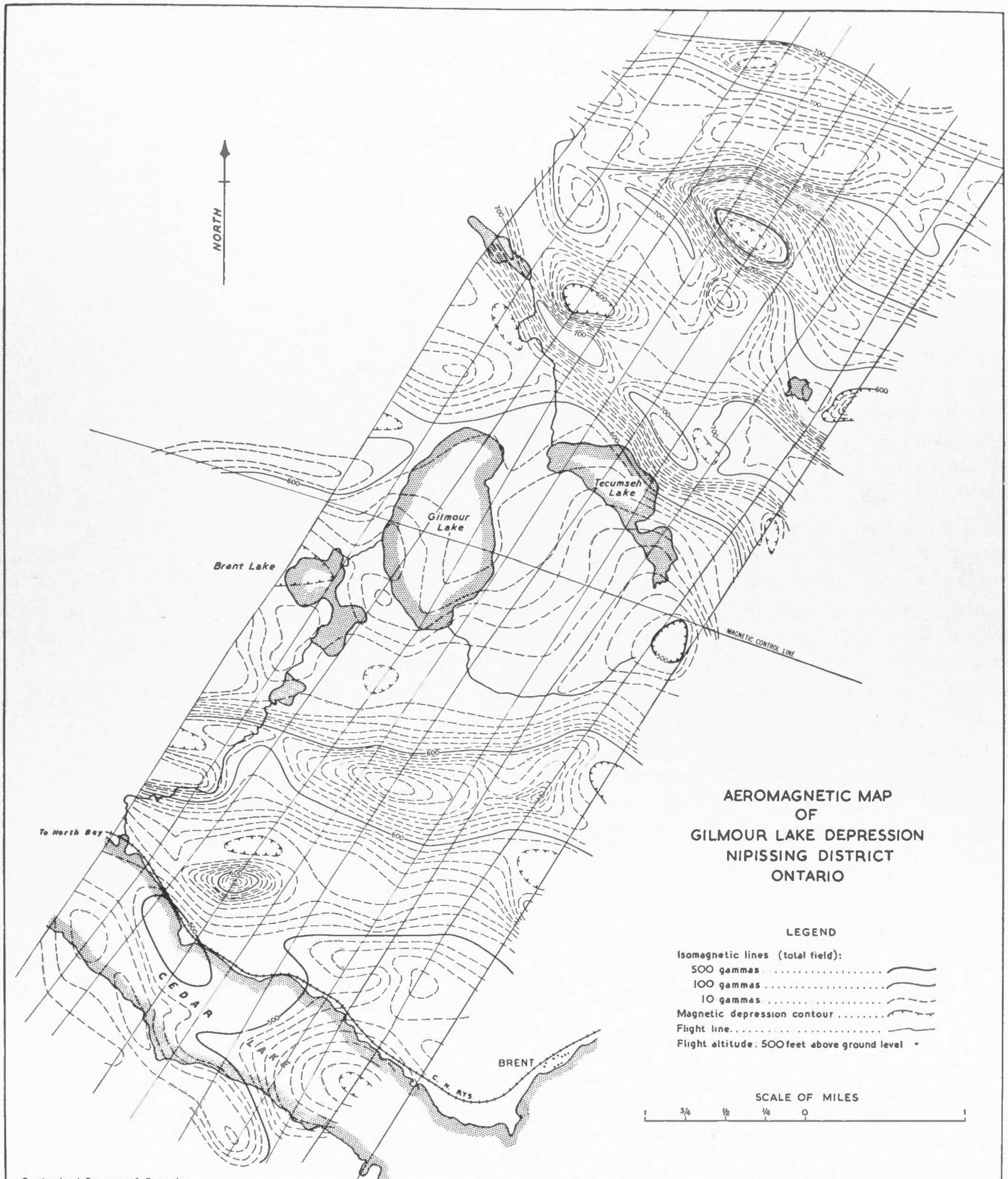

Figure 7. Aeromagnetic map of Gilmour Lake depression by Geological Survey of Canada.

observations, both airborne and ground, might change the relationship.

Outside the rim the variations are greater:

Airborne	150 gammas
Ground	450 gammas.

This ratio of 1:3 indicates the presence of magnetic material of higher susceptibility than that inside the crater. The material of higher susceptibility would have to extend to the surface or near-surface to affect the ground survey instruments three times as much as the airborne magnetometer. Outcrops of magnetic mineral-bearing rock do appear, as required by this hypothesis.

To summarize, the vertical force contour pattern outside the rim is more anomalous than inside. No large anomalies are indicated inside the depression. The pattern shows a sudden transition near the rim of the crater where the vertical intensity becomes quite variable with steep gradients.

The magnetic evidence is consistent with the picture derived from gravimetric and seismological studies: namely, that of a crater of considerable depth filled in with sedimentary rock and glacial debris. The absence of any large anomaly over the centre of the crater would seem to deny a volcanic origin.

The results of this survey suggest that airborne magnetometer surveys may provide useful diagnostic evidence in fossil crater studies. The results further suggest that an additional modified form of magnetic survey would be useful in this type of investigation; that is, geological rock samples could be taken inside the depression by drilling through the sedimentary layers which were presumably laid down after the formation of the crater, while others could be taken at intervals outwards beyond the rim, and tested for magnetic properties. The Baldwin formula could give some indication of the outer limit of disturbed material and debris which would have its remanent magnetism affected by the heat and impact. Although meteoritic and erosion basins are topographically similar, a significant difference in magnetic moment between rock in situ on the surrounding plain, and similar rock associated with the depression, would point to meteoritic origin of the crater. However, if no change in magnetic properties were found, it would be strong evidence for the erosion theory of origin. A detailed traverse and determination of the values of the magnetic elements, would be a preliminary requirement to help plan the selection of rock specimens. The astatic magnetometer operated by the Dominion Observatory could be utilized in an investigation of this type.

The writer is indebted to R. G. Madill, Chief of the Geomagnetic Division for helpful comments and suggestions.

PART IV

Seismic Observations

BY

P.L. WILLMORE

The seismic methods of investigating buried structures fall into two broad classes, which are known as the refraction and reflection methods respectively. In the refraction method charges are set off in the ground, and the times of arrival of seismic waves are observed at various distances from the shots. If the structure consists of a succession of plane layers, and if the velocity of propagation in each layer exceeds that of the layer above, the "travel-time curve" will consist of a series of straight lines, each of which will represent waves propagated through one of the layers of the structure. With suitable arrays of shots and seismometers, it is possible to determine the propagation velocity, thickness and dip for each layer, but the geometry of the ray paths usually requires the observations to be conducted over horizontal distances about six times as great as the thickness of the structure being investigated.

In the reflection method, the seismometers are set up quite close to the shot, and the method depends on the observation of the successive "echoes" produced when seismic waves, travelling essentially vertically through the structure, strike reflecting boundaries at various depths. This method avoids the requirement for large horizontal spreads, but it suffers from the disadvantages that the appearance of a reflection on the record yields little information which can serve to identify the reflecting horizon, and that the determination of the vertical scale of the structure requires an independent measure of the velocity in each layer. For these reasons, extensive reflection surveys are usually tied in to borehole data.

A crater-like structure presents special difficulties for either method, for if its depth is comparable to its horizontal extent it may be impossible to set out a refraction spread long enough to determine the velocities in the various formations, and the lack of velocity data will limit the interpretation of reflection records.

The method which was finally adopted at the Brent crater was to set up a 600-foot spread of geophones—subsequently referred to as short-range stations—at a number of points in or just outside the circular feature, and to fire shots up to 4,000 feet from each spread. Without expecting to penetrate to the undisturbed basement materials, velocities and thicknesses for several bodies of material within the crater were determined by observing refracted waves from these shots. At the same time, seismometers attached to v.h.f. radio transmitters were set up on the rim of the crater. These transmitted the seismic signals to a radio receiver which was set up beside the short-range recorder. In this way, the recordings of both long-range and short-range data could proceed simultaneously, under the control of a single operator. The conclusions of the seismic experiments were derived by combining data from the two types of equipment. The locations of the shots and recording stations, together with the survey points mentioned in this section of the text are shown on Figure 8.

The seismic work was carried out by the writer with the assistance of J. F. J. Allen and W. E. T. Smith. In addition, Sgt. Van Wert and Cpl. Norton were assigned to the party by the Royal Canadian Engineers, to assist in drilling shot holes and in handling explosives. Also, the Department of National Defence (Army) kindly loaned camouflet boring equipment and supplied a number of shaped charges.

The method of drilling shot-holes varied with the nature of the ground. In sand or gravel, the

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holes were drilled with a 4-inch hand auger to depths of as much as 15 feet. This tool could not be used efficiently in the rocky overburden which covers most of the crater floor, and first efforts to operate in this area were made with the Army camouflet equipment. Even this would not penetrate the worst ground, and further progress would have been extremely laborious if Sgt. Van Wert had not suggested that small "beehives" might be used. These are shaped charges about 5 inches in diameter, used by the Army to perforate concrete structures. A number of these were obtained, and proved very effective in drilling clean holes 3 or 4 inches in diameter down to a depth of about 4 feet.

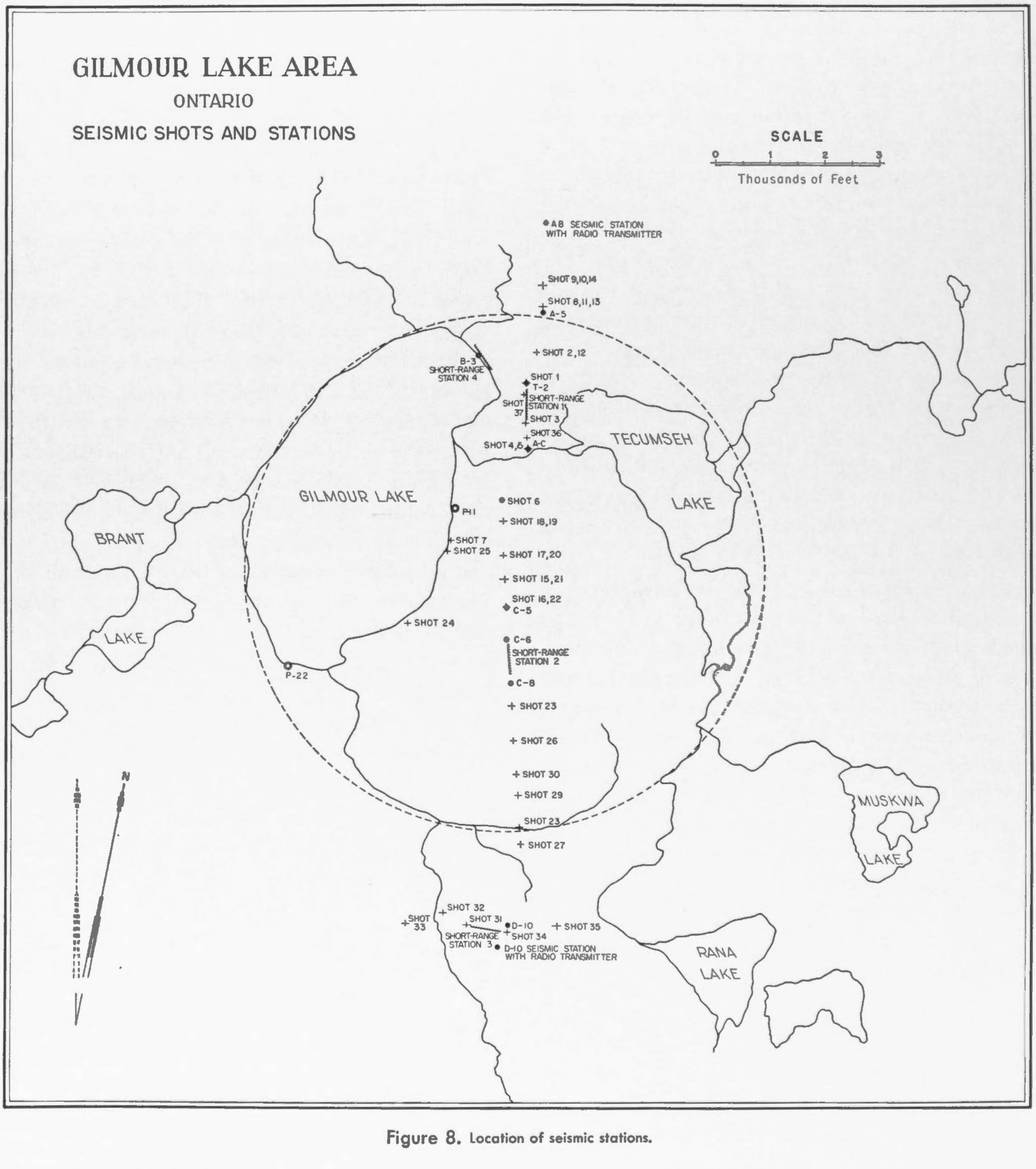


Figure 8. Location of seismic stations.

SHORT-RANGE RESULTS

The short-range equipment was set up first near T-2 (*see* Figure 8), secondly between C-6 and C-8, then near D-10 on the southern rim of the crater, and lastly on the north shore of Gilmour Lake near B-3. All the results observed at a given station are plotted on a single figure, the abscissa for each point being the distance in feet between one of the shots and a seismometer which recorded it, and the ordinate being the travel-time in seconds for the seismic waves. When shots are fired at both ends of the geophone spread, the results for waves travelling in the two directions are presented separately. The small numbers alongside individual points define the individual channels of the spread. In order to reduce the congestion of the diagrams, these numbers are entered only if they are needed in the discussion.

Short-range Station No. 1 (near T-2)

The results for this station are plotted on Figure 9. On referring to the section covering shots north of the geophones, it will be seen that the onsets at

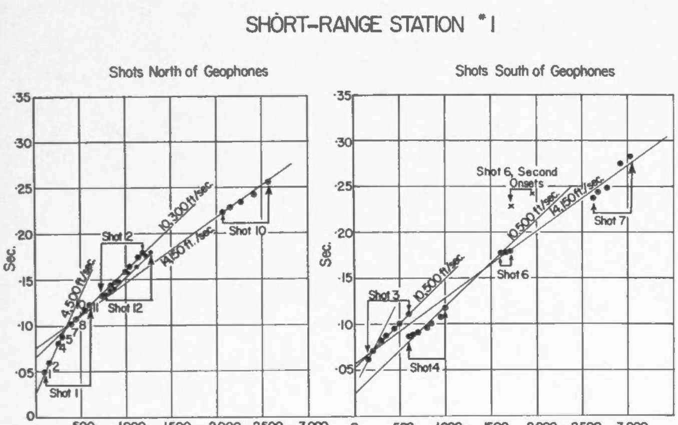


Figure 9. Travel-time curves, short-range station, No. 1.

channels 1-5 for shot 1 define a line with an intercept of about 0.025 seconds, and a velocity of 4,500 ft/sec. The intercept is presumably due to a lower velocity in the upper part of the overburden, which could be due to a lower degree of consolidation or to the presence of weathered material and organic matter. If the travel-time curve for this material is represented by joining the onset at geophone 1 to the origin, a velocity of 1,700 ft/sec. and a thickness of 25 feet are found. A lower velocity extending a shorter distance down from the surface would be equally consistent with the results.

The onsets of the waves from shot 1 at the remaining channels fit with those of shot 2 on to a single line, and define a velocity of 10,300 ± 170 ft/sec. The fact that the onsets for the two shots fit almost exactly on the same line indicates that the apparent velocity measured between the shot-points is the same as that under the geophones, and hence that there is no significant dip in the refracting layer. Figure 9 also shows that the onsets from shot 12 are about .007 second earlier than those of shot 2. The two shot-holes are within 15 feet of each other, but the hole for shot 12 was about 6 feet deeper than the other. The fact that the waves from shot 12 had to penetrate less of the overburden accounts for about half the observed difference in travel-time, while the fact that shot 12 was much larger and more heavily tamped, thereby producing sharper onsets, may account for the remainder.

The velocity of 10,300 ft/sec. is in the range of values to be expected from soft sedimentary rocks, which in the present case appear to correspond with the limestone found near the surface elsewhere in the crater. The depth of this layer under the geophones can be derived from the intercept of the travel-time curve. This intercept is 0.058 second, which, on being combined with the velocity and intercept in the overburden yields a value of 77 feet for the thickness of the more consolidated part of the overburden. Allowing for the less consolidated part, the top of the limestone is found to be about 100 feet below the surface.

The onsets from shot 10 form a clearly defined group, arriving early in relation to the lines defined by shots 1, 2, and 12, and giving an apparent velocity of a little over 14,000 ft/sec. It is shown later that a velocity of 14,150 ft/sec. is indicated for propagation at long distances across the crater, and it is assumed at this point that the onsets from shot 10 are propagated through the same material. On fitting a line with a velocity of 14,150 ft/sec. to the onsets of shot 10, an intercept of 0.083 second is found. It is necessary to defer the interpretation of this intercept until the short-range and long-range data are combined.

The records obtained from the shots south of the geophones were much inferior to those already discussed, and the travel-times were not accurate enough to fix the propagation velocities. The velocities in the various layers are therefore taken to be the same as those determined from shots 1 and 2, and the observed travel-times used only to fix the intercepts of the lines. When this is done, the wave through the overburden is found to have an intercept of 0.030 second, while the wave from shot 3 through the limestone has an intercept of .055 second. These results are taken to indicate the presence of about 30 feet of unconsolidated material and 40 feet of harder overburden below shot 3.

In the case of shot 4, the distance from the geophones is such that the observed waves are the ones through the limestone. A velocity of 10,300 ft/sec. fitted to the onset times yields an intercept of .025 second, which is about half that found for the shots north of the geophones. Since the intercept of a travel-time curve represents the time taken for seismic waves to pass through the overburden into the refracting layer and up again under the geophones, the disappearance of half this delay when the shot is transferred from the north of the geophone spread to the south represents the complete absence of overburden under the more southerly shot point. This is confirmed by the fact that hard grey clay was found in the bottom of the shot-hole, this clay being known to form a thin layer on top of the limestone in other parts of the crater. Only three clear readings were obtained from shot 6, but these also fit on the 10,300 ft/sec. line, with almost the same intercept as given by shot 4. Once again, the grey clay was found in the bottom of the shot-hole.

The onsets for shot 7 form a scattered group, and it is too early to fit this group on to an extension of the limestone line. Accordingly, the shot 7 onsets, like those from shot 10, are assumed to be waves propagated at depth with a velocity of 14,150 ft/sec. The intercept time found in this case is 0.057 second, and again the discussion of this value is deferred until the data is combined.

Short-range Station No. 2 (near C 7)

The results obtained with the geophone spread between C-6 and C-8 are plotted on Figure 10. Shots 16 and 22 were fired in the same hole, and yield a travel-time curve with the following equation:

$$t = -.0012 \pm .004 + \frac{\Delta}{10{,}620 \pm 530} \text{ sec.}$$

The velocity is in close agreement with that found for the limestone under line 1. The intercept is too small for its negative value to be significant, and indicates merely that the limestone is very thin under the shot-point and under the geophones. In the case of shot 16 the first onsets on channels 10, 11, and 12 were very weak, and this enables clear second onsets to be seen on the records. Three later onsets are combined with those from other shots observed at this station, and are believed to represent the waves travelling at 14,150 ft/sec.

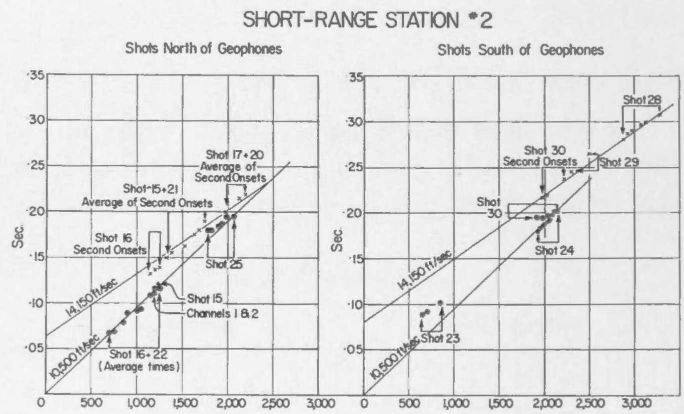


Figure 10. Travel-time curves, short-range station, No. 2.

Shots 15 and 21 show limestone onsets only on channels 1 and 2, while the second onsets are clear on all channels. Shots 17 and 20 showed the later onsets only. Shot 25 was a fairly large explosion in a deep hole, and gave clear first onsets lying close to the limestone line.

On turning to the second part of the figure, representing the travel-times for shots south of the geophones, it is seen that shots 23, 24, and 30 show waves transmitted through the limestone, while shots 28, 29, and 30 yield onsets associated with the lower layer. In the case of shot 23 the waves are .02 second later than expected if the shot had been resting directly on the limestone. This may be connected with the fact that the shot-hole encountered gravel instead of the hard grey clay which usually indicates the top of the limestone. If the velocity in the gravel were the same as that in the overburden elsewhere in the crater a thickness of about 90 feet would be required to explain the anomaly.

Short-range Station No. 3 (near D 10)

At station No. 3, the spread was laid out along the edge of the crater near D-10. The results are plotted in Figure 11. For each of the four shots the travel-times were consistent with a velocity of 15,500 ft/sec., which is the value obtained by applying the method of least squares to the combined data. The data from shot 35, however, were much more consistent than the rest and yielded a velocity of 14,640 ±480 ft/sec. when reduced by themselves. If this greater consistency is taken to justify the assignment of increased weight to these onsets, a combined velocity of less than 15,500 ft/sec. would be obtained.

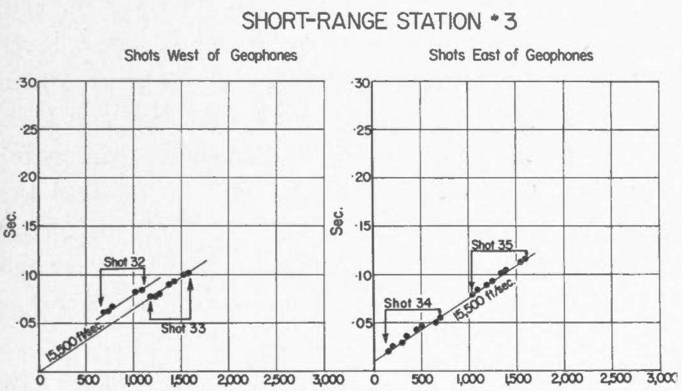


Figure 11. Travel-time curves, short-range station, No. 3.

The travel-time line for shot 33 passes almost through the origin, indicating that the overburden beneath this shot and under the geophones is very thin. Shots 32 and 34 yield intercepts of .019 and .012 second, which correspond to about 90 feet and about 55 feet of overburden respectively. Some or all of the overburden could be weathered material, and this would reduce the thickness required to explain the time delay.

Short-range Station No. 4 (near B-3)

At station No. 4 the geophone spread was laid along the shore of Gilmour Lake and recorded shots 36 and 37, near A-C and T-A respectively. In spite of the fact that large charges were used, the onsets

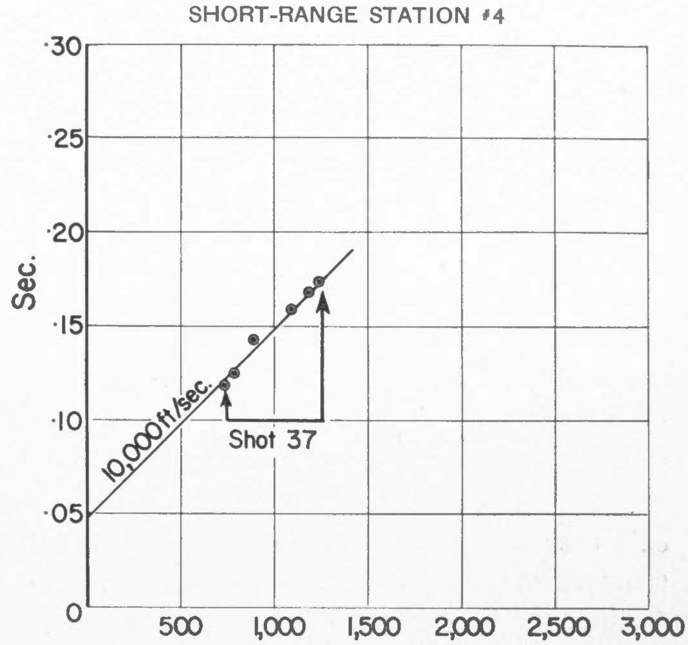


Figure 12. Travel-time curves, short-range station, No. 4.

are weak and only six of them are plotted (Figure 12). The travel-times indicate a velocity of about 10,000 ft/sec., with an intercept of .045 second. This result is very similar to that obtained under station No. 1, and indicates that the limestone extends almost horizontally from the vicinity of station No. 1 to the north shore of Gilmour Lake.

LONG-RANGE RESULTS

The travel-times for the first onsets at the radio stations near A-8 and D-10 are plotted in Figure 13.

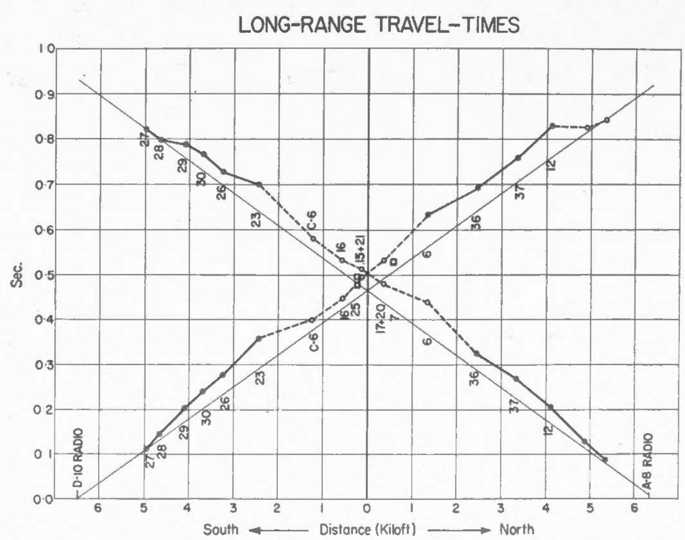


Figure 13. Long-range travel-time curves.

The distance scale is calibrated in thousands of feet, measured from the centre of the crater along the north-south diameter. Most of the shots were very near this diameter, and hence a single point on the abscissa can represent the distance of the shot-point from each of the two radio seismometers at the ends of the line. Shots 7 and 25 were some distance away from the perpendiculars drawn from the shot points to the north-south line. The travel-times have been corrected to allow for the fact that the distances from the seismometer to the shot-points differ slightly from the distances which were measured along the diameter.

The form of the travel-time curve differs markedly from the systems of straight lines which are characteristic of plane-stratified structures. The pattern is best revealed by drawing a pair of straight lines through the travel-time points for the shots nearest the northern and southern extremities of the shot-line. The travel-times for all shots fall above the two reference lines. In spite of some local discrepancies, the patterns of offsets produced by the two seismometers are strikingly similar, and both show a high degree of symmetry about the centre of the feature. The pattern strongly suggests that the waves from each shot spend a certain time in penetrating the sediments close to the shot-point, and are then propagated through a uniform "marker layer" towards the two seismometers. Remembering that the reference lines for the two seismometers must have the same slope and must pass below or very near to all the travel-time points, we find that the velocity in the marker layer must be within about 1 per cent of 14,150 ft/sec. If the marker lines are extrapolated across the full width of the diagram, their intersections with the ordinates drawn through the seismometers give the time taken for seismic waves to be propagated along the whole diameter of the marker layer. This time must be the same for each direction of propagation and to satisfy this condition it is necessary to introduce a small delay at A-8, which could indicate a few feet of overburden at that point. No such delay is required at D-10, which agrees with the conclusion drawn from station No. 3.

The data from station No. 3 indicate that the velocity near D-10 is a little higher than that which has been assigned to the marker layer. This means that the reference line for the onsets recorded at that station should perhaps be moved down a little, but the difference in velocity is so small that the error in the diagram as printed can hardly exceed .01 second.

CORRELATION OF LONG-RANGE AND SHORT-RANGE DATA

It has already been pointed out that waves through the marker layer appear on some of the short-range records. It should therefore be possible to combine both long-range and short-range data into a unified picture of the whole structure.

To do this, the ordinary equation for the travel-time t of a seismic wave is written in the form

$$t = x/v + D_1 + D_2$$

where x is the distance measured along the surface, v is the velocity of the wave in the deepest layer reached, and D_1 and D_2 represent the time lost in penetrating any materials with velocities less than v, which occur under the shot-point and seismometer respectively. When it is necessary to refer to the time taken to penetrate the low velocity materials at one end of a seismic propagation path the symbol D will be used without a suffix, regardless of whether the region concerned is under a shot-point or a seismometer. Each value of D is related to the dimensions of the structure by the equation.

$$D = \Sigma_r \frac{h_r}{v_r} \sqrt{1 - v_r^2/v^2}$$

where each value of v_r is the propagation velocity in a layer of thickness h_r. These equations only apply strictly when the structures are horizontally stratified, but they can be used as a fair approximation provided that the difference in the depths of the refracting layer under the shot-point and under the seismometer correspond to a mean dip of less than about 10°; and provided also that the upper surface of the refracting layer is not sufficiently contorted to interrupt the refraction path.

The group of short-range observations made at any one station contains an arbitrary component, for each observation yields a value of $D_1 + D_2$, whereas a complete solution would yield D_1 and D_2

separately. The value of D for each station is therefore chosen so as to make the complete structural picture as simple as possible.

At station No. 1 it is found that setting D = 0.04 second leaves discrepancies of less than 0.01 second with the long-range data for shots 6, 7, and 37, but that there is an error of .04 second for shot 10. The structural picture which is emerging from the data is that of a basin with steeply dipping sides, and it seems possible that the discrepancy at shot 10 is due to the difficulty of propagating seismic energy from the shot-point, into the dipping wall, and thence up to the geophone line which is on deep sediments nearer the centre (*see* Figure 14).

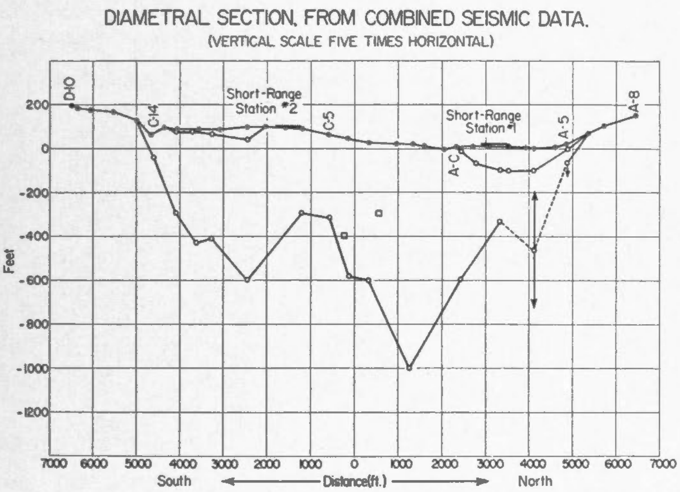


Figure 14. Section deduced from seismic data.

In the case of station No. 2, overlapping long-range observations are only available for shots 28 to 30, as the overburden at the other shot-points was too thin to tamp the relatively large charges required. It is immediately seen that the results for shots 28 and 29 cannot be accepted at their face value, for if the long-range D is subtracted from $D_1 + D_2$ for the short-range spread, there remain estimates of D_2 which exceed $D_1 + D_2$ for shot 16.

The discrepancy which has appeared is similar to that at shot 10, and may perhaps be explained in the same way (i.e. by assuming a propagation difficulty for waves travelling from shots near the edge of the feature to detectors nearer the centre). If this explanation is accepted, it throws doubt on the validity of the result from shot 30, and the estimate for D_2 must be based entirely on the evidence of shots 16 through 17 and 20 which are north of the geophone line. The values of $D_1 + D_2$ from these shots show a declining trend as the geophone line is approached. It is clear that they increase again south of the line, whether or not the exact numerical values of shots 30 to 28 are accepted. This must be interpreted as an anticline with its crest south of shot 16. The minimum height for the crest is obtained by dividing $D_1 + D_2$ equally between shot 16 and station No. 2, and thereby the crest comes about halfway between the two. If the division is made unequally, lower values of D will be obtained either for the shots or for the station, and the peak will therefore seem to come nearer the surface.

The combined seismic data are listed in Table II, and can be converted into estimates of thickness of limestone and overburden by using the velocity data from the short-range experiments. The structural picture deduced in this way is shown in Figure 14.

In interpreting the travel-times from the long-range data, two sources of error must be borne in mind. The first of these is that the seismic refraction equation may break down if the ray path from the shot-point to the seismometer is interrupted by low-velocity material. This condition is most likely to arise when waves from shots near one side of the crater are observed by the seismometer at the opposite end of the diameter, and may delay the seismic onsets. The other possibility is that waves through the limestone may arrive before the ones through the marker layer. This may lead to early onsets when shots near the edge of the crater are recorded at the nearer of the two radio seismometers.

Referring to Table II, either or both of these sources of error can affect the readings at shot 12, and could account for the relatively large discrepancy between the onsets from this shot at A-8 and D-10. The mean of the two readings has been adopted as a measure of the limestone thickness, whilst the ± sign indicates the departure from the adopted value which would arise if either of the readings were rejected and the other one taken as correct. By the same argument, the onset for shot 11 at A-8 could be read early, and a + sign has been inserted after the limestone thickness to indicate that the adopted

TABLE II

Summary of Combined Long-range and Short-range Data

Shot-point	D Recorded at A-8	D-10	Short range	Adopted D	Overburden contribution	Overburden below shot	Limestone thickness
	(sec.)	(sec.)	(sec.)	(sec.)	(sec.)	ft.	ft.
10 & 14	.009	−.004	.043 (reject)	0.002	say 0.002	say 6	0
13	.010	—	—	.010	say .006	say 20	60+
12	.036	.072	—	.054	.031	100	360 ± 270
1	—	—	—	—	.031	100	—
37 = stn. 1	.042	.055	.040	.046	.031	100	230
3	—	—	—	—	.028	70	—
36	.038	.050	—	.044	.006	20	580
6	—	.070	.061	.065	0.000	0	1000
7	—	.025	.017	.021	0.000	0	310
17 & 20	—	—	.040	.040	0.000	0	620
15 & 21	—	—	.038	.038	0.000	0	600
16 = stn. 2	—	—	.024	.024	0.000	0	380
25	0.012	.037	—	.025	0.000	0	390
23	.058	.070	—	.064	.023	60	640
26	.030	.044	—	.037	.008	20	480
30	.038	.040	.052 (reject	.039	.005	15	510
29	.030	.030	.058 (reject)	.030	.005	15	370
28	.000	.015	—	.007	0.000	0	110
27	.000	.000	—	.000	0.000	0	0

value represents a lower limit. Similar uncertainties appear in the interpretation of the results from shots 26 to 30, near the southern edge of the crater. Here, however, the discrepancies between the readings for the two radio seismographs are all within the limits of measurements and in most cases the onset at D-10 yields an apparently greater thickness of sediment than that from A-8. As this error is in the opposite direction from that to be expected from the types of misinterpretation which have been discussed above, it is assumed that it arises from inaccuracy of reading or variation in the velocity in the marker layer, and the mean is adopted as the best estimate of sedimentary thickness.

The striking symmetrical form of the diametral section strongly suggests the upper surface of the debris left in an explosion crater, and when the seismic results were first worked out it seemed highly probable that the "marker layer" consisted of this material. This hypothesis appeared to be confirmed by the fact that results from short-range station No. 4 showed that material with almost the same velocity as the marker layer occurred near the surface towards the edge of the crater. The drill-hole near P-11 disproved this hypothesis, for the material which was found about 400 feet below the surface was limestone and sandstone rather than an explosion breccia. On the other hand, a second drill-hole near P-22 (which is about the same distance from the centre as C-13 on the diametral section) did encounter breccia at a depth of about 80 feet. It therefore appears that the interpretation of the seismic results in terms of only two materials below the overburden is over-simplified. There is little doubt of the existence of a deep symmetrical basin whose rim coincides with the topographical feature. However it does not appear that the central boss suggested by the seismic data is composed of the same material as that whose surface dips inwards from the edges of the crater. Instead, it is suggested that the small values of D which occur near the centre indicate a mass of high-velocity sediments in this region. This mass does not necessarily have a definite boundary, as a graded increase in velocity or a number of small bodies of high-velocity material could produce identical effects on both the long-range and short-range seismograms.

PROPAGATION OUTSIDE THE CRATER

The seismic results which have been described so far have all been explained in terms of materials which propagate seismic waves with a velocity of 15,500 ft/sec. or less. This velocity is much less than the average value of 20,240 ft/sec. which is typical of the Canadian Shield (Hodgson 1953), and it would therefore be of great interest to obtain even a rough estimate of the total extent of the low-velocity materials around the crater. Such an estimate is obtained by considering the record of one shot (shot 5) which was recorded by a seismograph near Brent, for which the waves took 1.28 seconds to cover a horizontal distance of 20,200 feet.

The travel-time can be interpreted in two ways. Assuming that the first onset was produced by waves which penetrated the sediments and breccia at a steep angle, entering the Precambrian rocks somewhere near the centre of the crater, the travel-time equation

$$1.28 \text{ secs.} = D + 20{,}200/20{,}240$$

is formed, from which it is found D = 0.282 second. The contribution of the upper sediments is found from the diametral section to be 0.045 second, leaving about 0.237 second to be accounted for by the difference between breccia and the undisturbed basement. If the propagation velocity in the breccia is taken to be about 15,000 ft/sec. the thickness required is about 3,600 feet.

An alternative treatment of the results is to assume that the first onset at Brent was produced by waves which followed the usual path from the interior of the crater to D-10, and were then propagated near the surface for the rest of the way. In this case, the diametral section is used to estimate the propagation time from shot 5 to D-10 as 0.69 second, leaving 0.59 second for the waves to travel the remaining 11,260 feet to Brent. Again taking velocities of 15,000 ft/sec. for breccia and 20,240 ft/sec. for the Precambrian, it is found that 2,400 feet of breccia would be needed south of D-10 to make up the observed travel-time. Since the limestone appears to end about 1,500 feet north of D-10, the total distance from the edge of the limestone to the undisturbed Precambrian is about 3,900 feet.

Whichever propagation path is assumed to have produced the first onset at Brent, the thickness of breccia along it is seen to be of the order of 4,000 feet. The statement does not necessarily mean that a sharp boundary should be observed at this distance. Experience in drilling other craters has indicated a gradual transition from the most heavily brecciated material to undisturbed bedrock, and the figure of 4,000 feet should be taken as a rather crude estimate of "penetration distance" for cracks entering a transitional zone.

PART V

Geological and Gravity Evidence

BY

M.J.S. Innes

The results of the preliminary field investigation of the Brent crater in 1951 (*see* Part I) strongly suggested that the feature was formed by an explosion, probably due to a falling meteorite, sometime prior to the last period of glaciation. It was therefore considered that a geophysical investigation, coupled with the geological evidence, might provide important information as to the sub-surface structure of the feature and thus give indirect evidence of its origin.

Accordingly, detailed gravity measurements were carried out in 1953 on two separate surveys; the first during June in conjunction with the ground magnetic measurements, and the second in September during the course of the seismic observations. The presentation of the gravity results and their interpretation, which is the main purpose of this section, is preceded by an outline of the main geological features of the area. The possibility of an explosive origin for the Brent feature is examined in the light of the geological evidence.

The writer wishes to thank J. A. Robinson for his assistance with the gravity observations and reductions, and J. G. Tanner who supervised the drilling operations and logged the drill cores. Grateful acknowledgment is made to W. P. Eames and F. Plett who undertook the ground survey to locate the gravity stations and determine their elevation, and to the Topographical Survey of Canada for cooperation in the preparation of the topographic map. Indebtedness is gratefully acknowledged to officials of the Ontario Department of Lands and Forests for courtesies and for supplying air transportation for the field party on completion of the survey, and to J. McGaughy and T. Dixon for their hospitality while in Brent and their assistance in planning transportation. Dr. H. M. A. Rice, Geological Survey of Canada kindly reviewed the manuscript, and provided results of his inspection of the Brent feature in 1951. Finally, the writer wishes to express his appreciation to Dr. C. S. Beals, Dominion Astronomer, for helpful advice and encouragement during the course of this investigation.

GEOLOGICAL CONSIDERATIONS

Geology of the area

To the writer's knowledge, detailed geological mapping of this region has not been carried out. This outline is based upon observations during the geophysical operations, supplemented by a study of aerial photographs and the results of diamond drilling. The intention is to present only the general geological setting and structural relationships that are to be dealt with in the interpretation of the gravity anomalies.

Geologically, the Brent depression is in an area in which all the consolidated rocks, with the exception of a number of scattered outliers of Palaeozoic limestones, are of Precambrian age. It lies within the Grenville sub-province of the Canadian Shield, about 30 miles south of the boundary separating this province from the Superior province to the north (Harrison, 1957).

Accordingly, the region surrounding the feature is underlain by gneissic granites and biotite and/or hornblende gneisses believed for the most part to be of sedimentary origin. Although variable, some of the latter are coarsely crystalline and rich in garnet in grains up to $\frac{1}{4}$ inch in diameter, which are generally fractured and broken. In some places, the gneisses are indistinguishable from intrusive rocks and along traverses to the north and west appear to become more massive with smaller amounts of ferromagnesian minerals. A mass of pink biotite granite occurs near station A-15 (*see* Figure 3) but its extent was not observed. Exposures of gneiss on ridges to the south and west of the crater trend approximately east-west. To the east and north, however, the trend is northwesterly and the dip of the rock is vertical or nearly so. The only basic intrusives within the area of which the writer is aware, lie to the southeast of the crater near Muskwa Lake. In this region Satterly (1942) has reported gabbros and amphibolites, which grade into hornblende gneiss or garnet hornblende gneiss and which are cut by several pegmatite dykes up to 15 feet wide, containing mica of possible commercial interest.

The distribution of Palaeozoic outliers is conclusive evidence that considerable portions of this Precambrian area were covered by the sea during Palaeozoic time. Small areas of these rocks have been preserved in a series of down-faulted blocks, the nearest being some 20 miles north of the Brent feature near Mattawa (Caley and Liberty, 1957), along the Ottawa river. There are also reports from local inhabitants of limestones along the north shore of Cedar Lake to the west of Brent, but it is not clear if these rocks are in situ.

It is not too surprising, therefore, that Palaeozoic rocks have been preserved in the Brent depression. During the geophysical work, blocks of limestone and considerable amounts of shale were encountered along the eastern margin of Gilmour Lake and along the north-south ridges in the centre of the basin. Blasting operations in connection with the seismic measurements showed that it is highly probable that the entire basin is underlain by sedimentary rocks (Figure 15). This was confirmed by diamond drilling carried out in March 1955 after completion of the geophysical work.

That heavy continental glaciation affected this area is evident from the widespread drift cover and the semi-parallel arrangement of drift ridges and valleys. This evidence is very pronounced on aerial photographs and the direction of ice movement was apparently (Prest, 1957) from north to south. Strong local deviations from this direction have been caused by the bedrock topography. Thus it would appear that the main ice flow was deflected

Figure 15. Yellow dolomitic sandstone in place, near station C-14, uncovered by blasting for seismic observations.

by the granitic walls of the depression which resulted in the scouring out of sediments from Gilmour and Tecumseh lakes and in the formation of the arcuate ridges lying between these two lakes. The elevation profile for the E-line which crosses these ridges is shown in the lower part of Figure 16. It is believed that the variation in height is for the most part bedrock controlled and that the ridges are composed of, and owe their existence to, a more highly resistant lithographic limestone. If this is so, the variation in relief of the Palaeozoic surface due to glacial erosion is considerable, nearly 200 feet from the bottom of Gilmour Lake to the top of the ridges.

During the final retreat of the ice, irregular thicknesses of glacial debris, consisting of sand, gravel, boulders and clay, were deposited. It will be seen, later, both from the drilling results and from the geophysical observations that this unconsolidated material reaches a thickness of at least 100 feet in parts of the basin.

Results of Drilling

Two vertical holes were put down, D.D.H. No. 1 near the centre of the basin at station P-11, and D.D.H. No. 2 near the edge midway between stations P-21 and P-22, (Figure 3) about 250 feet from the contact between the granitic and sedimentary rocks. Unfortunately considerable difficulty was experienced with the drilling which made it necessary to abandon both holes before reaching the Precambrian floor. However, 554 feet of undisturbed Palaeozoic strata were penetrated by D.D.H. No. 1 and 58 feet by D.D.H. No. 2. The latter entered gneiss breccia at a depth of nearly 150 feet and continued in it, for 52 feet, to the bottom of the hole.

The lithology and thicknesses of the formations revealed by the drilling are summarized in Figures 17 and 18. In D.D.H. No. 1 the formations comprise in descending order, grey weathering, fine-grained lithographic limestone; fine-grained argillaceous limestone interbedded with shale and sandstone; grey, fine-grained sandstone composed largely of quartz feldspar and garnet; alternating beds of silty limestone, shale and sandstone. The cores have been examined by Dr. Liberty of the Geological Survey of Canada (Part II) and are considered to represent a normal sequence of sedimentation during the early Ordovician period. Some of the lower strata may possibly represent Cambrian time.

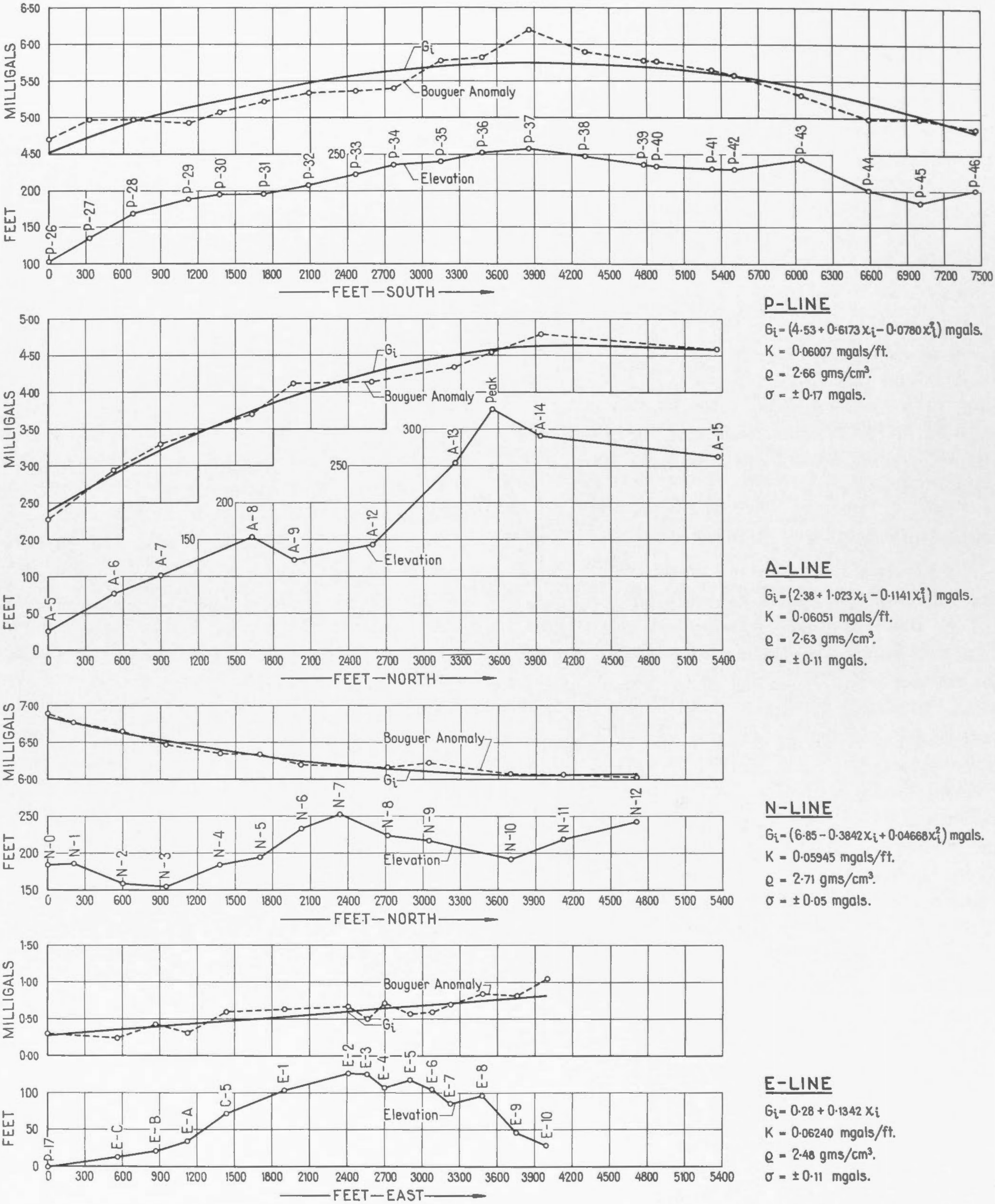
It may be remarked, however, that local environment seems to have exerted considerable control over the deposition of the sediments, for not only do the sandstones contain an abundance of garnet similar to that of the surrounding gneisses, but they are also composed in part of angular and sub-angular grains of quartz and feldspar which suggest that these minerals have not been transported great distances and are also of local origin.

Significance of the Breccia

The presence of the breccia may be of considerable importance in a discussion of the explosion hypothesis of origin for the Brent depression. While breccias may occur as the result of many different processes (Norton, 1917; Reynolds, 1928) they are the natural consequence of rock explosion regardless of how this may happen. The great meteor crater in Arizona, believed to have been formed in geologically recent times, is well preserved and is probably the most thoroughly studied explosion crater in the world. It has been estimated (Barringer, 1909) that millions of tons of uncemented, sharply angular rock fragments, of all sizes, from minute particles of mylonite or rock flour to huge blocks weighing as much as 4,000 tons were ejected by the explosion; many times these amounts were redeposited within the crater walls. Drilling operations in an effort to locate meteoritic material have demonstrated that the country rocks, Triassic and Permian sandstones and limestones, have been fragmented to a depth of at least 1,376 feet, or 830 feet below the crater's floor; but no accurate estimate of the depth to the undisturbed formations has been possible.

Recent investigations of three craters lying in widely separated regions of the Canadian Shield, and differing greatly in age, show similar evidence that intense rock shattering and brecciation accompanied their formation. These are the New Quebec crater, a water-filled depression nearly 2 miles in diameter in the Ungava region of northern Quebec (Meen 1950, 1957; Millman, 1956); Deep Bay, a huge crater nearly 8 miles in diameter, forming the

DETERMINATION OF ELEVATION FACTOR



P-LINE

$G_i = (4{\cdot}53 + 0{\cdot}6173\,x_i - 0{\cdot}0780\,x_i^2)$ mgals.
K = 0·06007 mgals/ft.
ϱ = 2·66 gms/cm³.
σ = ± 0·17 mgals.

A-LINE

$G_i = (2{\cdot}38 + 1{\cdot}023\,x_i - 0{\cdot}1141\,x_i^2)$ mgals.
K = 0·06051 mgals/ft.
ϱ = 2·63 gms/cm³.
σ = ± 0·11 mgals.

N-LINE

$G_i = (6{\cdot}85 - 0{\cdot}3842\,x_i + 0{\cdot}04668\,x_i^2)$ mgals.
K = 0·05945 mgals/ft.
ϱ = 2·71 gms/cm³.
σ = ± 0·05 mgals.

E-LINE

$G_i = 0{\cdot}28 + 0{\cdot}1342\,x_i$
K = 0·06240 mgals/ft.
ϱ = 2·48 gms/cm³.
σ = ± 0·11 mgals.

Figure 16. Gravity and elevation profiles.

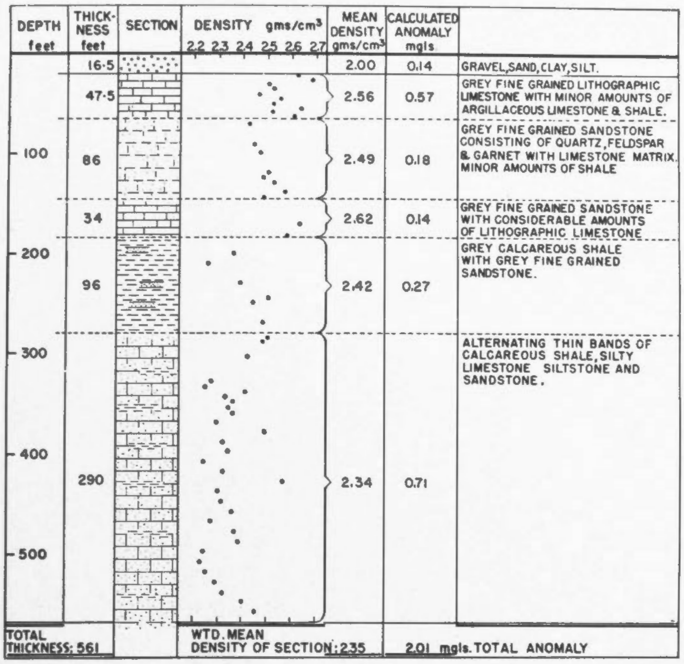


Figure 17. Geological section and corresponding densities for cores from D.D.H. No. 1.

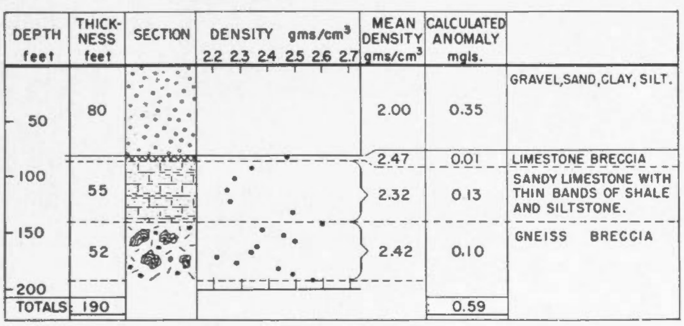


Figure 18. Geological section and corresponding densities for cores from D.D.H. No. 2.

southeastern part of Reindeer Lake in northern Saskatchewan (Innes, 1957); and the Holleford crater, about $1\frac{1}{4}$ miles in diameter, located in a well-settled farming community several miles north of Kingston, Ontario (Beals, 1957). The Holleford crater, like the Brent depression, is an extremely old feature, and it too is filled with Palaeozoic sediments. It was therefore of great scientific interest that drilling operations, carried out to determine the profile of the crater floor, revealed the existence of several hundred feet of fragmental material at depths consistent with those predicted on the basis of known characteristics of meteorite explosion craters.

The disclosure of fragmented gneiss in the lower levels of D.D.H. No. 2 at Brent may therefore be of considerable significance and it is unfortunate that the hole had to be abandoned before more complete information concerning the nature and extent of the deposit could be obtained. The breccia is made up of angular to sub-angular fragments of granite gneiss which contain garnets and which are probably petrographically indistinguishable from the paragneisses surrounding the crater. The core samples have fragments which vary in size from minute particles to blocks several inches across (*see* Figure 19). In the preliminary examination of the area float breccia containing much larger fragments was discovered (*see* Figure 20) and Dr. Rice reports locating an outcrop of the breccia, in a waterfall of the creek along the southeast margin of the feature (Figure 21) containing blocks measuring several feet.

No evidence of bedding or sorting of the material could be found. At one extreme the matrix consists of fragments so minute and so poorly cemented that in places the rock is friable and can be crumbled with the fingers. This may account, in part, for the poor drill core recovery in the breccia. At the other extreme the matrix of the breccia is a well indurated, coherent vitreous mass, the greenish grey colour probably due to disseminated chlorite and quartz.

While the association of fragmental material with the Brent crater lends considerable credence to the meteoric explosion hypothesis, it may be argued, however, that this rock is simply a granite wash deposit or basal conglomerate with arkosic material, such as commonly present at the base of sediments overlying a granite terrain. Beds of varying thicknesses of such material are reported (Roliff, 1954) between the middle Ordovician and Precambrian floor in southwestern Ontario. While acceptance of the latter argument would still leave the origin of the crater to be explained, a clear and definite answer cannot be given without more information concerning the amount of fragmental material underlying the Palaeozoic sediments. Considering the size of the crater, and to be consistent with what has already been learned from a study of explosion craters, a far greater thickness than the 52 feet penetrated in D.D.H. No. 2 would have to be present. The geophysical results may help to resolve this problem.

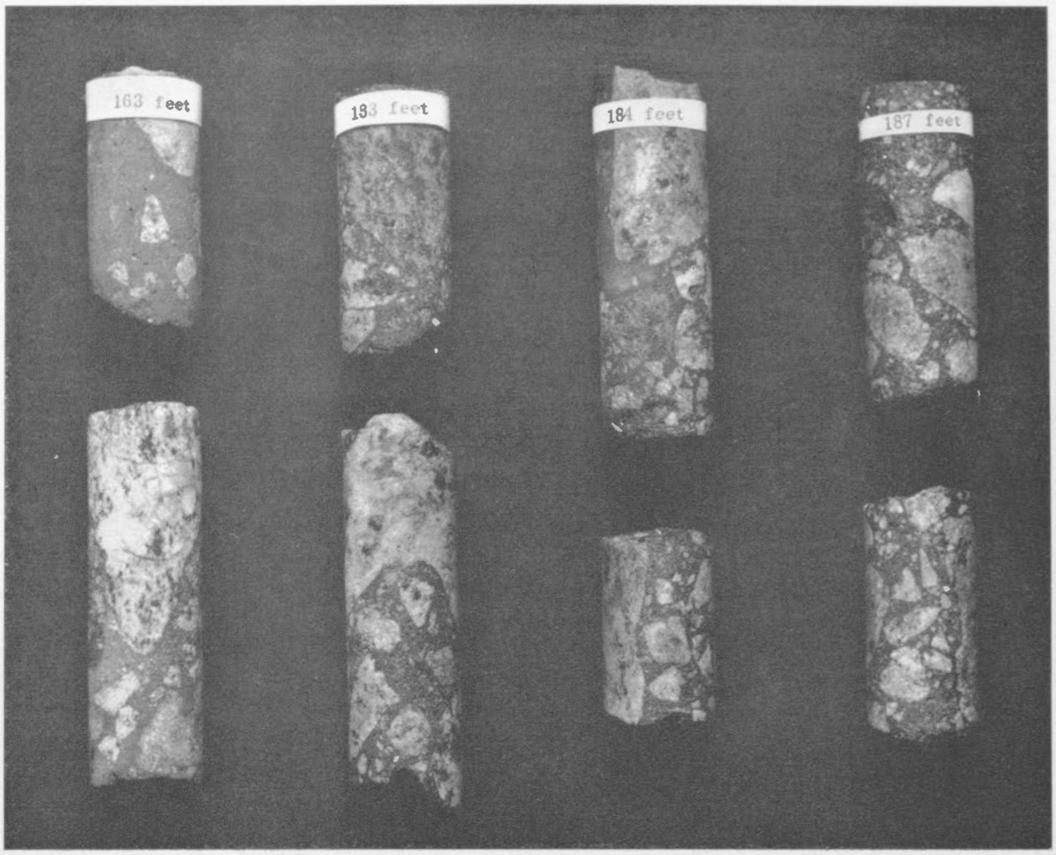


Figure 19. Specimens of breccia from D.D.H. No. 2.

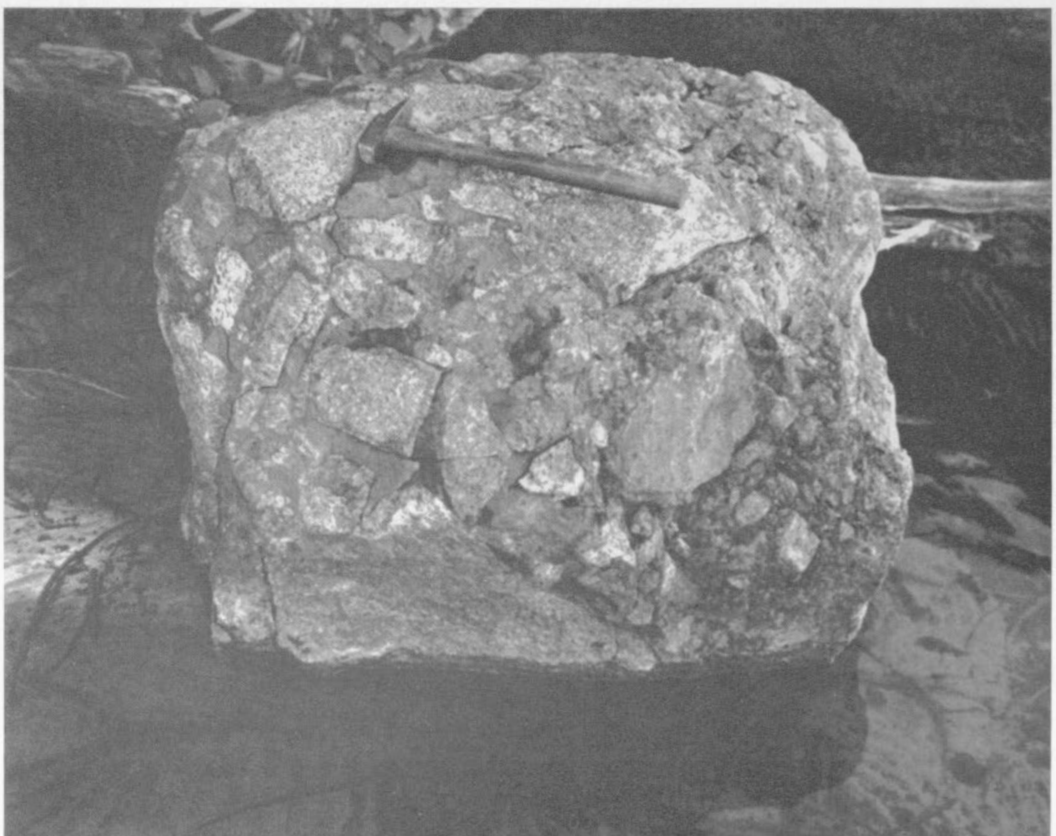


Figure 20. Breccia float on shore of Gilmour Lake.

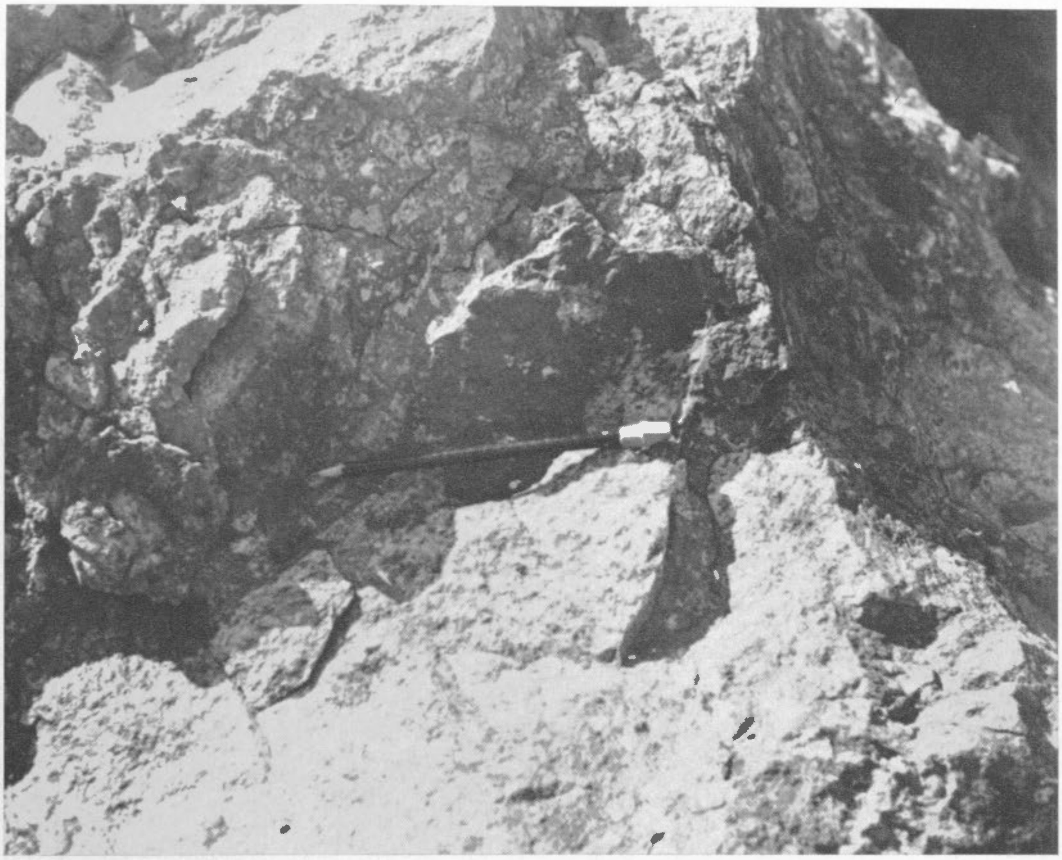


Figure 21. Breccia in place in creek bed along southeast margin of crater.

Structural and other Evidence

Although careful field investigation is required to unravel the structural details of this area, a study of the aerial photographs is most revealing and provides an over-all picture of the major structural features. Regional trends believed to reflect the bedding and foliation of the sedimentary gneisses in the vicinity of the crater, are indicated in Figure 22. A well developed fold structure lies to the northeast, which if examined stereoscopically shows up as a synclinal fold plunging to the southeast with steeply dipping limbs.

Whether due to a somewhat thicker, widespread mantle of glacial drift, or to the rocks being more highly metamorphosed and extensively granitized, the bedding and foliation of the gneisses is less pronounced to the southwest. Although the over-all pattern of the structural trends suggests a fold structure of some magnitude, its relation to the folding in the northeast is obscure. There is sufficient evidence, however, to say with some confidence that the general strike of the rocks to the northwest and south of the crater, is slightly south of a northwest-southeast direction.

The strike of the foliation and gneissosity measured at four sites on each side of the crater during the course of the geophysical work, are consistent with the structural trends shown in Figure 22. The results are as follows:

Station A - 14, north of crater	N41°W.
Station M - 4, east of crater	N51°W.
Station P - 29, south of crater	N86°W.
Station H - 14, northwest of crater	N91°W.

In addition, the strike of the gneisses near N - 15, southeast of the crater is N70°W according to Satterly (1942).

The most important result of this analysis is that there is no visible structural relationship between the Brent depression and the surrounding rocks. The trends of the latter are, for the most part, northwesterly and in no way do they appear to conform to the circularity of the crater. Their abrupt termination at the outer walls and their absence within, is strong evidence that the crater post-dates the deformation of the Grenville rocks.

The rim of a meteorite crater is formed not only by the fragmentary material ejected by the explosion but by the up-arching of the surrounding rocks, whether these be sedimentary strata or massive igneous rocks such as are found in the Canadian Shield. It is the consequence of forcible uplift and

The Brent depression, if a true explosion feature, has suffered great change through erosional processes since its formation. Its present rim, marked by the height of land, is approximately 3 miles in diameter and lies some 3,000 feet out from the well-defined 9,500-foot circle that delimits the crater floor. It is nearly half a mile beyond its original location* which indicates that approximately this amount of rock has been eroded.

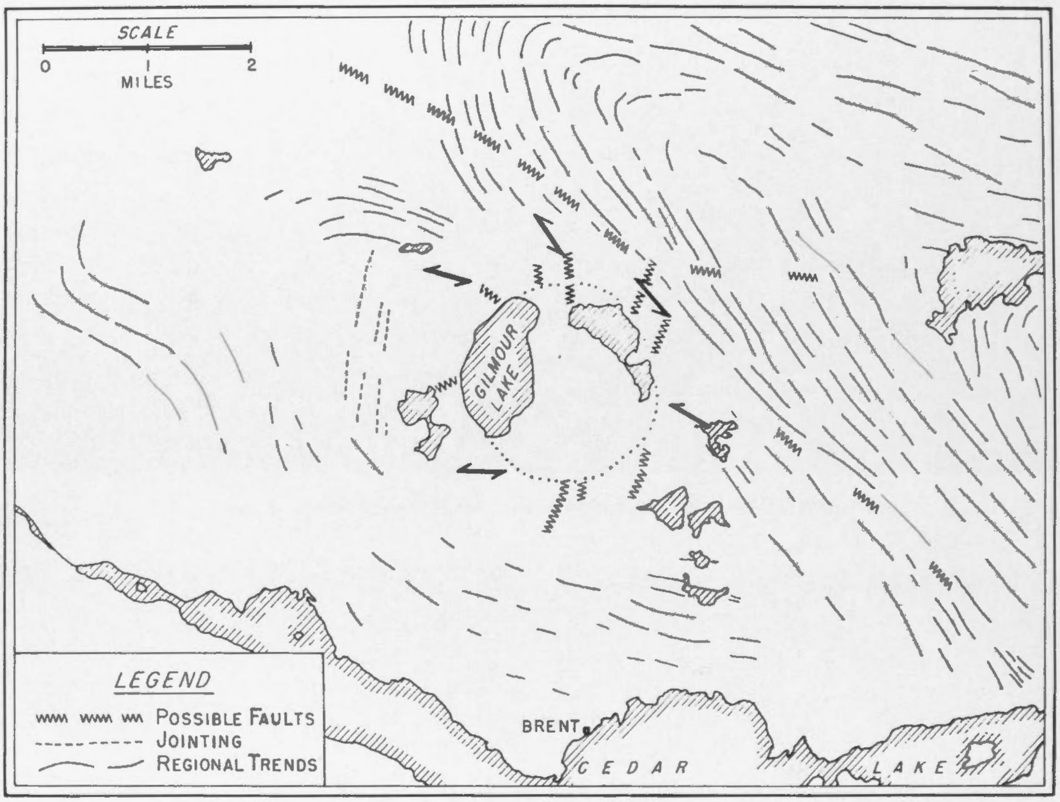


Figure 22. Regional trends, Gilmour Lake area.

is essentially a tensional phenomenon. The formation of multiple tension fissures and fractures lead to the expansion of the crust in the region surrounding the crater. It is this increase in volume or decrease in density that produces the negative gravity fields found associated with these features. It would be expected that intensive jointing and fracturing accompanying the uplift of the rim would permit infiltration and circulation of the surface waters to the lower levels, which would promote and accelerate erosion.

*An original diameter of 11,500 feet has been suggested by Millman.

In spite of its great age, and the work of erosion, one might expect the surface rocks to record some evidence of the fracturing and fragmentation that accompanied the formation of the crater. However, the dense undergrowth and heavy mantle of unconsolidated material on the inner slopes precludes this possibility. With the exception of the north-south set of vertical joints (Figure 22) observed to the west of the crater, which may prove significant, little can be learned concerning bedrock structure within this area from the aerial photographs.

There is evidence that this whole area has been affected by large-scale faulting in post-Mesozoic time (Kay, 1942; Satterly, 1944). A series of northwest-southeast trending normal faults having considerable vertical displacement have been mapped in the Pembroke and Renfrew districts to the southeast (*see* Figure 2). Linear depressions and scarps striking northwest, which appear to cut across the synclinal struture to the northeast of the crater, may prove to be the northwestern extension of this same set of faults. However, the near perfect circularity of the crater floor indicates no differential movement and suggests that the crater has suffered little disturbance since its formation, other than possible movements as part of a large crustal block. The same argument, of course, rules out the possibility of faulting and subsidence as a mode of origin.

Possible tension fissures produced at the time of the crater's formation are illustrated in Figure 22. These now form radial drainage channels for intermittent streams emptying into the crater.

Crystalline limestones in large amounts are normally associated with the Grenville gneisses although none were noted in the area. These rocks are much less soluble than ordinary and younger limestones, but weather more rapidly than the granitic rocks. As collapse structures or sink-holes, due to the removal by solution of less resistant beds, are common in all limestone-covered areas and in those underlain by salt-bearing beds (De Sitter, 1956), it may be argued that the Brent depression owes its formation to similar processes. If this is so, whether formed by differential erosion or abstractions from below, one would expect that the crater would retain some expression of the regional structure. Such, however, is not the case, for as previously shown the foliation and bedding of the gneisses maintain a general northwest-southeast strike which, near the crater, does not conform to the crater's circularity.

Finally, it should be remarked that a volcanic hypothesis suggesting the crater to be a deeply eroded vent or caldera, finds no support from the geology. Apart from the possibility that here as elsewhere in the Grenville province some of the gneisses may be of volcanic origin, no volcanic rocks are known to exist in the area.

GRAVITY INVESTIGATION

Field Operations and Reductions

The distribution of the gravimeter stations, which total 194, is given in Figure 23. The rugged terrain surrounding the basin and the heavily wooded floor within, made the gravimeter operations very difficult and the usual practice of establishing a rectangular array of stations could not be followed. The cutting of undergrowth and small trees was required for all traverses except those along the trail leading to Brent and around the shores of the three lakes. Although fewer than originally planned, the gravity stations seem plentiful enough to provide a clear picture of the main variations of the gravitational field.

The gravity observations were taken with Worden gravimeter No. 44, having a scale constant of 0.1114 milligals per division. Repeat observations at selected stations indicated that the error of a single determination is no greater than ± 0.04 milligals. A Cooke compass theodolite and Zeiss level with compass attachment were used to determine station positions and elevations. Closures were made whenever possible and show that the error in position is slightly less than one per cent, and that in station elevation less than 0.2 feet.

Bouguer anomaly values of the stations were calculated in the usual way using a surface density of 2.67 gms/cc. arbitrarily adopted at the beginning of operations before density data were available. It will be seen later that this value is in favourable agreement with the density values adopted for the rocks which form the rim of the crater, but differs considerably from the figure obtained from the material within. Fortunately the correctness of the latter is not critical because elevation changes within the basin are small and do not exceed 200 feet.

The gravity anomalies are all relative to an arbitrarily selected base station B-1, located on the beach at the northern end of Gilmour Lake (Figure 3). The absolute value of gravity for this station relative to the National Base Station in Ottawa is estimated to be 980.5947 ± 0.0005 cm/sec.[2] The height of base B-1 above the mean sea level is 1056.6 feet, determined by spirit levelling to the C.N.R. station in Brent. From this it may be deduced that a gravity anomaly of zero adopted for B-1 corresponds to an absolute Bouguer anomaly of −64.4 milligals.

The Bouguer Anomaly Map

The location of the gravity stations and their Bouguer anomalies contoured at intervals of 0.5 milligal are shown in Figure 23. Some topographical information has been included on this figure and shows that the circular structure produces a clear and unmistakeable gravity anomaly with a relief of about 5 or 6 milligals. Generally, the contours, apart from minor variations, are circular and form a gravity minimum concentric with the feature. It is

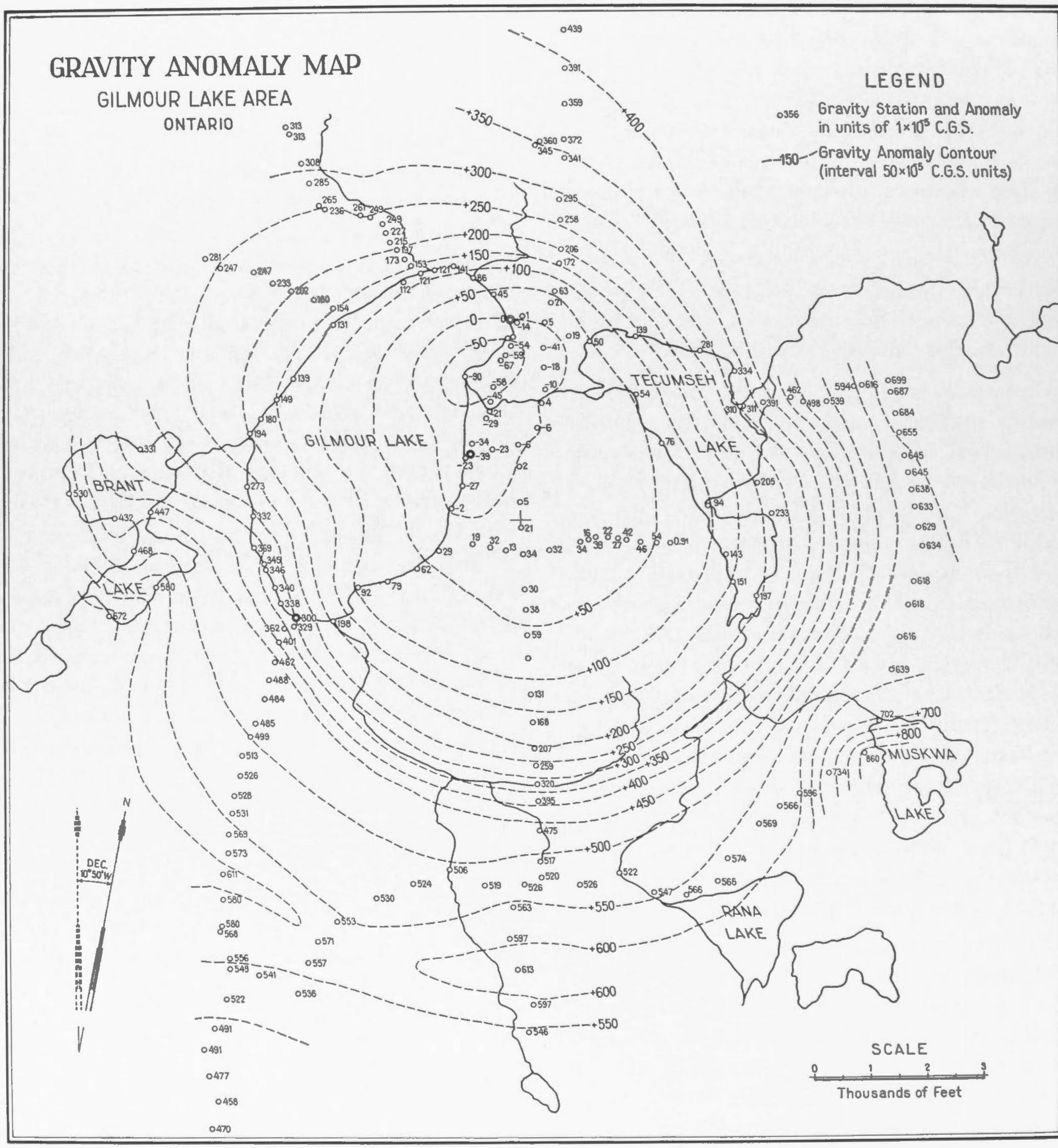


Figure 23. Bouguer gravity anomalies, Gilmour Lake area.

interesting to notice that while the variation over the central area is quite small, the gradient is greatest in the vicinity of the 9,500-foot circle, suggesting a near-surface course.

Outwards from this circle, in all directions, there is a tendency for the gravity values to become normal. Although too few stations have been observed to the east and west to verify this, peak values are obtained to the north and south about 4,000 feet from the 9,500-foot circle, near the present height of land surrounding the crater. The peak value to the south appears to be about 2 milligals higher than that to the north.

The gravity field does not have its smallest value at the centre of the feature, but reaches a minimum of −0.90 milligal at station P-2, about 3,000 feet to the north of the centre. Since this location is in the vicinity of the creek which drains Tecumseh Lake, it is not unlikely that the asymmetry is due to a greater thickness of overburden in this area. Assuming the additional gravity depression to be 0.7 milligal and the density contrast to be 0.5 gm/cm.^{3}, the thickness of overburden may be estimated at roughly 108 feet.

It was hoped that the gravity results together with the geological information would provide evidence concerning the sub-surface structure of the feature and thus give indirect evidence as to its origin. The most interesting qualitative fact about the gravitational picture is the way in which the contours follow the rim of the basin, and only at considerable distance tend to follow the trend of the granite gneisses. Any explanation of the gravity field would therefore require a circular body of low density material extending from near the surface to a considerable depth.

Such an interpretation is consistant with the hypothesis that the feature is of meteoric origin. If it were merely a depression of no great depth one would expect the granite and granite gneisses to exert the greatest control, so that the anomaly trends over these rocks would persist across the basin. If it were of meteoric origin the undisturbed floor of the crater would lie at great depth below the present surface and the unconsolidated glacial drift—Palaeozoic sedimentary rocks—and a considerable thickness of explosive debris and shattered material filling the crater would produce a negative anomaly field. Millman has estimated the depth of the original crater floor below the ground level to be about 900 feet. The undisturbed floor would therefore lie at a much greater depth.

Finally, it may be remarked that small positive gravity anomalies (also positive magnetic anomalies, *see* Figure 6) occur at stations D-20, D-21, N-15 and correlate with the basic intrusives previously mentioned. However, the absence of a positive gravity anomaly over this feature as a whole, is very strong evidence against the possibility that the crater may be the surface expression of a deeply eroded volcanic vent or an igneous intrusive phenomenon such as a basic plug.

Density Determinations of Surface Rocks

Before any quantitative interpretation can be made it is necessary to know something concerning the densities of the material within the basin and those of the surrounding rocks. Table III gives the location and density of all rock specimens obtained by surface sampling. The densities of the granitic rocks are fairly consistent and have a mean value of nearly 2.66 gms/cc. There is a wide difference, 0.55 gm/cc., between the mean densities of the two sedimentary rock types obtained within the basin.

Since there was no way of knowing their relative proportions, it was considered that a more reliable estimate might be obtained by using a least-squares method (Legge, 1944). In this method the elevation factor and the mean density of the topography is obtained from a consideration of the variation in gravity along a traverse where there is considerable change in elevation.

The results of the analysis carried out for various gravity and elevation profiles, both within and without the basin, are shown in Figure 16. In each case the elevation, smoothed gravity profile G_i, and the Bouguer anomaly have been plotted. The elevation factor K, mean density ρ, and the root mean square of the deviation φ, between the Bouguer anomaly profile and the smoothed profile are also given for each solution. The latter, φ, provides an estimate of the closeness of fit and hence a measure of the reliability of the value obtained for the elevation factor and mean density of the topography.

The granitic rocks along the P-line, A-line, and N-line were found to have a mean value of 2.67 which is in favourable agreement with the results from the surface density sampling. For the E-line, the only traverse within the basin which has an appreciable change in elevation, the analysis yields a value of 2.48 gms/cc. For reasons previously given, this value is considered more representative than that obtained by surface sampling and is the value assumed in the interpretation which follows.

TABLE III

A. *Samples obtained within the Basin*

Specimen	Location	Density	Mean
		gm/cc.	gm/cc.
Grey lithographic limestone........	C-5	2.66	
Grey lithographic limestone........	C-2	2.64	2.65
Grey lithographic limestone........	E-8	2.65	
Yellow weathering fine-grained sandstone..................	C-14	2.07	
	C-14	2.12	2.10
	C-14	2.10	

B. *Samples obtained outside the Basin*

Specimen	Location	Density	Mean
		gm/cc.	gm/cc.
Granite gneiss...............	A-15	2.60	
Granite gneiss...............	A-14.5	2.61	
Granite gneiss...............	A-13 North	2.67	
Granite gneiss...............	A-10 of	2.66	
Granite gneiss...............	A-8 rim	2.68	
Granite gneiss (garnetiferous) .	A-5	2.79	
Granite gneiss......	P-24 South	2.64	
Granite gneiss...............	P-2 of	2.63	2.66
Granite gneiss (weathered)....	P-2 rim	2.57	
Granite gneiss...............	M-4 East	2.64	
Granite gneiss...............	M-4 of rim	2.64	
Granite gneiss...............	X-1 West	2.69	
Granite gneiss.............	X-1 of rim	2.69	
Basal conglomerate and breccia (float samples only)	C-16 South	2.27	
	C-16 of	2.35	2.34
	C-16 rim	2.39	

Correction for Terrain and Regional Effects

The Bouguer anomalies for a north-south diameter, the A-C line, crossing the feature were recomputed using elevation factors determined in the preceding paragraphs. Corrections were also carried out at this stage for terrain effects. For a few stations along the line in the vicinity of the rim the correction for terrain amounts to nearly half a milligal, while the average for the whole line is less than one-tenth of a milligal. The corrected anomalies and elevation profile are illustrated in Figure 24.

It will be noticed that the anomaly profile is not entirely symmetrical and that it does not conform exactly with the configuration of the basin. Although the anomaly curve reaches a maximum value in both directions about the same distance from centre, the peak value of the south is about 1.5 milligals higher than to the north. This difference in peak values is interpreted as part of a large-scale regional trend and is consistent with the anomaly pattern indicated on the regional gravity map (Thompson-Miller, 1958) for this area. This map shows that the Brent feature lies in an area of predominantly negative Bouguer anomalies, which reach minimum values near Mattawa on the Ottawa River. The regional trend also appears consistent with the surface geology. The granite gneisses along the A-line become progressively massive to the north, with decreasing amount of ferromagnesium minerals and corresponding smaller densities (*see* Table III).

Assuming a linear relation, a regional correction has been applied to obtain the residual anomaly profile shown in Figure 25. With the exception of a slight variation, a depression of about 0.7 milligal centering about 3,000 feet north of centre, the corrected profile is symmetrical with a relief of about 5.2 milligals.

Quantitative Considerations

The thickness of the disturbing mass, or depth to the undisturbed Precambrian rocks, may be estimated from the gravity data, provided certain simplifying assumptions are made. Considering the anomaly pattern, the body could reasonably be assumed to take the form of an upright cylinder whose curved wall corresponds to the contact

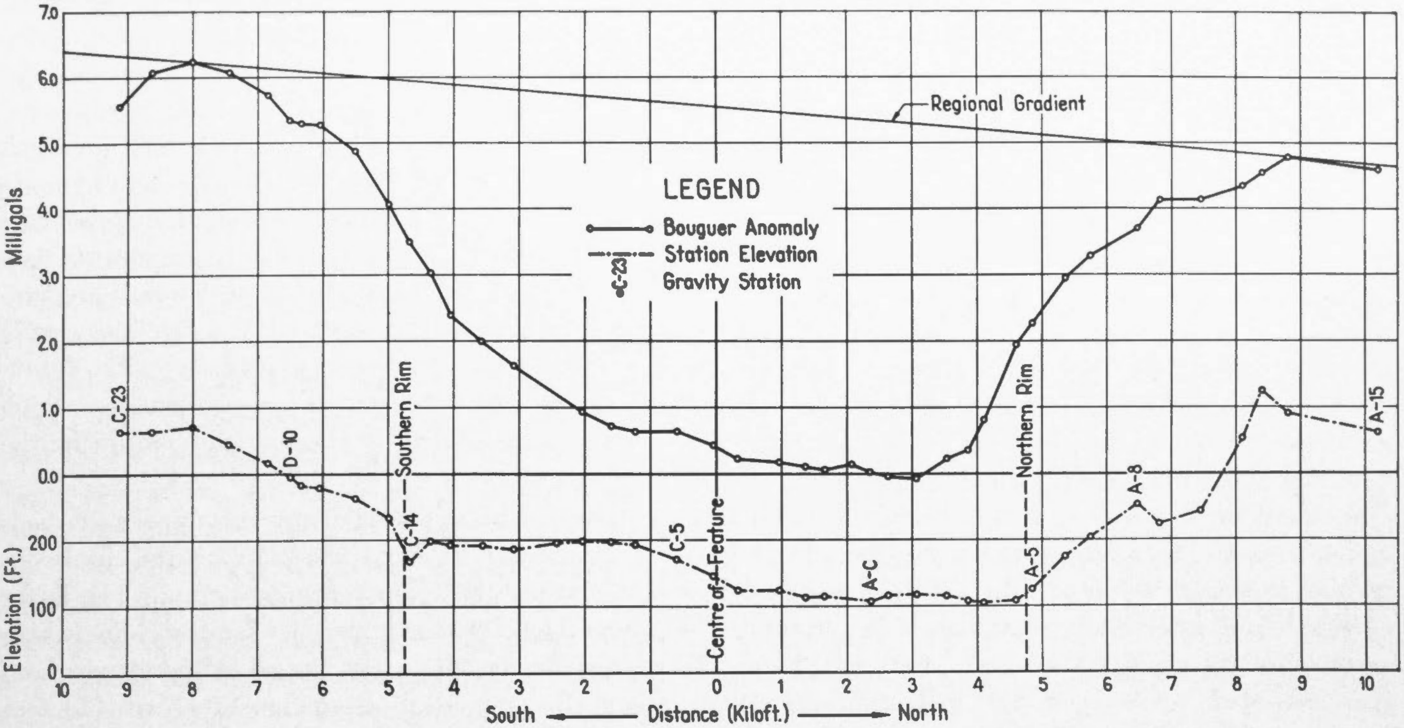


Figure 24. Bouguer anomaly profile across Brent crater.

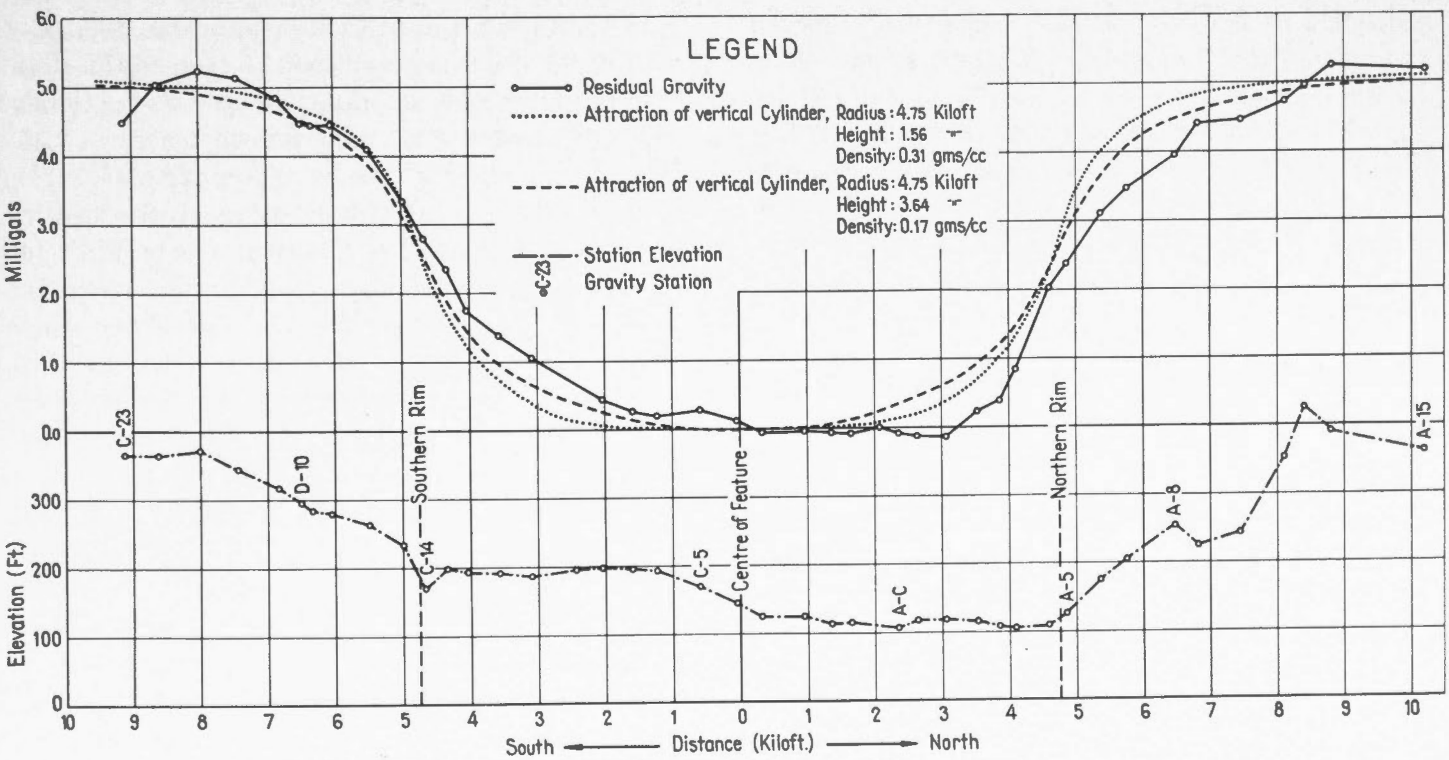


Figure 25. Residual gravity profile across Brent crater.

between the surrounding granitic rocks and sedimentary material within. The diameter of the body is 9,500 feet. It is marked by the pronounced drainage channel to the south, the western margin of Gilmour Lake, a minor depression to the north and the eastern margin of Tecumseh Lake, all of which emphasize the circular pattern of the feature.

In deducing the height of the cylinder or depth to the undisturbed floor of the basin it is assumed that the granitic rocks outside the basin are homogeneous with a density of 2.65 gms/cc. This value is the mean value of densities obtained for the granites along the P- and A-lines by surface sampling (*see* Table IV) and by the gravity profile method (*see* Figure 16). If it can be assumed that the density of 2.48 gms/cc., the value obtained for the material within the basin, persists with depth, a depth of 3,640 feet of low-density material is required to account for the gravity anomaly. For comparison, the computed curve is shown with the residual gravity profile in Figure 25.

An equally good fit can be obtained by assuming a much larger density contrast, 0.31 gm/cc. which leads to a correspondingly lesser depth of 1,560 feet. This solution, which is also illustrated, has been included to show the depths of sediments required to account for the anomaly if the greater proportion of the rocks filling the basin consisted of basal conglomerate and breccia of quite low density. Float samples of these rocks were found to have densities of 2.34 gms/cc.

The greatest difficulty in attempting to fix a depth to the undisturbed Precambrian floor from the gravity data arises from the uncertainty in estimating the density of the sediments within the basin. It seems reasonable, however, that the true mean density of the low-density material is not likely to exceed 2.48 gms/cc. nor be smaller than 2.34 gms/cc. The assumption of these densities and a cylindrical shape, therefore, lead to two estimates for the depth to the undisturbed floor, namely 3,640 feet and 1,560, which may be regarded as limiting values.

A more refined estimate for the thickness of the low-density material disturbing the gravity field may be obtained by taking into account the results of diamond drilling. The graphical representation of density data based upon drilling cores is given in Figures 17 and 18. Because of difficulties in recovering the cores, the density determinations average about one for every 10 feet of drilling. The densities are quite variable and range from 2.22 to 2.68 gms/cm^3. Fine-grained lithographic limestones which were encountered in larger proportions in the upper part of D.D.H. No. 1 have higher and more uniform densities than the shales and sandstones which predominate at the lower levels. As a result the profile shows a general decrease in density with depth. This is also evident from the mean densities which have been computed for the six beds comprising the vertical section.

The densities obtained for the uppermost beds of the section are in agreement with the result obtained using the gravity profile method. The latter gives a value of 2.48 gms/cm.^{3} for the E-line which crosses the central part of the basin and along which there was an elevation change of about 130 feet (*see* Figure 16). About the same density was obtained for core samples from the upper part of D.D.H. No. 1. The weighted mean density for the upper three beds, which have an overall thickness of 150 feet, is 2.46 gms/cm^3.

The contribution of each bed and the total attraction of the mass deficiency of each section has been estimated. The deficiency in gravity due to the 560 feet of sediments (having a mean density of 2.35 gms/cm^3) in D.D.H. No. 1 is approximately 2.0 milligals. If this density is maintained with depth, an additional thickness of 1,060 feet is required to account for the remaining anomaly of 3.2 milligals. This would indicate that the total thickness of low-density material near the centre of the basin is 1,620 feet, which is a minimum, since the densities are more likely to increase with depth.

Similarly it is estimated that the 190 feet of low-density material penetrated in D.D.H. No. 2 contribute a maximum of 0.6 milligal to the total anomaly of 2.8 milligals at the collar of the drill hole. The remaining 2.2 milligals is consistent with the result obtained above for the minimum thickness at the centre of the basin. The gneissic breccia encountered in the lower 50 feet of this drill hole may with further investigation prove to underlie the Palaeozoic rocks occupying the central part of the basin, and provide the greater control over the gravity field. The density of the breccia is quite variable and ranges from 2.0 to 2.6 gms/cm^3. Its mean density, based upon 11 samples is 2.43 gms/cm^3. While this is greater than the mean density of sedimentary rocks in D.D.H. No. 1 and suggests a correspondingly greater depth, there is insufficient evidence to alter the previous estimate of 3,640 feet for the maximum depth to the undisturbed floor of the crater, based upon a mean density of 2.48 gms/cm^3.

In the foregoing attempt to establish upper and lower limits for the depth of the disturbance it has been tacitly assumed that the anomaly is entirely due to the contrasting densities of sedimentary and fragmental material within the 9,500-foot circle and the surrounding granite gneisses. As pointed out in a previous section the crustal density near the rim of an explosion crater may be less than average due to fracturing and uplift. Such a deficiency in density would not be detected by the two methods of surface sampling. It is therefore possible that part of the anomaly associated with the Brent feature is due to an 'expanded' crust of the deeply eroded crater rim. The gravity anomaly map strongly supports such a possibility. It can be seen that the peak anomaly is coincident with the present location of the rim, 3,000 to 4,000 feet beyond the 9,500-foot circle separating the gneisses and sediments.

Total Mass Deficiency

Beyond these considerations there seems little point in attempting to carry the interpretation further. However, an estimate of the total mass deficiency of both the sedimentary and underlying disturbed and fragmented granitic rocks may be of some interest and prove useful in later investigations. A minimum estimate can be arrived at by computing the volume of our cylindrical model and multiplying by the mean density contrast of the section. This yields a mass deficiency of 9.9×10^{14} gms. or 1×10^9 tons.

A more direct and possibly more precise estimate of the anomalous mass may be made using a method developed by Sigmund Hammer, (1945). This method is based upon Gauss' theorem, in that the surface integral of the Bouguer anomaly, taken over an infinite horizontal plane, is proportional to the mass alone and is independent of its form or shape. The method has the added advantage that no assumptions need be made about the densities of the disturbing masses. The greatest error in the result stems from uncertainty in estimating normal background values.

In applying this method to the Brent survey it was necessary to infer gravity values for part of the unsurveyed area, especially in the northwest part of the map-area. The regional gradient was then subtracted from the Bouguer values and the integration carried out to the 5.5 isogal. The mass deficiency calculated by this method is 9.2×10^{14} gms., in good agreement with the direct geometric method.

It follows that the practical working formula, which relates the total volume V of low-density material and its density contrast φ is given by:

$$V = 3.24/\varphi \times 10^{10} \text{ cubic feet.} \qquad (1)$$

Thickness of the Breccia

It now remains to see if, by combining the gravity, seismic and drilling results, a more complete picture of the structure of this interesting feature is possible. The total mass deficiency due to both the sedimentary rocks and to the gneissic breccia which may occupy the floor of the crater and be derived from the original explosion debris, has been estimated from the gravity data. The configuration of the surface separating these two materials has been mapped by the seismic investigation. If these results are accepted and it is assumed that the densities obtained from drilling are representative, 2.35 gms/cm^3. for the sedimentary rocks and 2.42 gms/cm^3. for the breccia, it is possible to deduce a minimum value for the thickness of the fragmental material.

The final seismic interpretation (*see* diametral section, Figure 14), suggests that the sedimentary rocks occupy a deep symmetrical basin whose shape can be reasonably approximated by an inverted cone, truncated at a depth of about 1,000 feet. The diameter of the base of the cone is 9,500 feet, equal to that of the feature, while its height (or depth to apex) is estimated to be 1,600 feet.

If, as now appears unlikely, the crater has a central boss that can be represented by an upright cone 600 feet high, and diameter 4,000 feet, the sedimentary rocks are estimated to occupy a volume of 3.3×10^{10} cubic feet and to have a mass deficiency of 2.8×10^{14} gms. Since the gravity data indicate a total deficiency of 9.2×10^{14} gms. it may be inferred that the difference, 6.4×10^{14} gms., is due to underlying low-density material.

If this is similar to the breccia encountered in D.D.H. No. 2, its total volume is estimated to be 9.8×10^{10} cubic feet and indicates the breccia zone has a thickness of 1,200 feet. Within its limits of accuracy this result is unchanged if the central boss, suggested by the seismic results but not verified by the drilling, is deleted from the argument and it is assumed that the sedimentary material extends to uniform depth of 1,000 feet.

It should be emphasized however that 1,200 feet is a minimum estimate of the thickness for the breccia and is based upon a density of 2.42 gms/cm^3. If the Brent feature had an explosive origin one would expect the fragments in the breccia to increase in size with depth, with the result that the densities would gradually increase to those of the undisturbed basement rocks, 2.67 gms/cc. If this is a true situation, a correspondingly greater thickness of breccia would be required to satisfy the gravity data. It may well be, therefore, that the seismic results, although based on admittedly inadequate observational data, might be correct in indicating a total thickness of breccia of the order of 4,000 feet. Under these circumstances the mean density of breccia averaged over all depths would have a value of 2.57 gms/cc., part way between the values for the granitic rocks surrounding the crater, and the breccia at relatively shallow depths.

SUMMARY AND CONCLUSIONS

1. The Brent crater is a circular depression in Precambrian granite gneisses nearly 2 miles in diameter and is filled with Palaeozoic sediments of Ordovician age.

2. The gravity results show a circular minimum of about 5.2 milligals believed due, not only to the sedimentary rocks within the basin, but also to underlying gneiss breccia and disturbed bedrock conditions, consistent with an explosive origin.

3. The gravity field reaches peak values near the height of land surrounding the crater some 4,000 feet out from the contact separating the granite gneisses and sedimentary material. These negative anomalies are believed to reflect forcible uplift and fracturing of the crust in this area, accompanying the crater's formation.

4. Sediments 560 feet thick have been disclosed by drilling near the centre of the basin. If these persist with depth, another 1,100 feet of sediments would be required to satisfy the gravity data. On the other hand, if the material is breccia, as the evidence suggests, a depth from the surface of at least 3,600 feet would be required. Combined analyses of the drilling, seismic, and gravity results indicate that the breccia zone has a minimum thickness of 1,200 feet.

5. An explosion origin finds geological support. The circularity of the crater shows little evidence of conforming with the strike of banding in the gneisses. Structural trends which persist in a general way on opposite sides of the feature are terminated at the present height of land surrounding the crater. This seems to indicate that the crater's formation was completely divorced from, and post-dates, the folding of the Grenville rocks.

6. The near-perfect circularity of the present floor indicates that the crater has suffered little or no disturbance by local faulting. Radial drainage channels into the depression may originally have been tension fissures that developed during the crater's formation.

7. All the evidence produced in this investigation—the crater's circularity, negative gravity field, its great depth, independence of local geology and regional structure, evidence of jointing and fragmentation—seem to be satisfactorily explained by an explosion hypothesis.

8. It has been shown that a volcanic origin is inconsistent with both gravity and geological data. The possibility of a collapse or sink-hole origin, or other circular geological structure is most improbable on similar grounds.

9. Considering all possibilities an explosion by meteoritic impact remains the most plausible explanation for the crater's origin.

PART VI

Summary and Conclusions

BY

PETER M. MILLMAN

In the first five parts of this report, studies of the Brent crater by five independent techniques have been detailed. These investigations are summarized below and the significant points correlated.

First, the reasonably well established facts concerning the Brent crater:

(1) *Aerial photography and topographical survey*

A nearly-perfect circle, 9,500 feet in diameter, appears on aerial photographs. The area inside this circle has a more level surface topography than the local terrain and averages 250 feet lower than its immediate surroundings.

(2) *Surface geology and drilling operations*

A distinct topographical feature, roughly circular in outline, coincides in position with the circle found by aerial photography. This feature does not conform with the general character of the surface geology of the region. Within the circle, under a layer of surface soil and clay up to 100 feet thick, lie Ordovician sedimentary strata extending to a depth of at least 570 feet below the surface in the central portion. Near the circumference of the circle a brecciated material extends under the surface layer to at least 200 feet below ground level. Outside the circle the surface rock consists in general of gneisses and granites typical of the Canadian Shield. The mean density of the Ordovician sediments is 2.35 and of the breccia is 2.42, as compared with the density of 2.65 adopted as typical for the undisturbed bedrock for this area of the Canadian Shield.

(3) *Magnetic Survey*

Both ground and airborne magnetic surveys indicate very little variation in the magnetic field within the 9,500-foot circle in comparison with that outside the circle. The contrast between these areas is greater for the ground survey than for the airborne survey, suggesting that the heavier magnetic rocks of the Canadian Shield, which appear in surface outcrops around the circle, are buried to a depth of 1,000 or 2,000 feet inside the circle.

(4) *Seismic Survey*

Investigations by seismic methods indicate that, under a surface layer which varies from 0 to 100 feet in thickness, there is a material (sedimentary) in which seismic waves travel 10,500 ft/sec. with a thickness in depth varying from 300 to 1,000 feet. Under this there is another material (possibly of several types, sedimentary and breccia) in which seismic waves travel 14,150 ft/sec. There is some indication that this second material may extend beyond the circle to a distance of 4,000 feet in a radial direction. Outside this is the Canadian Shield where the velocity of seismic waves is 20,240 ft/sec.

(5) *Gravity Survey*

A gravity low, total range 6 milligals, is centred on the 9,500-foot circle. The steepest gradient of this low coincides in general with the circle. A low of this magnitude would be produced by a circular cylinder or plug of low density material, 9,500 feet in diameter and between 1,600 and 3,600 feet deep, surrounded and underlain by breccia of a minimum thickness of 1,200 feet.

From the above it is seen that the Brent crater is a deep-seated symmetrical feature in the Canadian

Shield. A circular depression, 9,500 feet in diameter on the surface, is filled to a depth between 1,000 and 2,000 feet with relatively light Ordovician sediments, the whole surrounded by a layer of breccia of medium density which extends to a depth between 3,000 and 4,000 feet, and has a horizontal diameter somewhere between 12,000 and 18,000 feet. The time of the formation of this feature is estimated as approximately 600,000,000 years ago.

As has been noted earlier it is difficult to explain the Brent crater on the basis of faulting or subsidence, and a collapse structure or sink-hole would show more connection with the regional structure. The absence of any volcanic evidence in the region, and the magnetic flat as well as the gravity low, preclude any explanation on the basis of a volcanic vent or igneous intrusive phenomenon. The similarity of this feature to others in the Canadian Shield studied recently (Millman, 1956; Beals, 1957; Innes, 1957) strongly suggests a similar origin for all. The circular outline, general range of diameter-to-depth ratios, nature of the associated brecciated material and the evidence of radial fracturing all point to an explosive origin. The meteoric impact hypothesis seems the best explanation for such an origin.

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