CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
Dominion Observatories

PUBLICATIONS
of the
DOMINION OBSERVATORY
OTTAWA

Volume XXIV · No. 6

A PROBABLE METEORITE CRATER OF PRECAMBRIAN AGE AT HOLLEFORD, ONTARIO

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Price: $1.50

ROGER DUHAMEL, F.R.S.C.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1960

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C. S. BEALS

ABSTRACT:—A circular feature 1.46 miles in diameter and 100 feet deep located at longitude 76° 38′ W and latitude 44° 27′ N in southeastern Ontario has been investigated as a possible meteorite crater. Stereoscopic studies of aerial photographs in conjunction with geological and geophysical investigations indicated the presence of a circular depression in Precambrian rock filled in and covered over by Palaeozoic sediments. Three diamond drill holes at distances of 1,400 feet, 2,500 feet and 3,750 feet from the centre were sunk to see whether the depth below the sediments and the sub-surface structure were consistent with a meteoritic origin. The results showed a depth and profile close to those predicted for a meteorite crater of the observed diameter. Below the sediments a thickness of several hundred feet of shattered and pulverized rock was found for which no adequate explanation has yet been found except that of meteorite impact and explosion.

RÉSUMÉ:—Une dépression circulaire de 1.46 mille de diamètre et d'une profondeur de 100 pieds située par 76° 38′ de longitude ouest et 44° 27′ de latitude nord, dans le sud-est de l'Ontario, a été examinée en vue de déterminer s'il s'agit d'un cratère météorique. L'étude stéréoscopique de photographies aériennes exécutée conjointement avec des relevés géologiques et géophysiques ont indiqué la présence d'une dépression circulaire dans le roc précambrien, remplie et recouverte de sédiments paléozoïques. Trois sondages à des distances de 1,400 pieds, 2,500 pieds et 3,750 pieds du centre ont été effectués afin de déterminer si les profondeurs sous les sédiments et la couche inférieure sont d'origine météorique. Les résultats ont démontré une profondeur et un profil se rapprochant de ceux qui sont prévus pour un cratère météorique du diamètre observé. Une couche de roc fracassé et pulvérisé d'une épaisseur de plusieurs centaines de pieds a été repérée sous les sédiments. Cette couche ne peut être expliquée que par le choc et l'explosion d'une météorite.

Introduction

Systematic studies of meteorite craters in Canada had their beginning with the investigations by V. B. Meen (1950, 1951) of the Chubb or New Quebec crater in northern Quebec. Meen's conclusion that the Chubb crater, 2 miles in diameter, at that time the largest known, was due to meteorite impact received general support from later studies by Harrison (1952) and Millman (1956) although their conclusions differed from his in certain details.

Shortly after Meen's first results were published an examination of aerial photographs of the Algonquin Park area of Ontario revealed another crater also about 2 miles in diameter but with the kind of topographic relief and geological character suggestive of great age. (Millman, Liberty, Clark, Willmore and Innes, 1960). Later Meen (1957) made another discovery of a smaller crater in northern Labrador known as the Merewether crater and this was followed by what has been, up to the present, the greatest find of all, a tremendous crater of 7½ miles diameter at Deep Bay, Saskatchewan (Innes 1957). Although the meteorite origin of these craters as yet lacks final proof the probability that they are due to this cause is considered to be high, and the fact that so many have been found within a short space of time suggests that the Canadian Shield is a good place to look for additional examples. With this object in mind a search of Canadian aerial photographs was instituted in 1955 and an account of the preliminary results has been given elsewhere (Beals, Ferguson and Landau 1956; Beals 1957, 1958).

So far the most important result of this search has been the discovery of the Holleford crater which was first detected by G. M. Ferguson and Miss A. Landau on RCAF photograph numbers A-13969-43 and -44. Reproductions of these two photographs are contained in a pocket in the back of this publication. A stereoscopic study of this pair of prints established the circular character of the feature, the existence of a rudimentary rim and the fact that the inner were much steeper than the outer slopes.

A visit to the crater gave general confirmation to the information gained from aerial photographs but it was immediately seen that the stereoscope had given an exaggerated idea of the topography, which was less impressive than had been expected. While the crater had a diameter of well over a mile the average depth was less than 100 feet and it was clear that if this was truly a meteorite crater it had been filled in and covered over by sedimentary deposits. In addition it was apparent that the sedimentary cover had been subject to considerable erosion, creating a drainage channel out of the crater and otherwise interfering with the symmetry of its form. In spite of these disturbing effects the general crater-like character of the feature was well maintained and it was decided to investigate it further, making use of topographical, geophysical and diamond-drilling techniques in the hope of gaining a more definite understanding of its origin.

Figure 1. Aerial view of Holleford crater. The large circle indicates the top of the rim while the dip of the strata is shown by the small arrows. The three drill holes are indicated by the circles 1, 2 and 3, lower right of centre. Top of the figure is North.

Location and Surface Topography

The longitude (76° 38′ W) and latitude (44° 27′ N) of the crater place it about 17 miles northwest of Kingston, Ontario. The village of Holleford lies partly within its circumference and several roads cross the rim, while one descends close to the floor of the crater. Knowlton Lake lies close to the eastern boundary and the village of Hartington is 2½ miles to the southwest on the highway from Sharbot Lake to Kingston.

Almost the entire area of the crater is covered by early Palaeozoic sedimentary strata which slope gently inward towards the centre. Owing to the effects of erosion the circular form is more clearly outlined in some parts of the feature than others, but there appears to be no exception to the rule that all strata dip radially inward. The details of the topography can be more easily followed by reference to Figure 1. In this figure the circumference of the crater is indicated by the heavy circular line while separate areas are outlined by heavy broken lines.

Approximately in the centre of the photograph is a roughly circular area 2,200 feet in diameter designated as the floor of the crater. This lowest part of the crater, at an altitude above sea level of 492 feet, is all of closely the same level, although the dark wooded parts, which are bog, are a few feet lower than the lighter areas of pasture land. It is partly flooded in spring and even in midsummer water is close to the surface in many places. This part of the crater is almost entirely featureless and the more interesting structural aspects are found in the sectors surrounding it.

Looking outward from the centre, the arc ABC constitutes a moderately impressive cirque, rising to about 80 feet above the floor with maximum elevations of up to 600 feet above sea level and unbroken by any marked erosional irregularity. The effect of erosion is however made apparent by the line of rock outcrops marked by the light unbroken line a b c. In the vicinity of these outcrops there is an abrupt change in slope, the area above the outcrop being nearly flat. It seems probable that this outer area has been planed off by erosion possibly due to glaciation and if this is correct the conclusion follows that this topographically higher area is stratigraphically lower than the crater floor. The point is illustrated in Figure 2 (lower half) where full lines represent actual strata and dotted lines the part presumed to be removed by erosion.

Following the circle around counterclockwise the arc C D E defines a sector of the crater where the walls rise to an average height of 50 feet above the floor. Most of this sector has been rendered very irregular by erosion and the north-south road crossing it is featured by a series of gradual rises and sharp descents which at first appeared to have no obvious connection with crater structure. However, a careful study of the aerial photographs along with ground observations indicated that the irregularities could logically be explained in terms of the sketch diagram of Figure 2 (upper half).

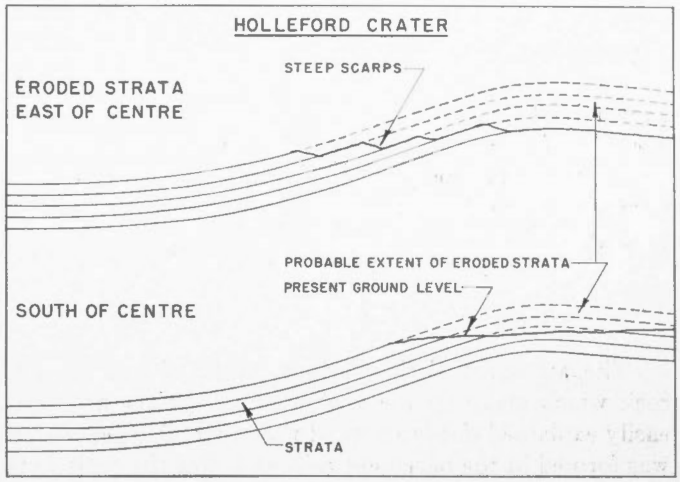

Figure 2. Suggested explanation of present ground topography in terms of eroded strata.

Here it is seen that erosion has exposed a series of strata resulting in a succession of gentle slopes directed toward the centre of the crater together with short steep scarps in the opposite direction. The abrupt changes in the level of the road are explained by the fact that it cuts diagonally across several of these features. In Figure 1, the strike of the outcrops is indicated by light unbroken lines with arrows to show the direction of dip of the strata.

The irregular sector starting with the arc E F G and extending inward to the floor of the crater is a uniformly flat area consisting of wooded bog and pasture land and represents the drainage pattern out of the crater. It is extended outward beyond the crater circumference to the vicinity of nearby Knowlton Lake which is at a considerably lower level. There is a cliff-like slope along the line e e e which is one of the boundaries of the area. Part of the corresponding boundary on the northern side of the drainage pattern, indicated by the letters g g g, follows for several hundred feet the base of a fairly steep hill which seems to have the characteristics of a mound of glacial debris. Nearer the centre the west boundary of this sector follows rather closely the edge of a wooded bog which is a conspicuous feature of the photograph. The entire area of this sector is closely at the same level, 492 feet above sea level, corresponding to that of the crater floor.

The irregular sector G H I A has been much modified by erosion and presents aspects somewhat similar to those already described in connection with sector D E F. The erosion has been deeper and more irregular and in the areas indicated by the letters i i i the level is close to that of the crater floor. There is a relatively steep scarp from 10 to 20 feet high along the line h h h with corresponding gentle slope toward the centre of the crater. This scarp and the associated dip of the strata is an important indication of the location of the crater circumference in the northwest sector. In this, as in other sectors where such features appear, all scarps or abrupt changes in slope accompanied by rock outcrops are shown by light unbroken lines with arrows indicating the dip of the strata. When the stereoscopic pair of photographs in the pocket of this report are viewed through a suitable instrument, these features are clearly indicated.

Diameter

The attitudes of the various strata of sedimentary rock which make up the visible crater surface are most easily explained if it is assumed that a circular depression was formed in the basement rock and that the sediments were deposited within the depression and upon the sloping sides. As a working hypothesis it has been assumed that the depression was a meteorite crater with a raised rim surrounding it and the term "diameter" as used here refers to the diameter of the rim measured to the level where the slope is zero, i.e. the highest point on the rim. In the present instance the location of the original rim must be inferred from the dip of the surface strata which becomes more and more indefinite as the top of the rim is approached. Moreover, there are places where, due to erosion or thickness of drift, there are no indications of dip at all. In addition, an over-all study of the topography indicates that any raised rim which may have originally existed was largely, but probably not entirely, eroded away before the deposition of sediments.

The area where indications of dip are most clear is the sector C D E of Figure 1. Unfortunately the slope approaches zero just on the edge of a cliff dropping to the shore of Knowlton Lake and this somewhat reduces the weight of rim locations in this area. There are, however, some good indications of dip on the western edge of the crater, and the scarp in sector G H A marked h h h gives a useful indication of minimum diameter. The hill traversed by the road north of the line g g g has flat-lying strata outcropping on its eastern slope, indicating that it is near the crater rim, but the top of the hill and its southern and western slopes have no outcrops and there is evidence that the rock strata in this location are covered by a glacial mound.

The diameter finally adopted is 1.46 miles or 2.35 kilometres. The writer feels reasonably confident that it is not in error by more than 5 per cent and it seems likely that any subsequent adjustment will make it larger rather than smaller.

Surface Geology

The geology of the crater and its surroundings has been studied by M. J. Frarey (1955), Geological Survey of Canada, and his conclusions may briefly be summarized as follows.

Precambrian rocks are distributed along the west, north and east sides of the depression area. These rocks are a mixture of crystalline limestone and biotite gneiss with other constituents such as quartzite and pink granite associated with the limestone. Small outcrops of Nepean sandstone (believed to be Cambrian) are present. These outcrops are thin, consisting of quartz grains and pebbles colored red by iron oxide.

Ordovician rocks are found south of the crater and, to some extent on the west. In places the Ordovician limestone is observed lying directly over the Precambrian rocks, indicating the scattered nature of the deposition of the Nepean formation. The Ordovician rocks cover the entire depression area and practically all of the rim as delineated by the circle of Figure 1. The limestone beds are physically intact, undisturbed apart from the gentle dip toward the centre. Frarey concludes that the condition of the Palaeozoic beds restricts to Precambrian time any meteoritic impact or other disturbance forming the depression. In his discussion of a possible origin for the depression he points out that there is no visible geological evidence for a meteorite origin, but that other possibilities such as volcanism, differential erosion, sinkhole formation, block faulting or subsidence are unpromising. He suggests geophysical observations or diamond drilling to ascertain the depth of the depression for comparison with known meteorite craters.

Geophysical Evidence

Magnetic Observations

Fortunately, with the aid of the Geological Survey of Canada an aeromagnetic map of the region was located and studied to see whether there were any magnetic anomalies which appeared to have a relationship to the form and location of the crater. The results of this study are best illustrated by the map itself, a part of which is illustrated in Figure 3. Here the crater rim is shown as a circle in the centre of the figure. The magnetic contour interval is 10 gammas, the base intensity being arbitrary.

It is seen that no anomalies occur within the rim of the crater and those which occur outside the rim have no obvious relationship with the crater structure. Accordingly, if the crater was formed by an iron meteorite, the quantity of material remaining in the crater was too small or was buried too deeply to be recorded by an aeromagnetic detector flying at an altitude of 500 feet. Indeed modern theory would indicate that a large part of any iron or stony meteorite which could

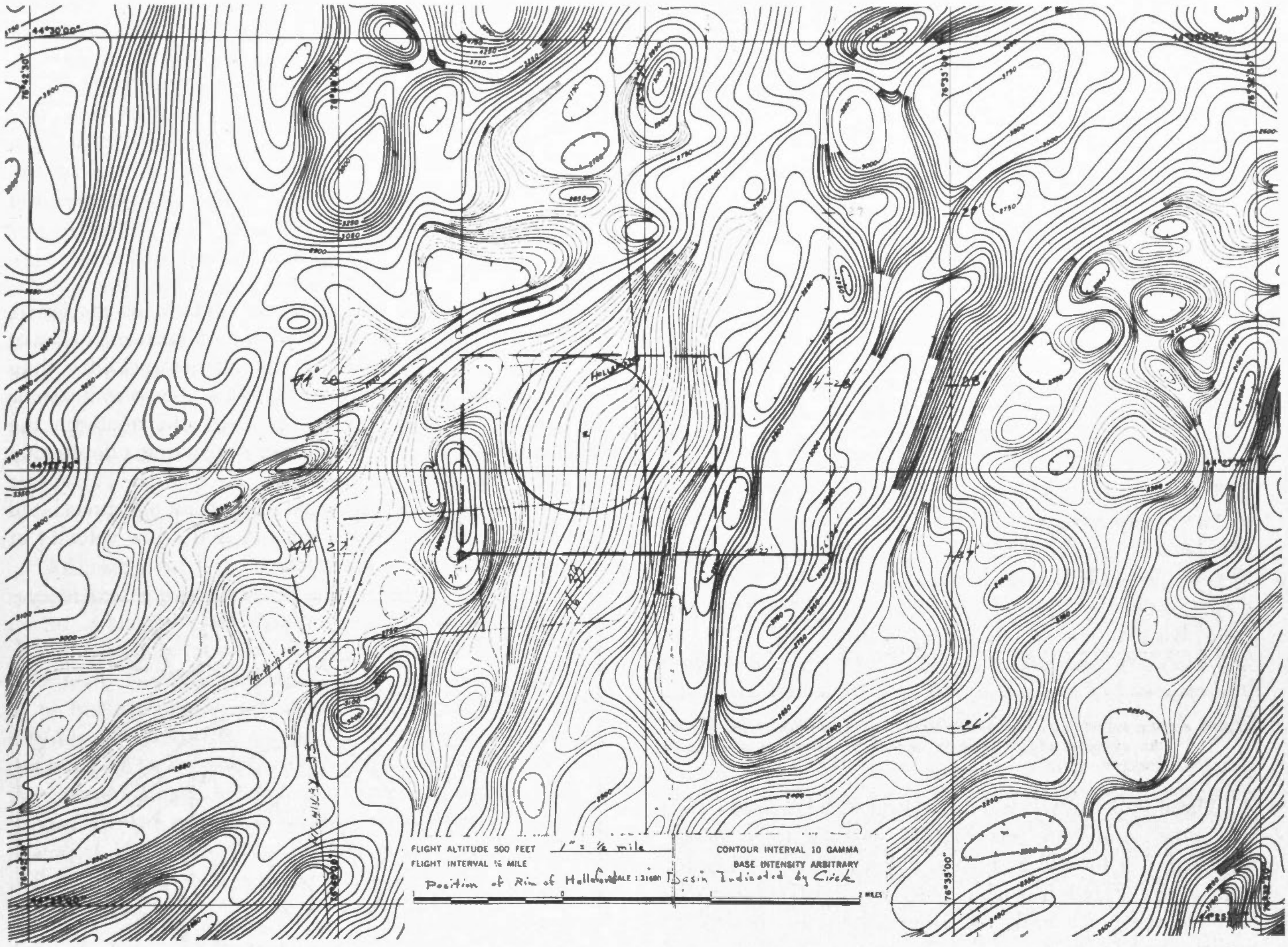

Figure 3. Aeromagnetic map of Holleford crater vicinity. It can be seen that there is a minimum of magnetic disturbance within the circle outlining the crater.

have formed the crater would have been blown out of it by the resulting explosion. On any impact theory of origin, therefore, the undisturbed magnetic pattern could be interpreted as a consequence of the removal of a large volume of basement rock from within the rim and its replacement by sediments of lower and more uniform susceptibility.

The aeromagnetic evidence is not favorable to the idea of a volcanic origin for the crater, since it seems likely that such a phenomenon would have shown itself on the map in a pattern in some way associated with the circular area outlined by the rim. While the information given by the aeromagnetic map cannot be said to have provided positive evidence of an impact origin, the evidence it does provide is not such as to discourage further investigation by other means.

Seismic Methods

A seismic study of the crater and its surroundings was made by J. H. Hodgson and P. L. Willmore of the Seismological Division. A number of arrays of seismometers were set up along a diameter and shots were fired to determine the nature of the material under the limestone strata filling the crater. A number of trials resulted in values of velocity for the swampy soil cover (1,100 ft/sec) and of the limestone strata (17,000 ft/sec). No other onsets were recorded. From this it was inferred that the relatively hard, dense surface limestone gave a velocity higher than the underlying material, resulting in the refraction of the seismic waves away from the surface. It was accordingly concluded that no results of any value could be obtained by applying the standard methods of refraction seismology within the crater.

Since much of the country surrounding the crater is underlain by Ordovician limestone similar to that within the crater, the next step in the seismic study was to determine the limestone velocity and the basement velocity by means of a series of relatively long-range shots outside of, and some distance from, the crater. The resulting velocity for the limestone was 16,800 ft/sec and for the basement 19,000 ft/sec.

It was then felt that some information concerning the material under the crater might be obtained by firing a number of shots within the rim and recording them at distances ranging from 3,000 feet to 12,000 feet outside the crater. If, as seemed probable, the material under the crater was of lower velocity than either the basement or the surface limestone, this might well show up in an analysis of the travel times. The results are illustrated in Figure 4.

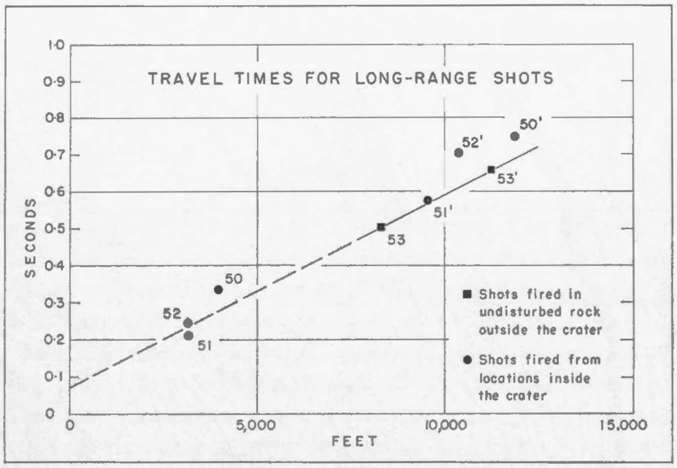

Figure 4. **The travel-times for seismic shots fired inside the crater are on the average late, relative to those fired outside in undisturbed rock.**

Three shots, numbered 50, 51 and 52 were fired inside the crater, and were recorded by seismographs outside the crater. A fourth shot (No. 53) was fired at a point outside the crater, in such a position that the ray paths to both receivers could be assumed to lie entirely in undisturbed basement rock. The results are illustrated in Figure 4, in which the number alongside each recorded observation refers to the shot, and the accented and un-accented numbers distinguish between the two stations. The two records of shot 53 define the bedrock velocity of 19,300 ft/sec and the onsets for shot 51 fall fairly close to the same travel-time line. The onsets for shots 50 and 52 showed an average delay of nearly $\frac{1}{10}$ sec.

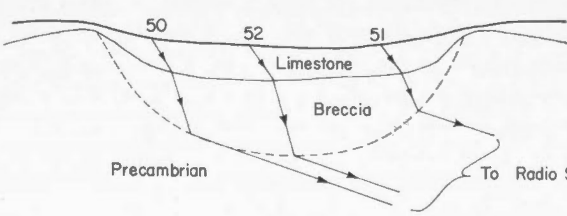

Figure 5. **Diagram illustrating ray paths of seismic shots fired inside the crater.**

The situation which could well explain these results is illustrated in Figure 5. Here it is seen that all three shots traverse first the limestone layer, then the assumed breccia, before entering the basement rock. The geometry of the figure suggests that shots 50 and 52 would penetrate a greater thickness of breccia than 51. This, combined with local conditions impossible to predict, could account for the different behaviour of shot 51. While these results are not definitive, they are nevertheless consistent with the presence, under the crater, of a considerable thickness of low-velocity material of the kind associated with a meteorite impact, namely, the broken and shattered layers designated as breccia.

Gravity Studies

Both the magnetic and seismic data were consistent with the idea of a depression filled with material of lower density and more uniform magnetic susceptibility than the surrounding country rock. While these indications were not of positive character they did reinforce the indications of the surface geology suggesting a depression in the Precambrian basement filled with Palaeozoic sediments, with the additional suggestion of a brecciated layer with a relatively low density and a low velocity of propagation for seismic waves.

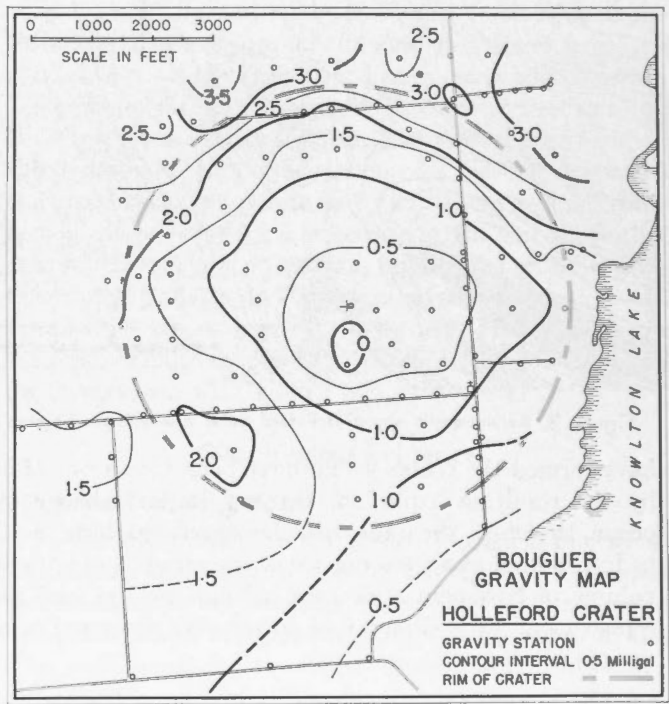

Figure 6. **Diagram illustrating the negative gravity anomaly over the Holleford crater.**

It was considered that if these indications had any meaning they should also be reflected in the gravity field over the crater. Observations of gravity were made by members of the Gravity Division and the area was covered by a network of gravity stations. A. M. Bancroft analyzed the data and although the results are being published elsewhere, his main conclusions are essentially as follows:

In Figure 6 is shown the Bouguer anomaly map of the region. The contours are circular and follow in a general way the outline of the crater depression. The gravity low in the centre indicates an anomaly of approximately two milligals. This suggests a circular depression filled with material which is on the average of a lower density than the surrounding Precambrian rocks. Since the sediments on the surface of the crater are of dense lithographic limestone of closely the same density as the Precambrian it is evident that the low-density material must be at considerable depth. It could consist either of lower density sediments or breccia, or both. Bancroft has estimated that the maximum depth to the top of the low-density material is 300 feet and that its thickness is between 400 and 1,600 feet. It is therefore concluded that between 700 feet and 1,600 feet of drilling would be necessary to be reasonably sure of penetrating the low-density material and reaching undisturbed bedrock.

The Diamond Drilling Program

Although surface studies suggested that meteorite impact was a promising possibility for the origin of the crater, it became clear that they could not by themselves provide definite answers to the crater problem. Since practically the entire original crater surface was believed to be buried beneath sedimentary layers, only a method capable of penetrating to considerable depths and bringing samples to the surface could lead to a definite result. It was accordingly decided to attempt a diamond drilling program in the hope of obtaining information concerning the depth and shape of the original crater surface and the materials of which it was composed.

Plans for this program were considerably influenced by previous experience at the Brent crater where there was a similar situation of a crater in Precambrian rock filled with Palaeozoic sediments. At Brent a hole drilled with an EXT drill (core $\frac{15}{16}$ in.) near the centre attained a depth of 570 feet but failed to reach the original crater surface. A second hole drilled near the edge of the crater succeeded in penetrating the sediments where it encountered fragmented material at 135 feet identified with the brecciated rock expected with any explosion crater. The difficulties encountered in the deeper hole were largely due to erosion of the walls of the hole by the drilling water, in layers of poorly consolidated sediments. Because no casing was used, the hole became enlarged and caused vibration of the drilling rods, diminished efficiency and sometimes loss of rods and drills. Some of these difficulties could no doubt have been avoided by the use of casing but primarily the drilling rig was too light and it was decided to use heavier equipment at Holleford. Accordingly AXT core ($1\frac{1}{4}$ in. diam.) or B core ($1\frac{5}{8}$ in. diam.) was specified for recovery. A general description of the type of equipment used in diamond drilling has already been given by Bremner (1955).

Hole 1 *(Surface 492 ft above sea level)*

In choosing a location for the first hole, considerable weight was given to the previous experience in drilling at the Brent crater. In order to make reasonably sure of a positive result it was decided to drill the first hole 1,400 feet from the centre of the crater or 0.37 of the distance from the centre to the edge. This hole was on the farm of H. D. Babcock who kindly gave permission to drill on his property and was very helpful throughout the life of the project.

Drilling was commenced on November 28, 1956. The drill rig was set up on solid rock consisting of sedimentary limestone so that no difficulties due to overburden were encountered. NX I.D. 3-inch casing was used to a depth of 20 feet, and cemented in place preparatory to drilling with BX rods and casing. The hole was cased with BX (I.D. $2\frac{3}{8}$ inches) to 174 feet when drilling commenced with A rods. At 174 feet water at high pressure appeared in the hole and was forced out by gas pressure around the casing. Below 174 feet AX rod was used inside the BX casing and at 205 feet gas was again encountered which partially filled the drilling hut and was ignited by a lantern used for night operations. The resulting explosion started a fire which burned the hut to the ground and seriously damaged the equipment.*

Because of necessary repairs drilling did not recommence until January 5, 1957. The progress of the drilling in hole No. 1, subsequent to the above occurrence was somewhat erratic and difficult to relate clearly in detail. Numerous difficulties were encountered and considerable lengths of drill rod were lost. The final results for Hole No. 1 may briefly be summarized as follows:

BX core was recovered to a depth of 640 feet. AX core was recovered between 640 feet and 1,128 feet. At 1,128 feet a considerable length of drill rod became stuck and the hole had to be abandoned. The sedimentary layers were found to extend to 750 feet and below this level broken, fragmented and pulverized rock was encountered, subsequently referred to as breccia. It was hoped to drill through the breccia and thus measure its thickness, but the drilling difficulties prevented this.

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*One unexpected result of the release of gas pressure was that it interfered with the flow of underground water which supplied Mr. Babcock's well. The well, 100 feet deep and 946 feet from the drill hole went completely dry for several days and although some of the water eventually returned, its quantity was never sufficient for the farm needs. Since the well was inside a cattle barn it was difficult to deepen it. A well was accordingly drilled nearby in the belief that water would be found in the natural basin formed by the crater within which the well and a substantial part of the Babcock farm was located. Water was finally located at 220 feet but it proved to have a high salt content (twice that of sea water) and was thus useless. Eventually on advice from E. I. K. Pollitt of the Geological Survey of Canada, drilling was commenced 700 feet from the original well, in strata which were topographically lower but stratigraphically higher than those containing the salt water. Fresh water was found at 75 feet and the well was pushed to 150 feet to ensure an abundant supply.

Hole 2 (*Surface 537 ft above sea level*)

When it became clear that the first hole could not be pushed beyond 1,128 feet a decision had to be made how to use to best advantage the limited financial resources of the project. It would have been desirable to ascertain the depth in the centre of the crater but this would have been very expensive and success was by no means certain. There were also definite advantages to holes nearer the rim for the purpose of ascertaining the crater profile. It was accordingly decided to drill two additional holes nearer the rim. The location of Hole 2 is indicated on Figure 1 by a filled circle. It is 2,500 feet from the centre on land owned by Mr. Babcock. It was possible to locate the rig on solid rock and as a result of experience gained in Hole 1 the work went forward much more smoothly. BX core was recovered to a depth of 630 feet and AX core between 630 feet and 1,486 feet, where the hole was stopped. The sedimentary layers extended to 440 feet and below this for 160 feet the cores consisted of rock fragments without any indication of stratification. At 600 feet solid rock was encountered and continued to the bottom of the hole.

Hole 3 (*Surface 582 ft above sea level*)

This hole, at 3,750 feet from the centre as indicated in Figure 1, is close to the rim of the crater. It was drilled in a hay field and the overburden was about 9 feet thick. The surface rock was sedimentary limestone and 64 feet of sedimentary core of diameter $1\frac{5}{8}$ inches was recovered. There was about a foot or two of breccia or conglomerate mixed with the sedimentary limestone at 64 feet. What is presumed to be the crater rim, consisting of Precambrian rock was encountered at 65 feet. The hole was carried to 443 feet, B core being recovered for the entire depth and as in Hole 2 a considerable variety of rock was encountered.

Analysis of Drilling Results

The Crater Profile

The profile of the crater as deduced from the three drill holes is shown in Figure 7. This profile may be considered as the crater surface defined as the area left bare by the original explosion plus such erosion as took place before the deposition of sediments. There are no means of estimating how old the crater was and how much erosion had taken place before deposition began. This naturally interferes with the validity of any comparison with well authenticated objects like the Barringer or New Quebec craters. Nevertheless, in predicting in a general way the depths of holes to be drilled in a program of this kind, there seems no alternative but to assume that the buried crater is similar in a general way to known objects. In addition to comparing it with earthly craters, whose numbers are very small, it is also possible to make use of Baldwin's relationship of depth to diameter of lunar and terrestrial craters. Before making such a comparison it should first be emphasized that any raised rim originally associated with the Holleford crater must have been largely eroded away before the crater was buried under Palaeozoic sediments. A crater like Holleford of 7,700 feet diameter should, according to Baldwin's relationship, have had a rim rising approximately 480 feet above the plain although the scatter of points on the diagram makes this figure uncertain by a factor of 2. It is clear, however, from a study of aerial photographs and from a contour map of the area prepared from them that no more than a rudimentary rim now exists. There are numerous Precambrian outcrops to the north, east and west of the crater area but it would be difficult from them to assign a level for the plain surrounding the crater of less than 480 feet above sea level. The ground level at Hole 3 was measured by altimeter as 582 feet and subtracting 64 feet, the thickness of the sedimentary rock at this point, leaves 518 feet which indicates a rim height above plain level of 38 feet. There is actually a Precambrian outcrop of crystalline limestone on the rim diametrically opposite Hole 3, designated by the capital letter I on the circle outlining the rim (Figure 1). It is in an area which appears to have suffered heavy erosion and its altitude of 517 feet is, within the errors of measurement, the same as that at Hole 3. There is some evidence of a slightly higher rim from 800 to 1,500 feet to the west of Hole 3 where the land rises to 600 feet but this additional height may be due to greater thickness of sediments. It is difficult to believe therefore that any part of the present rim rises as much as 100 feet about the plain and in discussing the profile of the crater it is necessary to regard it as having only the remnants of a rim.

In planning the drilling program, rough estimates of the depth to the breccia in Holes 1 and 2 were made at 800 feet and 400 feet respectively. The actual depth of sediments in Hole 1 was 750 feet while that in Hole 2 was 440 feet. No estimate was possible for the depth of Hole 3 except that it should be much less than the other two holes. The resulting depth of 65 feet represented satisfactory agreement with expectation. These estimates were made before any firm conclusions had been reached as to the character of the rim, and before any serious attempt had been made at estimating the crater's diameter. They served a useful purpose in giving the drillers some idea what to expect but have since been superseded by a more precise estimate. For a more significant comparison with prediction we make use of

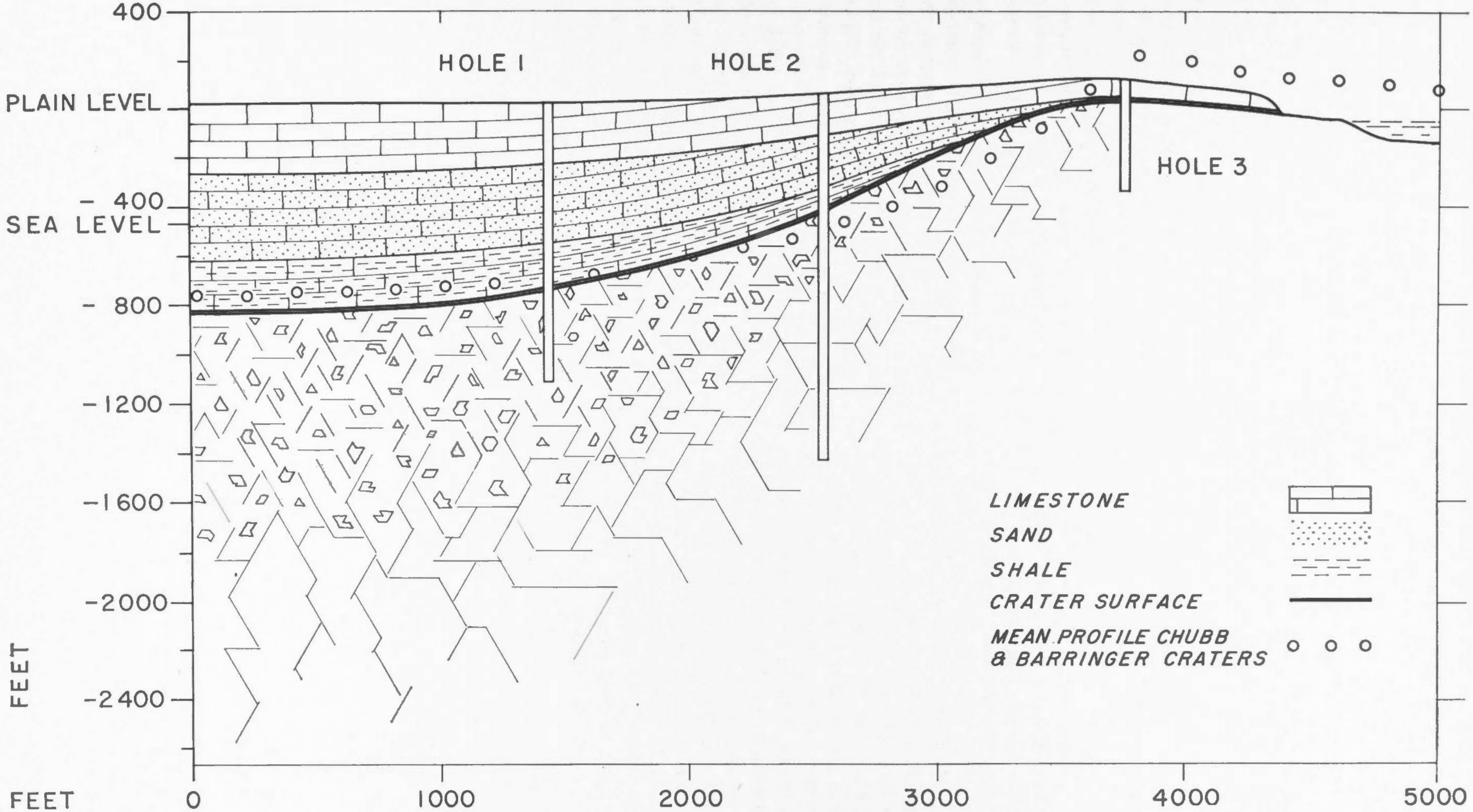


Figure 7. Profile of the Holleford crater as reconstructed from drill-hole and surface observations. It will be seen that the original crater surface dips nearly 800 feet below plain level, while the zone of fractured rock extends to an estimated depth of about 2,400 feet. The estimate of breccia depth at the centre depends on theoretical considerations advanced by J. A. Rottenberg.

the following empirical relationships between the diammeters, depths and rim heights of lunar and terrestrial craters due to Baldwin (1949):

If D = log diameter (ft), d = log depth (ft) and E = log rim height above plain (ft) then the following equations have been found to apply:

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

$$\text{and } E = 0.097\, D^2 + 1.542\, D - 1.841 \ldots\ldots (2).$$

Of these two equations (1) is illustrated graphically in Figure 8. Making use of these equations to predict depth below plain of a crater 7,700 feet in diameter leads to a depth of 674 feet. If the estimate of the plain level is accepted as 480 feet, and the surface location of Hole 1 as 492 feet, then the actual depth of the hole to the crater surface should be 686 feet, or of the order of 50 to 75 feet less, since the hole was not in the centre of the crater. Although rock breccia appeared as early as 655 feet the definite contact between sediments and breccia was at 755 feet. It appears therefore, if the estimate of the plain level is correct that the crater is rather more than 100 feet deeper than predicted by Baldwin's relationships. An examination of Baldwin's empirical curve, however, indicates that the scatter of the points both for lunar craters and explosion pits is quite large, of the order of $\pm$ 0.25 in the logarithm, which would correspond in the present instance to more than $\pm$ 200 feet so that the agreement is still reasonably good. As an indication of the fit (1) above may be used to calculate the hypothetical rim height, which comes to 486 feet. If this is added to the measured depth below plain of 742 feet the resulting crater depth is 1,228 feet; adding 75 feet as a correction to the centre (*see* Figure 7) makes 1,303 feet. The logarithm of this figure, plotted on Baldwin's curve is shown in Figure 8. The point is so close to the curve as to be well within the probable error of the general empirical relationship, indicating satisfactory agreement.

An additional comparison between prediction and observation is shown in the diagram of Figure 7. Here the three holes are plotted on a diagram representing a section of the crater with its filling of sedimentary material. For comparison, a mean profile derived from the New Quebec or Chubb crater (Millman, 1956) and the Barringer crater (Nininger, 1956) has been used. The Chubb crater is 11,500 feet in diameter while that of the Barringer crater is 4,000 feet. Since the Holleford crater diameter within the limits of error of its determination is almost precisely the mean of the two it was considered that a linear interpolation should provide a valid basis of comparison.

The interpolated crater profile is shown on the diagram by the small circles while the Holleford crater profile (insofar as it can be deduced from the three drill holes) is shown as a full line. Indications are given of the depths of the drill holes and of the sedimentary material. Having regard to the uncertainties of prediction for an object like an explosion crater it is clear that the agreement for the part of the crater below plain level is as good as could reasonably be expected. The absence of an appreciable rim is the most serious disagreement with prediction but erosion and deposition over a period of 100 to 200 million years could produce the result that has been observed. As long as the crater rim remained intact (preventing, for example a stream from flowing through the crater) that part of the profile below plain level would likely escape severe erosion. Indeed the production of talus slopes and rock slides could operate to protect the lower part of the structure. If the crater were partially filled with water, lake deposits could act as further protection to the underwater areas, but the rim itself would be subject to the usual erosion suffered by any elevated part of the earth's surface.

The rim must eventually have been breached by the Palaeozoic seas but here the effect would be very different from that which would be produced by ordinary erosional processes (which could result in drainage through the crater). Once the sea invaded the crater, deposition would begin on the bottom and sloping sides of the structure while protection from currents would be provided by the remaining parts of the rim. The rim itself would be subject to wave and tidal action for many years during the time the sea was rising. No doubt the rim would become a ring of islands on which erosion would act relatively rapidly. The shattered condition of the rocks of the rim would undoubtedly encourage this action. The final result when (as appears to have been the case) the sea rose still higher would be to inundate the remains of the structure which would then be covered over and preserved from further erosion by the Palaeozoic sediments which still cover almost the entire area.

Materials Produced by the Explosion

It has been pointed out that the shape of the Holleford crater surface corresponds closely to what might have been predicted for a typical meteorite crater of its size and age. Evidence of this kind has much greater validity if it can be shown that the materials of which the crater surface is composed are also in accord with prediction. In making predictions of this kind main reliance is placed in the data from the Barringer crater, the most completely authenticated large terrestrial meteorite crater known. A favorable consideration here is the fact that the Barringer crater though smaller (4,000 feet in diameter) is of the same general order of size as Holleford (7,700 feet in diameter).

While scientific discussions of the Barringer crater have been concentrated largely on the metallic meteorites found in its vicinity, it is well known that the crater

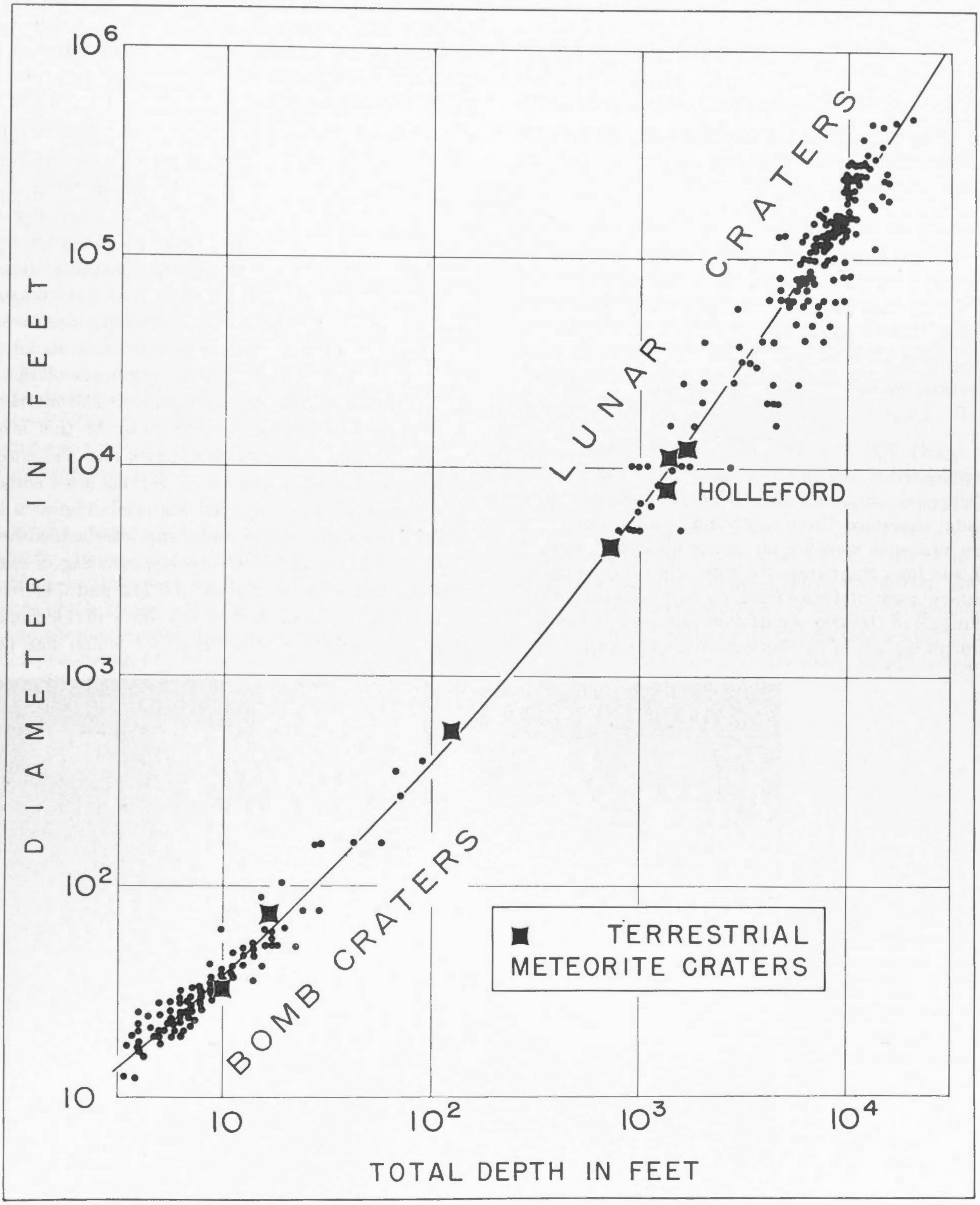


Figure 8. Baldwin's curve illustrating the relationship between diameter and depth for lunar and terrestrial craters, (logarithmic scale). The two craters immediately above Holleford on the diagram are New Quebec and Brent. The one immediately below is Barringer.

surface is made up almost entirely of broken rock fragments of all sizes such as boulders, rock breccia, rock flour and conglomerate (Baldwin 1949, Nininger 1956). Close-up photographs of the crater surface lead to the same conclusion. Recently through the courtesy of Dr. P. M. Millman the writer has had the opportunity of examining a very extensive collection of material gathered from a number of representative locations of the crater both on the surface and at considerable depths. The material consists practically entirely of rock fragments of various sizes, fine sand and rock flour beyond question produced from the country rock of limestone and sandstone by the explosion which formed the crater.

Even in the absence of such detailed evidence it would still appear certain that fragmented materials of all sizes would constitute the surface of an explosion crater. In drilling such an object it could confidently be predicted that if it were truly a meteorite crater, rock breccia would be encountered as soon as the drill penetrated the concealing sedimentary layers. In discussing the crater profile it has already been indicated that rock breccia was encountered at approximately the predicted depths. Some details of the character of the material encountered in the various holes follow:

Hole 1

For nearly 700 feet the drill cores recovered from Hole 1 consisted of sedimentary limestone typical of the early Palaeozoic era. Dr. T. E. Bolton, Geological Survey of Canada, examined these cores and pointed out that, although the cores were by no means uniform they did not differ in important respects from other specimens of sedimentary rock of Ordovician or earlier age in that general region of Ontario. Apart from the very important indication of age given by the surface rocks found in the crater, this investigation is not directly concerned with the Palaeozoic strata. It is confined almost entirely to the fragmental material which is considered to be produced by the assumed explosion, and the original country rock from which this material is derived.

At about 650 feet the rock interpreted as explosion breccia began to appear interbedded with sedimentary material. The identification of such material at this depth is complicated by the fact that a large proportion of the country rock in the vicinity of Holleford is crystalline limestone which, when finely pulverized does not differ greatly from fragments of some of the sedimentary rocks. There are, however, numerous fragments of material quite foreign to the sedimentary rocks which could logically be attributed to fragments of the basement rock shattered by an explosion. The interbedded breccia continues down to 755 feet. At this level all evidence of stratification disappears and the cores are composed of rock fragments of various sizes embedded in a matrix of finely divided material. Figure 9 shows examples of sedimentary rocks and interbedded breccia. At 671, 672 and 720 feet breccia consisting of small to medium fragments is shown. At 742 and 744 feet the cores contain a good deal of the finely divided material referred to above as the "matrix" which has become

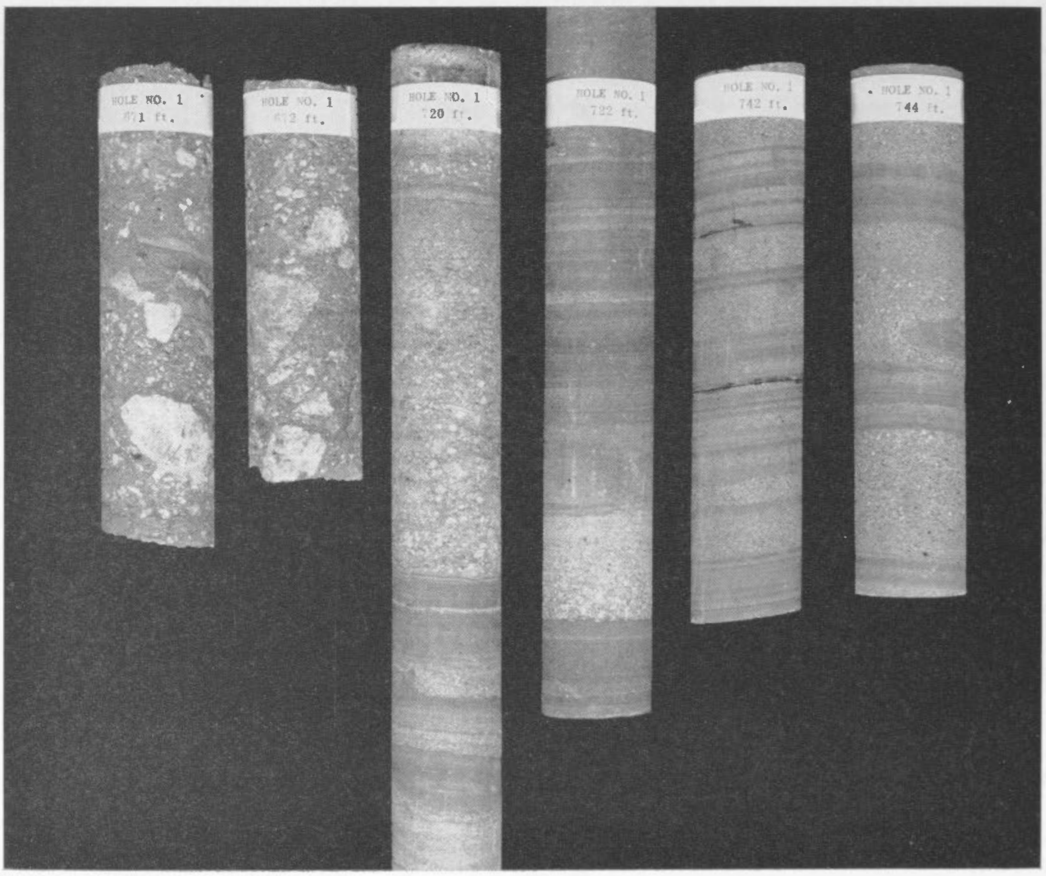


Figure 9

Interbedded breccia near the contact between sediments and fractured rock. The lighter colored material at depths 742 feet and 744 feet is believed to be finely divided explosion debris washed into the crater before the deposition of Palaeozoic sediments.

mixed with the sediments. In Figure 10, the three cores on the left show examples of pure sediments and interbedded breccia, while the three on the right are pure breccia where all indication of bedding planes has disappeared. A careful examination of cores in the vicinity of 950 feet indicates that at this level there are few sizeable fragments and the main volume of the core is of the finely divided matrix material. Above this level, as the illustration suggests, there are many fragments of appreciable size. Below 950 feet to the bottom of the hole, sizeable chunks of rock ranging from a few inches to a few feet in diameter are common. Figure 11 shows cores of some of the coarser material encountered at these depths while Figure 12 illustrates a block nearly 4 feet thick of light-colored biotite gneiss. Although the core was broken into short segments in the core barrel the breaks are fresh and it is clear that a single chunk of rock is involved. The two ends of the multiple specimen show stains of the dark grey-green matrix in which this large fragment was imbedded.

Hole 2

Cores from the upper part of the hole consist of sedimentary limestone of Ordovician age normally encountered in that part of Ontario. At 354 feet rock fragments begin to appear, interbedded with the sediments and these fragments become increasingly frequent as the depth increases. Some of the cores containing such interbedded breccia are shown in Figure 13. The contact between the sediments and pure breccia is less sharp than in Hole 1 and this is attributed to the fact that the wall of the crater slopes steeply here, so that it would be normal for talus material from the slope to be mixed with the sedimentary layers. Below 440 feet no bedding planes are evident and the cores consist mainly of rock fragments with a fine-grained matrix which usually, but not always, gives a test for limestone.

Below 500 feet the size of the rock fragments increases rapidly and the last clearly marked breccia is at a depth of 600 feet. Figure 14 illustrates the contrast between sedimentary layers and breccia with cores from 387, 391, 455 and 472 feet. Drilling was continued to 1,486 feet in order to have a good section of the rock in the crater vicinity and to make reasonably sure that the breccia and other layers affected by the assumed meteoritic explosion had been penetrated.

Below the layer of breccia, relatively undisturbed rock, presumably of Precambrian age, was encountered. In the first hundred feet and to a lesser extent at greater depths, numerous cracks were found in the rock which may have been caused by a shock wave from the meteorite impact. It is difficult to be certain of this since it is common to find rocks at all depths intersected by cracks and fissures. Many of the cores were found to consist of

Figure 10
Sediments, interbedded breccia and pure breccia in Hole 1.

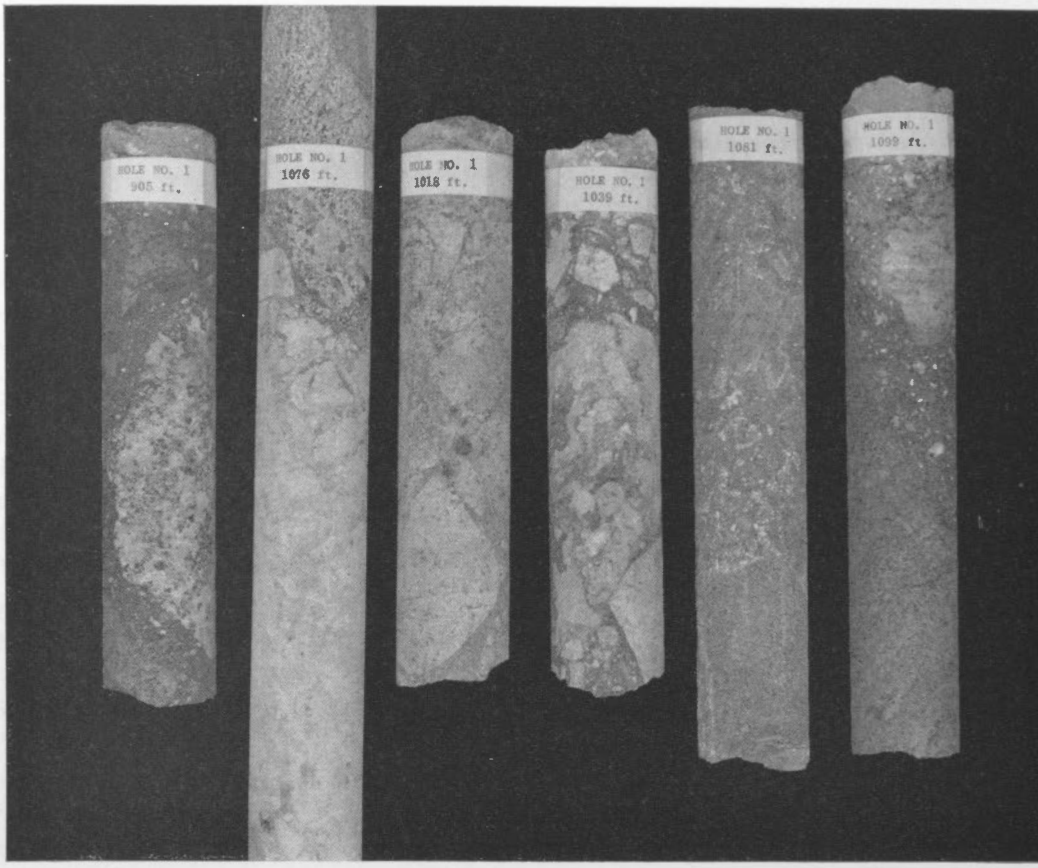


Figure 11

Bouldery material at depths below 900 feet in Hole 1.

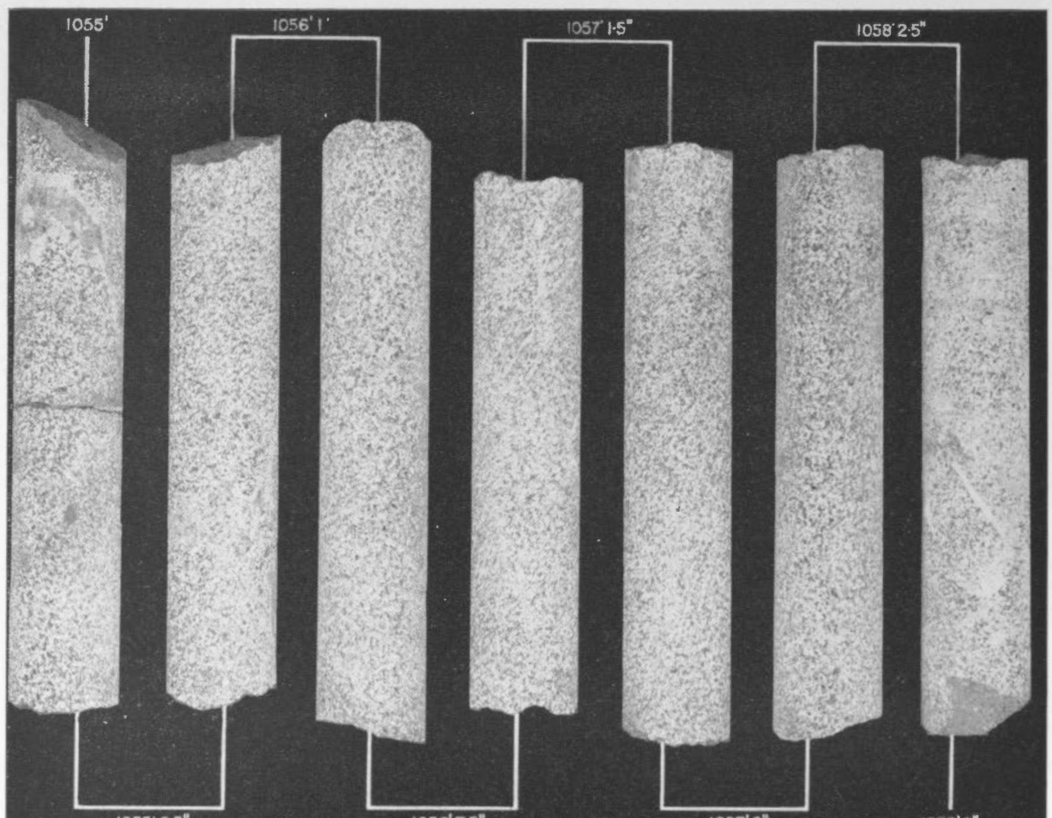


Figure 12

Single large rock fragment 3 feet 9 inches thick in Hole 1. Note stains of matrix material at 1,055 feet and 1,058 feet 9 inches.

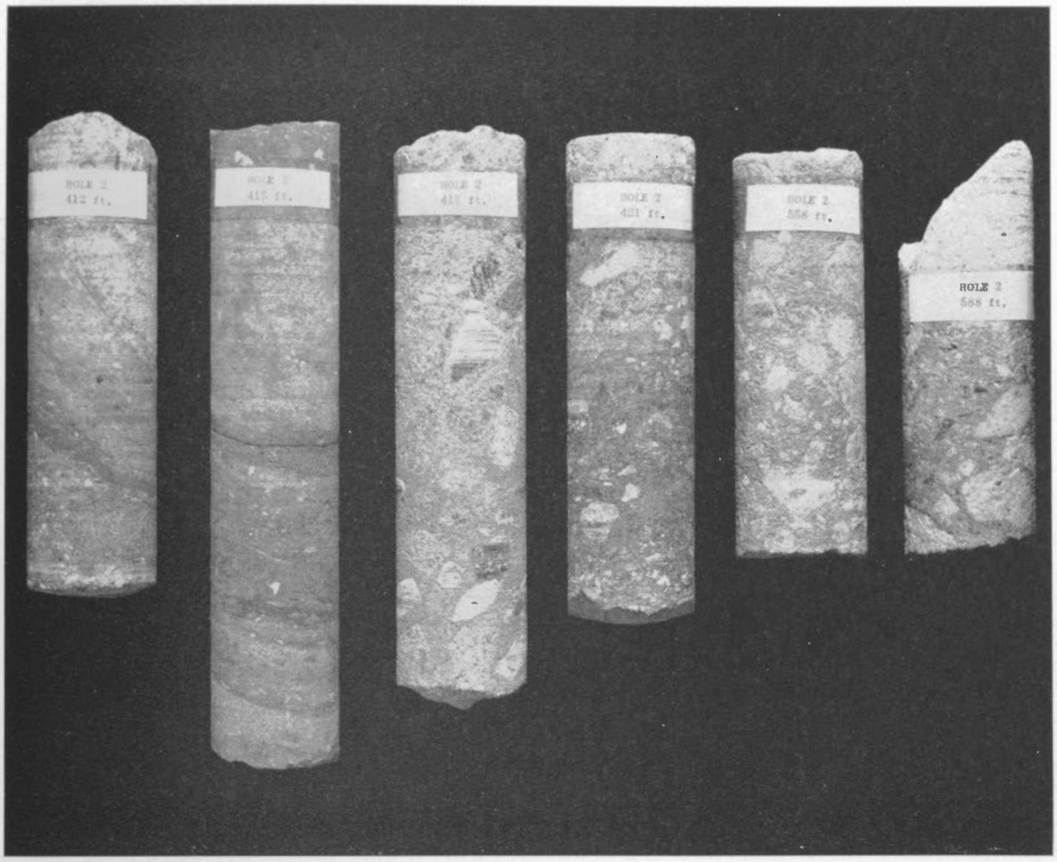


Figure 13

Interbedded breccia above 425 feet and pure breccia below 550 feet in Hole 2. Note indications of stratification at 412 feet and 415 feet.

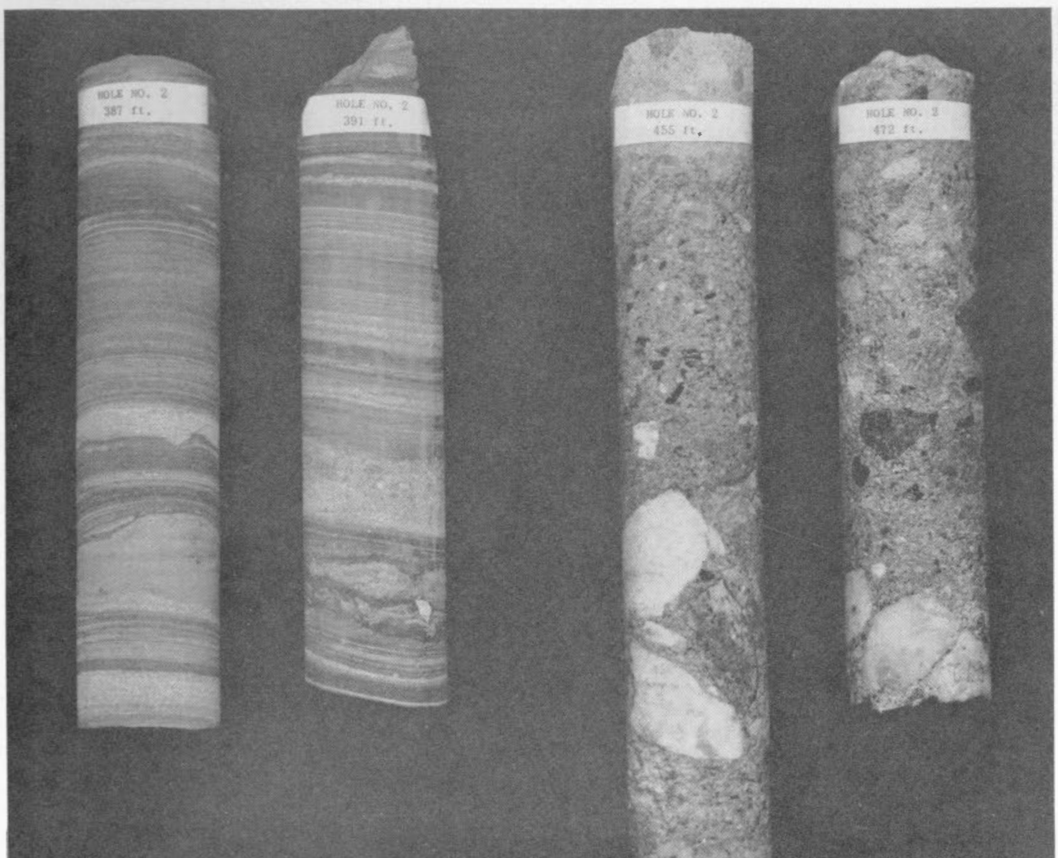


Figure 14

Comparison of sediments and breccia in Hole 2.

crystalline limestone, though numerous other types of rock were also present, the petrology of which is discussed in a later paragraph. At 840 feet, as shown in Figure 15, some green biotite gneiss was encountered, splintered by artificial-looking cracks which were filled with calcite crystals. It seems quite possible that these cracks were a consequence of the shock wave from the meteorite explosion. Rocks of a lower depth with cracks of quite different character are shown in Figure 16.

Hole 3

This hole was relatively shallow compared with the others and the sedimentary rock was confined to the first 65 feet. At about 64 feet rock fragments began to appear interbedded with sedimentary rocks, and at 65 feet undisturbed basement rock was reached. The hole was pushed to 443 feet and again as in Hole 2 a considerable variety of rock was encountered much of which consisted of crystalline limestone. Figure 17 illustrates the nature of the cores obtained at various levels including the rock fragments found at the contact between the sedimentary layers and the basement. These fragments, as can be seen, were of rather different character from those met with in the other two holes.

Dr. K. R. Dawson, Geological Survey of Canada, undertook to examine a representative selection of cores from the Holleford crater and his report on these cores is quoted: "The rocks encountered in the cores from the Holleford Crater include from top to bottom grey limestone and limey sandstone, polymict breccia, crystalline limestone, biotite and biotite-pyroxene gneiss, lime silicate rocks and rarely amphibolite. The polymict breccia consists of fragments of the last four rock species in a paste of unaltered grains of potash feldspar, clinopyroxene, quartz, hornblende biotite and rarely calcite cemented by a microscopic aggregate of mica-illite, kaolinite and chlorite". Thin sections of the breccia as well as other rock types in Holes 1 and 2 are illustrated in Figure 18.

The grey limestone and limey sandstone are the sedimentary rocks with which the crater is filled. The breccia is the crushed rock zone which extends below 1,128 feet in Hole 1, to 600 feet in Hole 2, and 65 feet in Hole 3. The remaining rocks mentioned in Dr. Dawson's report are those encountered below the breccia in Holes 2 and 3. The variety of these rocks is considerable as is shown in Figures 9 to 17. It will be seen that the above technical description of the breccia is consistent with our assumption that it was formed approximately in situ, the circumstances of the explosion causing the thorough mixing of rock types, as observed in the thin sections of some of the cores and the production of breccia of uniform composition in others.

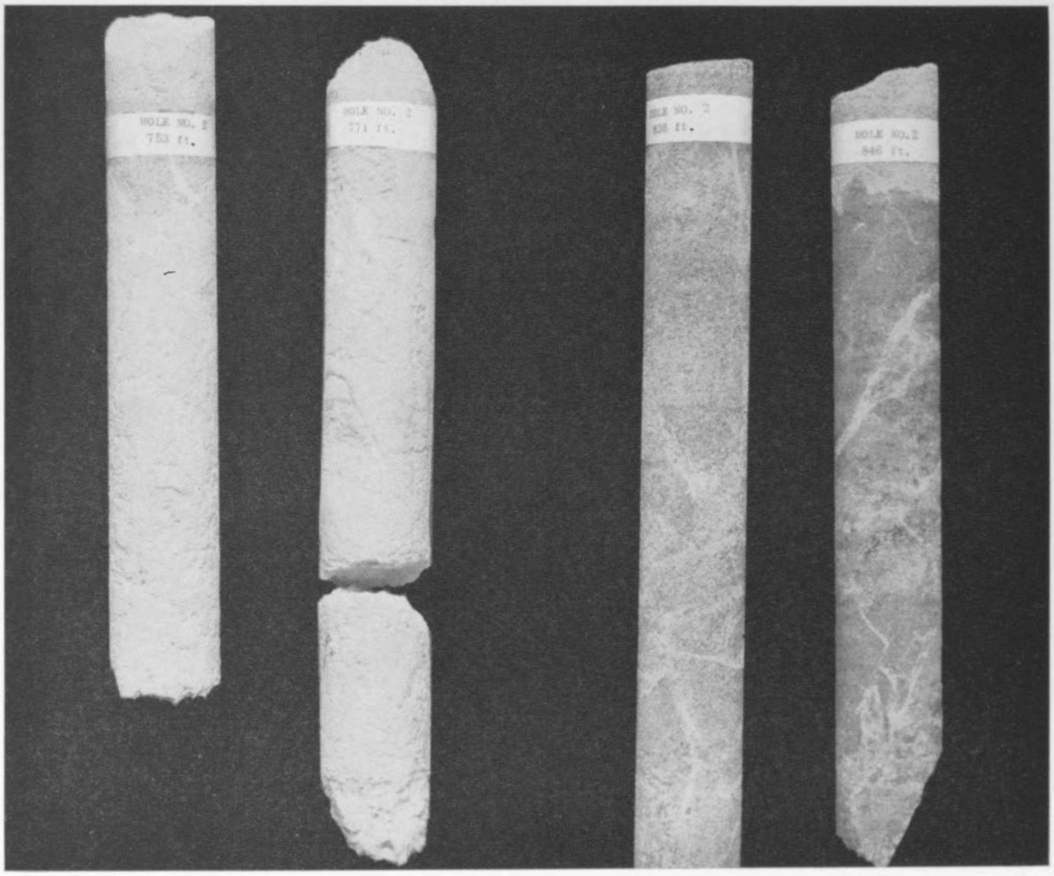


Figure 15

Basement rock below 750 feet in Hole 2. There is clear indication of fracturing, possibly due to shock wave from explosion.

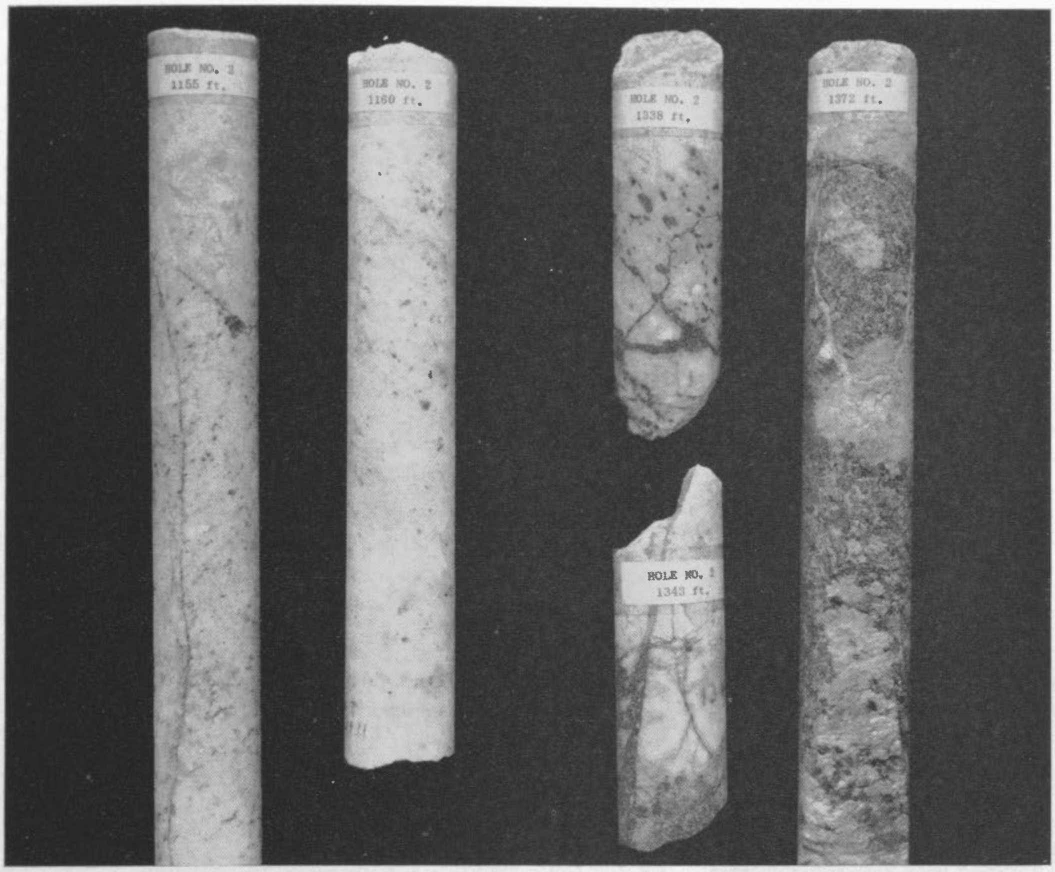


Figure 16

Basement rock below 1,150 feet in Hole 2. The cracks are typical of this kind of rock and may be unconnected with the explosion.

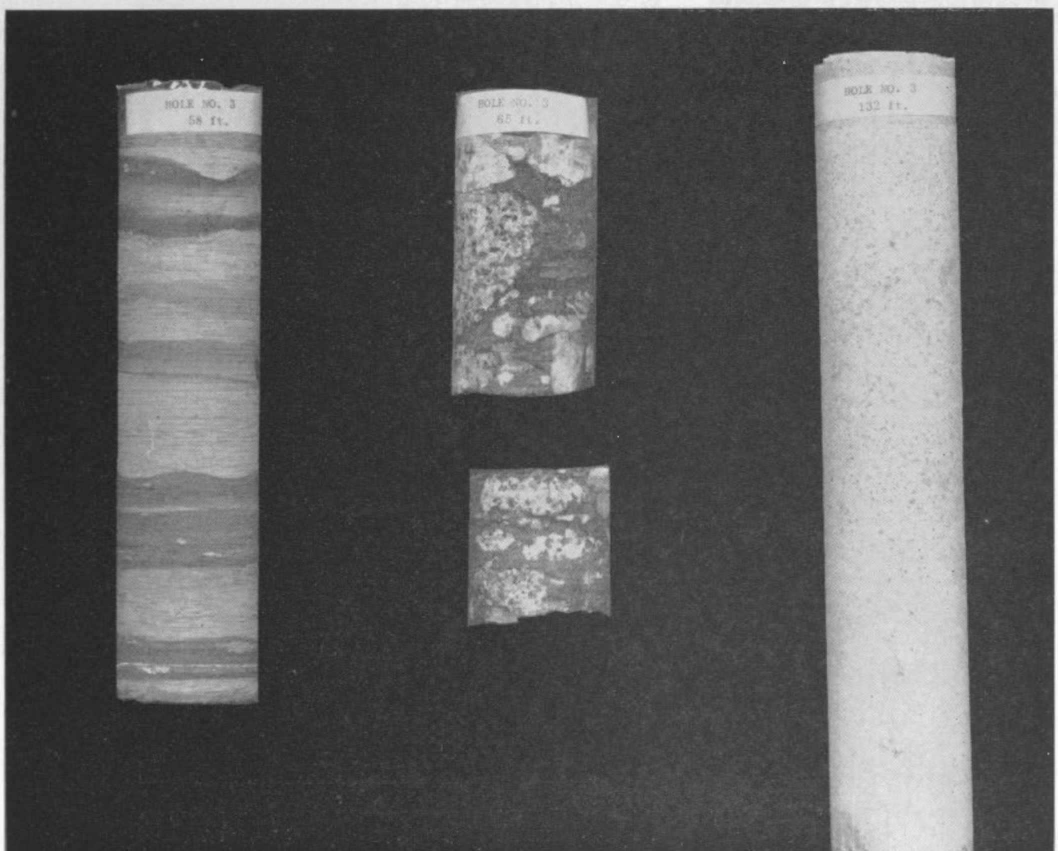
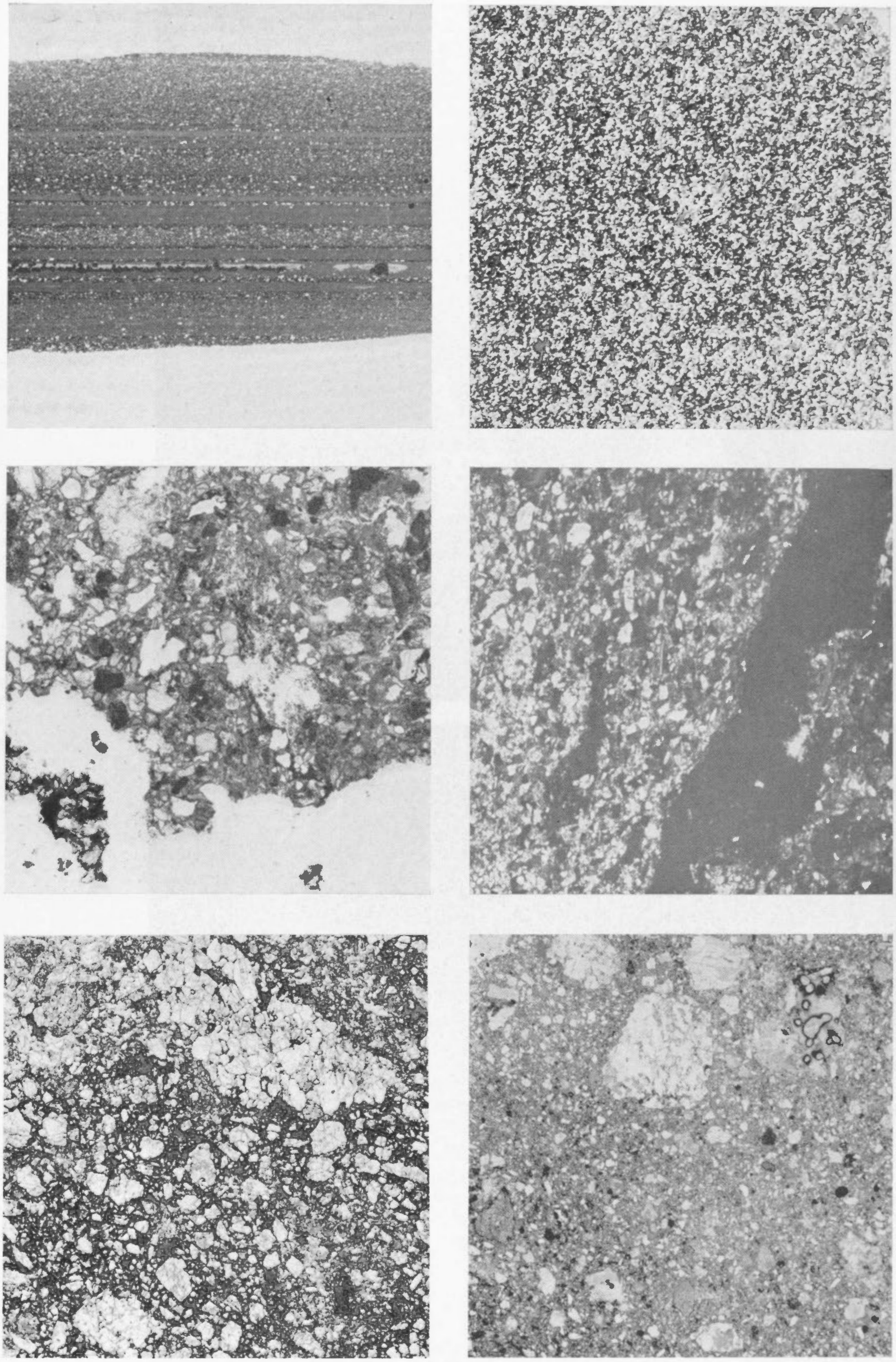


Figure 17

Sediments, thin layer of breccia and basement rock in Hole 3.



THIN SECTIONS OF HOLLEFORD CORES

Figure 18. Thin sections of cores, Holleford crater; Hole 2, 384 feet, sedimentary rock. Hole 2, 1,325 feet, granitic basement rock. Hole 2, 429 and 438 feet, conglomerate breccia. Hole 1, 1,035 and 909 feet, finely divided pyroxene breccia probably representing rock shattered in place.

The Search for Meteoritic Material

A careful visual examination of the cores from Holleford disclosed no metallic iron or iron oxide fragments such as are found in the Barringer crater, so a more detailed examination was conducted by magnetic methods. The first was a study of the magnetic moment per unit volume of the cores with the aid of a recently constructed astatic magnetometer belonging to the Division of Geomagnetism. This instrument is extremely sensitive, being able to detect the presence of magnetization of less than 10^{-7} cgs units per c.c. in a piece of core of the order of 7.5 cm. in length. All of the cores below the Palæozoic strata in Holes 1, 2 and 3 as well as some of the cores above the contact were examined by J. L. Roy of the Division of Geomagnetism. Mr. Roy examined each piece of core in the above mentioned levels for the three holes. In addition to the brecciated material, which showed no evidence of stratification, about 100 feet of sediments immediately above the breccia were also examined. It was considered that these sediments, (which differed from the other sediments filling the crater in that they contained considerable quantities of rock fragments) might also contain some of the finely divided material produced by the explosion and subsequently transported back into the central part of the crater by wind and water. In Holes 2 and 3 which penetrated into undisturbed rock below the breccia, all the cores from the basement rock were examined in order to provide a basis of comparison.

The results of these measurements are illustrated in Tables 1 and 2. In Table 1 are shown the values of M/cc, the magnetic moment per unit volume in cgs units, for the ten most strongly magnetic specimens in the breccia of Holes 1 and 2. At the bottom of each column is shown the average value of M/cc for the entire depth covered. Many specimens showed values of magnetic moment too small for measurement and it is clear that there is a very great range in the magnetic characteristics of the material making up the breccia of these two holes.

TABLE 1.—SPECIMENS OF LARGEST MAGNETIC MOMENT

Breccia of Holes 1 and 2

Hole 1		Hole 2	
Depth	M/cc	Depth	M/cc
768	1.56×10^{-5}	597	4.80×10^{-5}
783	4.50×10^{-5}	597.3	9.60×10^{-5}
854	1.56×10^{-5}	597.8	5.10×10^{-5}
964	1.46×10^{-5}	598.4	38.20×10^{-5}
986	1.92×10^{-5}	598.6	6.40×10^{-5}
1003	1.36×10^{-5}	598.9	7.25×10^{-5}
1028	6.87×10^{-5}	602	7.00×10^{-5}
1046	4.86×10^{-5}	604	6.90×10^{-5}
1064	1.60×10^{-5}	604.6	9.40×10^{-5}
1106	2.30×10^{-5}	608	3.96×10^{-5}
Average M/cc for Breccia Hole 1, 0.139×10^{-5}		Average M/cc for Breccia Hole 2, 0.469×10^{-5}	

TABLE 2.—SPECIMENS OF LARGEST MAGNETIC MOMENT

Precambrian Basement, Holes 2 and 3

Hole 2		Hole 3	
Depth	M/cc	Depth	M/cc
1198	103.00×10^{-5}	306	15.00×10^{-5}
1327	87.00×10^{-5}	307	19.00×10^{-5}
1330	76.00×10^{-5}	309	30.00×10^{-5}
1413.0	71.50×10^{-5}	309.5	56.00×10^{-5}
1413.6	520.00×10^{-5}	310	18.75×10^{-5}
1413.8	131.00×10^{-5}	313	74.50×10^{-5}
1435	89.00×10^{-5}	313.4	37.00×10^{-5}
1437	76.00×10^{-5}	319	40.80×10^{-5}
1445	124.80×10^{-5}	319.5	17.90×10^{-5}
1474	202.80×10^{-5}	320	21.60×10^{-5}
Average M/cc for Hole 2 Basement, 2.338×10^{-5}		Average M/cc for Hole 3 Basement, 5.647×10^{-5}	

M/cc for ferromagnetic substances 10 to 100

It is worthwhile to compare the values of M/cc of Table 1 with similar values in Table 2 for core specimens from the undisturbed Precambrian of Holes 2 and 3. (The Precambrian was not reached in Hole 1). Here again the ten highest values of M/cc are shown for the two holes and these values are also compared with the average values for the rock throughout the depth observed. It is immediately apparent that both the average and the maximum values for the undisturbed Precambrian are greater than for the breccia, but it should be emphasized that all values are encountered from nearly zero, for crystalline limestone, to 520×10^{-5}, for dense basic rock like amphibolite. It is apparent that all values of magnetic moment given in these lists are small relative to ferromagnetic substances, which have values of M/cc of the order of 10 to 100 cgs units per cc.

The first step in analyzing the results was to study in detail a number of the more highly magnetic cores to see whether any separate particles of significantly high magnetic moment could be found. The cores were first inspected visually and then broken up by hand tools and searched with a magnet. In every case the high values of magnetic moment appeared to be due to small fragments of Precambrian rock imbedded in the matrix of finely divided material forming the cementing agent of the cores. No fragments which could reasonably be attributed to metallic iron or massive iron oxide were located.

As a further check, Dr. K. R. Dawson, Geological Survey of Canada, studied the cores with the aid of machinery which pulverized the rocks and separated the particles of high magnetic susceptibility from the non-magnetic constituents. Dr. Dawson not only studied all the specially magnetic samples in this way, but also selected massive amounts of cores (one specimen every 5 feet) from both holes. This selection included not only cores consisting of breccia but also specimens of sediments immediately above the breccia which were considered to contain finely divided fragmented material washed back into the crater before the main bulk of the Palaeozoic sediments were laid down.

Although, as in the case of practically all igneous rocks or rock fragments, numerous particles of high magnetic susceptibility were found, the nickel content of the specimens was not essentially different from that of many typical terrestrial rocks. The largest percentage found for a single specimen of material subjected to chemical analysis was 800 p.p. million whereas meteoritic nickel iron should show a nickel content of from 3 to 15 per cent.

These studies, which gave negative evidence for nickel, should be considered in their relation to the effectiveness of the sampling technique which involved cores with an average diameter of 1.47 inches. Comparing the area of such a core with that of the crater itself (diameter 7,650 feet or 91,900 inches), and disregarding the curvature of the crater surface by treating it as a plane, a single specimen taken at the crater surface corresponds to 2.2×10^{-10} of the total area. This is a very small fraction and while it would increase considerably with the decrease of the crater diameter at depth, it would still not be surprising if such a technique should fail to locate nickel in the cores even if it were certain that some nickel-iron fragments were present diffused throughout the mass of breccia. From what is known of the Barringer crater it is by no means certain that evidence of meteoritic fragments would have been unearthed by a comparable procedure, i.e. three holes at random, widely spaced along a radius within the crater. An additional uncertain factor for Holleford is the unknown effect of chemical disintegration and diffusion operating over a very extended period of time.

Although the inadequacy of the sampling leaves the matter of the presence or absence of nickel-iron uncertain, consideration should be given to the possibility or even the probability that the Holleford crater was formed by a stone meteorite in which the usual nickel iron content was absent or very low. Even to consider such an idea goes strongly counter to all the evidence so far collected from the vicinity of well authenticated recent meteorite craters. Also, while it is true that stone meteorites outnumber the irons by a large factor, many of the stones have nickel-iron as an important constituent; while such large meteorite craters as Barringer and Wolf Creek as well as the cluster of small craters caused by the Sikhote Aline fall were certainly caused by nickel-iron meteorites. It has been suggested that even a very massive stone meteorite could not form a large crater since it would break up and be dispersed in the earth's atmosphere, as many stones have been observed to do in the past.

In spite of the impressive array of evidence associating nickel-iron meteorites with large craters, the unquestioning acceptance of the view that such features cannot be due to impacts of other rock types, would place restrictions on hypotheses, otherwise logical, which deserve consideration in trying to explain observed phenomena of the solar system. For example the earth is presumably a normal member of the solar system and if it were broken up there could be many large fragments which contained no nickel-iron. Conversely if in the moderately distant past there had been many meteorite falls consisting of rocky material of the kind found in the earth's crust the chance of identifying them as extraterrestrial objects would be slight. The uncertainty over the origin of tektites is a good example of the desirability of keeping an open mind on this subject. Many earthly rocks are hard and coherent compared with the average meteorite stone, and might well survive a journey through the earth's atmosphere.

In view of these considerations the scientific importance of extending the data on fossil craters and if possible finding specimens of the meteorites which produced them can scarcely be over-estimated. It is emphasized by the degree to which the following information on meteorites has influenced our thinking about the earth and the solar system.

1. The work of H. A. Urey (1958) on the origin of meteorites has shown how complex are the processes which went into the making of the minor planets or asteroids. He has advanced strong reasons for believing that catastrophic planetary collisions involving large bodies are involved, with later re-integration of the fragments into more complex bodies which are in turn broken up to form meteorites. It is difficult to see how it would have been possible even to guess at the character of these processes without the evidence provided by meteorite falls.

2. Studies by Paneth (1953), Opik and Singer (1957), Singer (1958) Ehmann and Kohmann (1958) and others on the radioactive decay products of meteorites and the nuclides due to bombardment by cosmic rays during the journey of the meteorites through space, have provided valuable information on the ages of meteorites and of the solar system, and suggest the possibility of testing the intensities of cosmic rays in former times. In addition it has been shown that the proportion of different varieties of helium, in particular the appearance of He^3 affords

a possible means for the identification of non-nickeliferous meteoritic material and this might be of considerable importance in the study of ancient craters.

3. Ideas concerning a molten iron core for the earth are based to a large extent on the information provided by iron meteorites.

4. Finally it has been suggested (Skerl, 1957) that some of the terrestrial metallogenic provinces are due to the bombardment of the earth by very large meteorites in the distant past.

Up to the present all studies of meteorites and the conclusions from such studies are based on examinations of relatively recent meteorite falls and it is possible that they are all related to one extra-terrestrial collisional event or to one related series of events which may not give a sufficiently general picture of conditions in the region of the solar system involved. If this should be the case then the finding of meteoritic material in a number of very ancient craters would be extremely valuable since it would test the general validity of these hypotheses and conclusions by providing evidence dating from an earlier and perhaps much more extended period of time. Unfortunately, no such material has as yet been identified in the Holleford cores. It would appear, however, that the best, if not the only chance of finding meteoritic material from very ancient falls, is by additional searches at the sites of fossil craters such as the one here described.

Results of Rock Density Measurements

Measurements of rock density under the crater surface make it possible to test directly the conclusion, from the gravity results, that the crater was filled with material of relatively low density. Systematic measurements of cores every 5 feet were made in all three holes by R. J. Buck and L. W. Sobczak of the Gravity Division. The results are listed in Tables 3, 4 and 5, where average values of density are given against depth. Averages for approximately every 20 feet are shown for each hole and the general character of the rock is also indicated. These indications are based on direct visual examination and differ in some details from the petrographic report given previously. A study of the figures in the tables leads to the following general conclusions.

1. The density of the hard lithographic limestone at and near the surface is comparable to, though slightly less than, that of the average basement rock of Holes 2 and 3. The averages for the first hundred feet of sedimentary rock of Holes 1, 2 and 3 are 2.71, 2.70 and 2.69 respectively. The corresponding basement averages for Holes 2 and 3 are 2.81 and 2.71.

2. In general the density of the sediments decreases with depth, minimum values being 2.27 for Hole 1 and 2.16 for Hole 2. These densities were measured about 2 years after the drilling and for some of the porous sandstone, evaporation of moisture has no doubt decreased the effective density. The difference is probably not great enough to invalidate the general comparison, however, and there seems no doubt that these low-density sediments have had a strong influence on the gravity field.

3. The Precambrian basement rock shows a very considerable variation in density, extreme values ranging from 2.71 to 3.07. It is perhaps significant however that the larger values are associated with Hole 2 where the basement is first encountered at a depth of 600 feet or 63 feet below mean sea level. In Hole 3 on the other hand,

TABLE 3.—MEASUREMENTS OF CORE DENSITY

Hole 1

Depth	Mean Density	Description
0– 24	2.69	Lithographic limestone
24– 40	2.71	
40– 63	2.71	
63– 83	2.71	
83– 102	2.71	
102– 119	2.73	
120– 140	2.67	Limestone grading into green shale
140– 160	2.67	Dark shale
161– 182	2.65	Dark shale grading into limestone
178– 198	2.72	Limestone
200– 220	2.72	Limestone grading into shale
220– 240	2.55	Shale grading into sandstone
240– 260	2.46	Sandstone
260– 334	2.40	
334– 380	2.37	
380– 400	2.53	Limey sandstone
405– 440	2.37	
450– 470	2.27	
470– 495	2.49	
495– 520	2.55	Shaley limestone
520– 554	2.55	Limestone grading into sandstone
553– 571	2.41	Sandstone
571– 590	2.41	Limey sandstone
591– 610	2.46	
610– 630	2.37	
630– 650	2.50	
650– 675	2.60	Limestone
676– 700	2.60	
701– 725	2.65	Shaley limestone
725– 750	2.68	Limey breccia (quartz, mica, feldspar)
750– 789	2.74	
788– 813	2.53	Limey breccia
813– 839	2.59	Limey breccia (powdery)
839– 864	2.48	
864– 889	2.46	
889– 915	2.37	
915– 935	2.45	
938– 963	2.39	
968– 989	2.44	
989–1015	2.64	Breccia
1015–1040	2.64	
1040–1065	2.79	
1065–1088	2.70	
1090–1128	2.62	

TABLE 4.—MEASUREMENTS OF CORE DENSITY

Hole 2

Depth	Mean Density	Description
0– 23	2.76	Shale with calcite
23– 43	2.61	
43– 62	2.74	
63– 83	2.68	
83– 103	2.70	Shale
103– 123	2.63	
123– 144	2.73	
144– 163	2.70	
163– 183	2.58	Shale grading into limey shale
183– 203	2.42	
204– 231	2.35	
231– 255	2.32	Limey sandstone
259– 289	2.39	
290– 326	2.16	
327– 354	2.32	Limey sandstone into shaley sandstone
354– 374	2.63	Sandy shale
376– 392	2.59	Quartzitic shale
392– 410	2.63	Quartzitic shale grading into limey breccia
412– 435	2.61	
435– 455	2.62	Limey breccia
455– 475	2.69	
475– 495	2.66	
495– 515	2.75	Limey breccia with mineralization
515– 535	2.77	Granodiorite (mica, quartz and pyrite)
536– 554	2.69	Quartz, mica, + ferromagnesium minerals and coarse grained
554– 574	2.92	
577– 598	2.86	
598– 617	2.94	Granitic type of rock
617– 642	2.85	
649– 672	2.82	Granitic type becoming more fine grained
672– 697	2.81	Some calcite stringers
698– 725	2.81	Metamorphic zone grading into breccia
727– 757	2.77	Fine-grained brecciation grading into schist
757– 777	2.80	Schist
777– 801	3.07	
801– 827	2.94	
827– 852	2.78	Schistic breccia
853– 878	2.83	
880– 909	2.78	
914– 938	2.92	
938– 964	2.90	
966– 991	2.85	Schist
992–1016	2.77	
1016–1045	2.71	Schistic breccia
1048–1074	2.78	
1075–1100	2.74	Schistic breccia grading into limestone
1105–1134	2.70	Crystalline limestone (marble)
1135–1160	2.72	
1163–1199	2.71	
1200–1225	2.74	Marble
1226–1251	2.73	
1251–1275	2.86	
1275–1300	2.90	Fine-grained, crystalline limestone and impurities
1300–1325	3.04	Crystalline limestone grading into gneiss
1326–1355	2.76	Gneiss grading into altered breccia
1355–1379	3.05	Altered breccia
1379–1404	2.97	
1405–1430	3.19	Altered breccia grading into crystalline limestone

TABLE 5.—MEASUREMENTS OF CORE DENSITY

Hole 3

Depth	Mean Density	Description
0– 30	2.69	Limey shale
30– 48	2.66	Shale
48– 68	2.72	
63– 80	2.71	Breccia in shaley matrix
80– 100	2.60	Metamorphic breccia with calcite
100– 124	2.64	Low temperature zone with mica
125– 145	2.67	Calcite, quartz and talc
145– 165	2.66	
164– 180	2.71	
180– 200	2.69	Grading into crystalline limestone
200– 220	2.74	Crystalline limestone
220– 240	2.65	Dark altered rock
240– 260	2.74	Crystalline limestone
260– 278	2.68	
280– 300	2.69	Dark, low-temperature, metamorphic rock, grading into crystalline limestone
300– 320	2.78	Crystalline limestone in contact with dark basic rock
320– 340	2.79	
340– 360	2.82	Basic rock
360– 380	2.72	
380– 402	2.79	Some calcite stringers
402– 422	2.73	Crystalline limestone

the basement is first encountered at a depth of 65 feet or 517 feet above sea level. The values of density for the two holes thus refer to entirely different levels of the country rock and this must be considered in assessing the origin of the gravity field of the crater.

4. The breccia in Hole 1 has an average density of 2.56, extreme values being 2.79 and 2.37. It is clear from a study of individual specimens that the larger values are associated with bouldery material while the lower values are due to the more finely divided material previously referred to as the matrix.

Rather surprisingly the average density for the breccia in Hole 2 is 2.74. This result is no doubt largely due to the greater proportion of bouldery material in the cores. In a centrally located explosion the finer material is likely to be nearest the source, the larger fragments being ejected to greater distances. In addition, since the crater surface at this location has a relatively large slope of the order of 27 degrees it is probable that rock slides and the accumulation of talus material has influenced the character of the breccia.

It thus appears that the gravity contrast between the breccia and the basement is an important factor in the observed gravity field and that this field, represented in Figure 6 is a consequence of both the breccia and the low-density sediments. Although the density contrast of the sediments is greater, it is probable that the breccia, which is believed to occupy a much greater volume, is the main determining factor for the gravity field. This result gains added significance from the gravity results at Brent (Millman et al., 1960) and Deep Bay (Innes, 1960) two craters differing in size but showing an anomaly pattern generally similar to that at Holleford. A quantitative discussion of the gravity data for these three craters is being published elsewhere by M. J. S. Innes.

Correlation with Seismic and Magnetic Results

It is clear that the low densities encountered in the breccia are to a large extent a consequence of the state of division of the material and even for those breccia cores which show a relatively high density the materials are usually rather weakly recemented and must have very different elastic constants then the undisturbed basement rocks. Rocks of this character would be expected to have lower velocities for seismic waves than the undisturbed Precambrian and this provides a logical explanation for the seismic results of Figure 4. The fragmentation of the material is also consistent with the magnetic results, since the random distribution of magnetized rock particles would normally produce a volume of material with low magnetic moment.

Age of the Crater

Evidence concerning the minimum age of the crater has been derived from geological reports on the sediments adjacent to and actually inside the crater by Drs. M. J. Frarey and B. V. Sanford, Geological Survey of Canada. Frarey's report places the origin of the circular feature in Precambrian time, although the surface rocks observed within the crater were sediments containing Black River fauna corresponding to the early Ordovician. He observed Nepean sandstone in the crater vicinity and while at that time such rocks had not been found within the rim there was a general inference that all the observed sediments had been deposited after the formation of the crater.

Examination of drill cores gave no evidence of Palaeozoic fragments in the breccia and this again suggested that the crater was older than any of the nearby sedimentary rocks. A study of the sedimentary cores above 750 feet revealed about 400 feet of whitish quartz sandstone which Sanford tentatively identified as belonging to the Potsdam formation. If this is correct, the evidence of the crater sediments pushes the minimum age well back into the Cambrian. Since the crater had evidently undergone massive erosion before the deposition of the sediments mentioned above it seems reasonable to accept Frarey's original conclusion that it was formed in Precambrian time. It would, therefore, appear that the impact which formed the crater occurred in late Precambrian time anywhere from 500,000,000 years to 600,000,000 years in the past.

Energy of the Explosion

Although original studies of the energy of an explosion required to produce a crater the size of Holleford have not been part of the present investigation, such studies have been carried out by a number of other investigators. These include Wylie (1943), Baldwin (1949), Hill and Gilvarry (1956), Opik (1958) and Macphail (1960). Most of these studies have referred specifically to the Barringer crater.

Wylie, Baldwin, and Gilvarry and Hill based their calculations on the amounts of chemical explosives of known heat of combustion required to produce mine craters. Their methods of extrapolation differed and it seems probable that greatest weight should be assigned to that of Gilvarry and Hill which takes into account the character of Baldwin's depth-diameter relationship in estimating the relationship between energy and crater size. Opik approached the problem from the point of view of hydrodynamics, assuming that the displaced material would act like a liquid at the pressures involved in meteorite impact. However, where the matter of energy was involved the problem resolved itself into an estimate of the amount of work done in crushing and ejecting the crater material, making use of the known strength of the rocks. Macphail, whose work was done at the Dominion Observatory, also based his calculations on the work done in crushing and ejecting the material. He made use of ore-dressing data in estimating the amount of energy required to shatter and pulverize the rock, and assumed that a paraboloid of diameter 4,000 feet and altitude 600 feet was raised to a height of 1,200 feet. (Part of this would simply fall back into place while the remainder would be ejected or forced upward to form part of the rim). Making suitable allowances for the inefficiency of the cratering process, e.g. the dissipation of energy as heat, seismic waves etc., he derived a value for the energy for the Barringer crater of 5×10^{23} ergs.

Results of the various investigators are shown in Table 6. In this table the energy in ergs of the explosion is shown for each of three craters, Barringer, Holleford and New Quebec (Chubb) as the upper of two rows of figures. The lower figure in each case is the mass in grams of the meteorite on the basis of 20 km/sec as the impact velocity. Since all but one of the calculations were originally made for the Barringer crater the curves presented by Gilvarry and Hill are used to extend the calculations to the Holleford and New Quebec craters. This process, as will be seen from the table, results in a value of energy for the Holleford crater of 6 times and New Quebec of 20 times that of Barringer.

The lack of agreement between the various estimates is a measure of the intractable nature of the problem and it now seems doubtful whether any estimate based either

TABLE 6.—ENERGY AND MASS RELATED TO CRATER DIAMETER

Impact velocity 20 km/sec.

Crater Diameter		Wylie	Baldwin	Hill and Gilvarry	Öpik	Macphail
Barringer (4,000 ft)	Energy ergs	9.4×10^{21}	3.3×10^{21}	2.0×10^{23}	5.2×10^{24}	5.0×10^{23}
	Mass grams	4.7×10^{9}	1.6×10^{9}	1.0×10^{11}	2.6×10^{12}	2.5×10^{11}
Holleford (7,700 ft)	Energy ergs	56×10^{21}	20×10^{21}	12×10^{23}	31×10^{24}	30×10^{23}
	Mass grams	28×10^{9}	10×10^{9}	6×10^{11}	15×10^{12}	15×10^{11}
Chubb (12,000 ft)	Energy ergs	188×10^{21}	66×10^{21}	40×10^{23}	104×10^{24}	100×10^{23}
	Mass grams	94×10^{9}	33×10^{9}	20×10^{11}	52×10^{12}	50×10^{11}

Making use of Macphail's value of energy and assuming that the Holleford crater was produced by a spherical stone meteorite of density 3.0, the diameter of the meteorite comes out at 100 metres or 328 feet.

upon extended extrapolation or direct calculation of crushing and ejection can claim with any certainty to be within a factor of 10 of the true value. Some hope for more reliable estimates of energy is suggested by recent results of underground atomic explosions but the available data are not yet sufficient to use for plotting an energy-versus-diameter curve, let alone making the dangerous extrapolations necessary for correlation with large meteorite craters.

Summary and Discussion

Review of Evidence from Holleford

The main significance of these results is the demonstration, with a high degree of probability, of the existence of a meteorite crater with an age of the general order of 500,000,000 years. It is true that the evidence is less complete than might be desired. For example, only one radius has been studied, but an examination of the aerial photographs leaves little doubt of the radial symmetry of the feature. Similarly the lack of identifiable meteoritic material is disappointing, but this may be attributed to the minuscule sampling afforded by the three small drill holes. Even for the Barringer crater it is by no means certain that a comparable sampling technique would have turned up any nickel-iron specimens. There is the further possibility or probability already mentioned that the meteorite which formed this crater was of an entirely different type of material than that producing recent meteorite craters. If, as seems entirely possible, such material is similar to terrestrial rocks it could remain undetected even though present in fairly massive quantities.

Apart from the matter of meteoritic material, evidence of a kind difficult to disregard is the profile of the crater, fundamentally similar to the Barringer and New Quebec features. The rudimentary nature of the rim scarcely affects this conclusion since the processes of erosion operating over even a moderate span of geological time would inevitably eliminate this part of the structure. These same erosion processes which tend rather quickly to reduce an elevation to ground level would under certain circumstances and (granted a sufficiently great length of time) reduce the entire plain to a level below the crater floor, wiping out entirely the original profile. In the present instance it is clear that long before this result could be achieved the whole area was covered by an invading sea which filled the crater and resulted in the deposition of Palaeozoic sediments which have preserved the basic structure until the present day. The fact that the crater was found under these circumstances suggests that similar areas, where ancient sediments have been eroded nearly to the basement level, would be worth searching for similar examples.

In addition to the evidence provided by the shape of the circular depression, the location of several hundred feet of unstratified rock breccia beneath the crater floor is further strong evidence in favor of an impact origin. The lack of bedding planes and the state of division of the material point to an explosion *in situ* with meteorite impact the most probable source.

Basis for Further Search

The initial search of aerial photographs of the Canadian Shield was partly inspired by the finding of the New Quebec feature, a relatively recent crater of strikingly distinctive form closely resembling the Barringer crater. It is now apparent that objects like the Barringer crater and the New Quebec crater are so rare as to be practically non-existent and the future of this branch of astronomical-geophysical science is likely to depend mainly on the ability of the investigator to recognize remnants or vestiges of crater structures which have no very close resemblance to a recent undamaged crater. Having regard to what is known of the Holleford, Barringer and Chubb craters it seems worthwhile to try to visualize the sort of remnants most likely to be encountered, considering the variety of geological influences which are expected to affect the crater over a period of hundreds of millions of years. Some of the possibilities are outlined as follows:

1. An ancient crater could lose its rim by erosion and still remain a fairly conspicuous feature such as an approximately circular lake filled with water.

2. A crater located in an area never covered by water could by the ordinary processes of erosion gradually become obliterated and disappear as a conspicuous landscape feature. Such an object might, nevertheless, be detected on aerial photographs by configurations of vegetation or drainage patterns.

3. In areas covered by sedimentary rocks where the cover is thin, the circular shape and raised rim of a buried crater may influence the attitude of the sediments sufficiently to be detected.

4. A crater originally filled in or covered over by sediments may at a later time have the sediments eroded sufficiently to reveal a circular feature.

5. A crater filled with sandy or other deposits might, if buried and subjected to heat, pressure and/or silica or calcite recementation, attain a hardness and resistance to solution comparable to that of the containing rock. If subject to severe erosion the altered sediments might retain their structure and identity sufficiently to stand up, at least in some degree, above the surrounding plain.

6. A geological study of rock outcrops could reveal uptilted strata in a circular arrangement indicative of a crater formed in sedimentary rock. (The sediments surrounding the Barringer crater are tilted in this manner).

7. An ancient crater and its surroundings could be subject to such severe erosion that the original crater surface (whether or not protected by sediments) would be completely destroyed, leaving only the underlying breccia whose circular distribution could give a clue to its origin.

8. According to G. P. Kuiper, who has carried out what are probably the most definitive modern observations of the moon, the central peaks of some lunar craters may be igneous intrusions of hard basic rock. A similar suggestion relative to earthly craters has been made by J. M. Harrison, Director of the Geological Survey of Canada. He points out that an impact of sufficient violence could act as a trigger to release latent volcanism within the earth's crust which could complicate the interpretation of fossil craters. The simplest case would be that of a hard central peak on an earthly crater which might well remain intact while the crater rim, composed of debris and shattered rock would be removed by erosion. To judge by observations of the moon such a situation is most likely to be encountered in a large crater of the order of some tens of miles in diameter. A combination of impact and volcanism also appears to be the most logical explanation of a number of lunar craters with rims corresponding to an impact origin and flat featureless floors probably due to lava flows. In a similar occurrence on earth it is possible that the rim would be rapidly destroyed by erosion leaving the lava floor with no very clear indication of its origin except its circular form. There is also the possibility that the volcanic phenomenon would be of sufficient magnitude to obliterate all trace of the impact which set it off, including the original circular crater form.

While the enumeration of the above possibilities does not offer any easy solution to the problem of fossil craters it does suggest that any circular feature not otherwise accounted for should be examined very carefully before it is discarded as a crater possibility. It is difficult for an astronomer, looking at the evidence for impact on our sister planet the moon, to escape the conclusion that the earth must have been subjected to at least some of the same kind of bombardment. If this is so it would indeed be astonishing if it were to turn out that the fossil craters so far located such as (Brent, Deep Bay, Holleford) and others for which less definite evidence is available, (Beals, Innes and Rottenberg, 1960) were the only ones of their kind. It appears more likely that many others remain to be discovered if the search for them is pushed with sufficient perseverance and over a sufficiently large area of the earth's surface.

Acknowledgments

In expressing appreciation for help received during the study of this crater, special mention should be made of Mr. Ray Babcock of Holleford on whose farm the holes were drilled and who was of the greatest assistance throughout the investigation. Although Mr. Babcock was subjected to extreme inconvenience due to the loss of his well he encouraged continuance of the drilling and without his attitude of forbearance the project could not have been brought to a successful conclusion. Warmest acknowledgment is also made to scientific colleagues in the Department for geological help and advice and for assistance in applying geophysical techniques to the problem. These include J. M. Harrison, B. A. Liberty, K. R. Dawson, M. J. Frarey, T. E. Bolton, K. Pollett, of the Geological Survey of Canada; M. Haycock of the Mines Branch; M. J. S. Innes, J. H. Hodgson, P. L. Willmore, A. M. Bancroft R. J. Buck, L. D. Sobczak and J. L. Roy of the Dominion Observatory. The Geographical Branch undertook the responsibility for drilling Holes No. 2 and 3 and thanks are due to the Director, Dr. N. L. Nicholson for making possible an exceedingly valuable addition to the data of this investigation.

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