THE SEARCH FOR FOSSIL METEORITE CRATERS—II

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The Holleford Crater

THE Holleford Crater, longitude 76° 30′ W, latitude 44° 47′ N, was discovered by G. M. Ferguson and A. Landau (Beals, Ferguson and Landau, 1956) as a result of a search of aerial photographs in Southern Ontario. A study of the aerial photographs with the stereoscope indicated a relatively shallow circular depression with some indication of raised edges approximating 1·46 miles in diameter. The village of Holleford lies partly within the crater circumference and several roads cross the rim while one descends close to the floor of the crater. Geological studies on the site indicated that almost the entire crater area was covered by Paleozoic sediments of Ordovician age which dip gently inward toward the centre (Frarey, M. J., 1955). The area has been subject to heavy erosion and the circular form of the feature is more clearly defined in some areas than others but there appears to be no exception to the rule that all strata dip radially inward toward the centre. The crater thus appears to correspond to Type 3 but it also has resemblances to Type 4 and Type 5. The general area in which the crater is located is rather thinly covered with sediments and there are numerous outcrops of Precambrian rock in its immediate vicinity. There appears to be only a single Precambrian outcrop within the circumference and it occurs as a low hillock of crystalline limestone on the north-eastern sector of the crater rim. This outcrop is approximately 38 ft. above the surrounding plain, suggesting that the rim of the crater had not been entirely eroded away before the deposition of sediments. The depth of the visible crater is approximately 100 ft. and the surrounding hills, particularly on the south, east and west form a moderately impressive cirque when viewed from a point near the centre. The adopted centre is at 492 ft. above sea-level, about 12 ft. above the surrounding plain, while the visible rim rises, at its highest point in the south-west, to an elevation of 600 ft. above sea-level. The fact that the true crater rim is covered with sediments renders its exact location difficult, but it is considered that on the average its position can be fixed within 100 ft. On the west the estimated position of the rim is on the edge of a cliff dropping steeply about 150 ft. to Knowlton Lake.

A consideration of the overall geology of the area suggested the existence of a circular basin in the Precambrian basement filled with Palæozoic sediments. This hypothesis was tested by geophysical observations with the following results.

Geophysical Results.—Analyses of the results of geophysical surveys indicate that the physical properties of the crustal rocks underlying the Holleford crater have undergone changes similar to those observed at the Brent crater. As found for Brent the gravity contours at Holleford (Fig. 7) are roughly circular and in a general way follow the outline of the depression. Correcting for regional effects it is found that the crater produces a negative anomaly of about 2·2 milligals. It is impossible accurately to assess the portion of the anomaly that is due to the Palæozoic sediments now filling the crater and draped over the rim, and that portion that would result from low density fragmental material believed to underlie the sedimentary strata. However, the surface exposures of the latter consists of dense lithographic limestones with densities somewhat larger than those of the surrounding Precambrian rocks. As a considerable thickness of these limestones within the crater would tend to compensate for any sedimentary material of lower density at depth, overlying the crater floor, it is concluded that the total observed anomaly may be taken as a reasonable estimate of the gravitational effect of the brecciated and fractured zone. On this basis and assuming 0·16 gm. per c.c. (as observed at Brent) for the mean density contrast between the fragmental material and normal country rock, the gravity minimum indicates that the breccia zone under the Holleford crater is at least 1,000 ft. thick.

The gravity results, therefore, point to a considerably smaller amount of fragmental material underlying the Holleford crater than was found at Brent, as might be expected considering the relative sizes of the two craters. Because of this and because the characteristically high propagation velocity of the hard lithographic limestone lying within and forming a mantle some 50 ft. thick on the rim and on three sides of the crater prevented penetration of the seismic waves to lower levels, the results of the seismic investigation at Holleford are less definitive than those obtained at Brent. However, analysis of the travel time curves obtained by firing a number of shots near the centre of the crater and recording them outside at distances of 3,000 to 12,000 ft. from the rim showed definite evidence of an underlying low velocity layer. No such layer was indicated in the records obtained at the same stations for shots fired outside and well removed from the crater

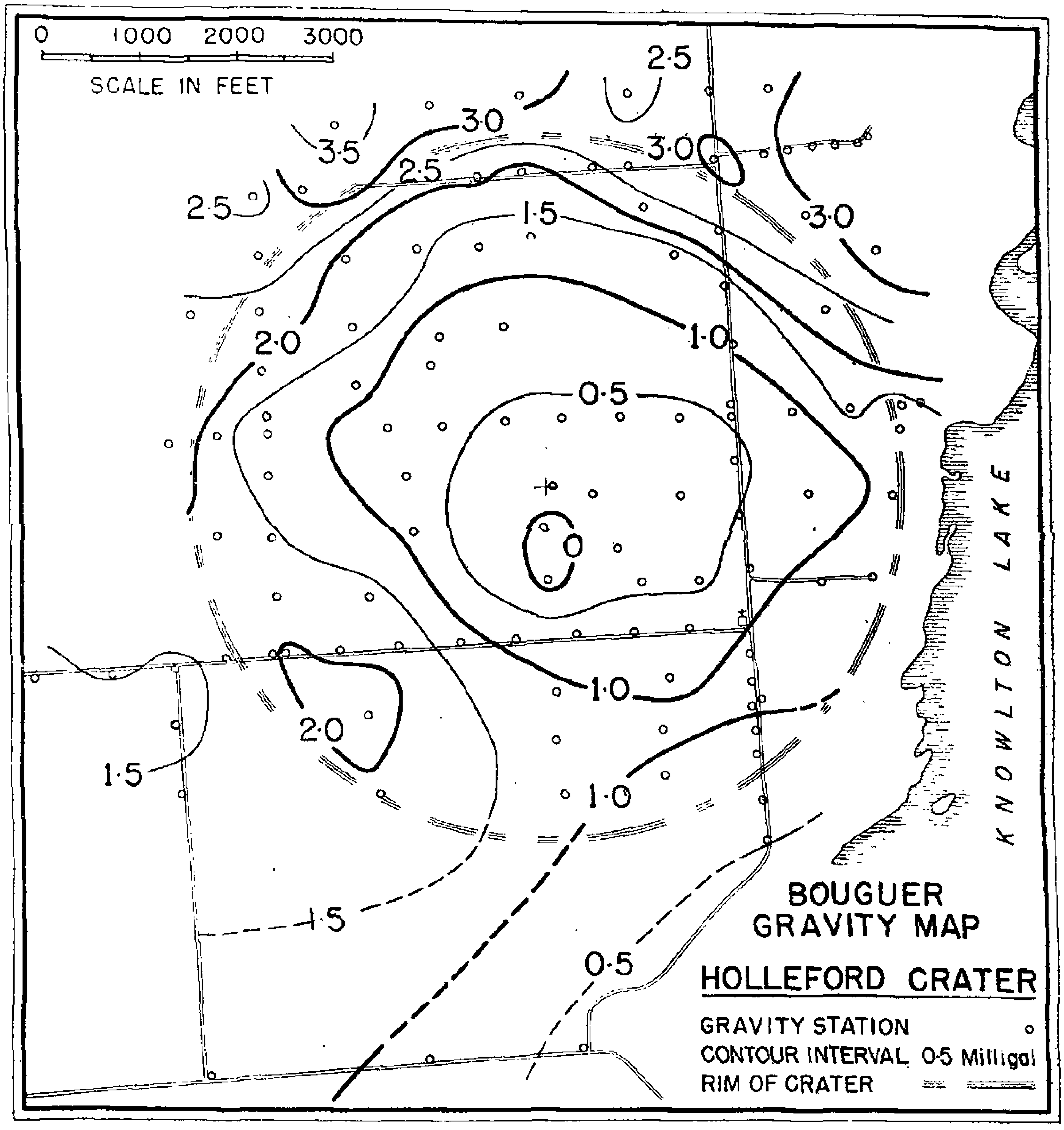

FIG. 7. Gravity contour map, Holleford Crater.

to ensure that the seismic paths traversed undisturbed basement rocks. While no quantitative results as to its thickness were possible, the low velocity material underlying the crater might well be identified with the zone of broken and shattered rock characteristic of craters formed by meteoric impact and explosion.

Although no ground magnetic surveys have been carried out over the Holleford crater, an aeromagnetic map of the area was made available for study by the Geological Survey of Canada. The map gives anomalies of total field intensity, contoured at intervals of 10 gammas, and is based upon measurements recorded at a flight altitude of 500 ft. above terrain. The anomaly contours trend in a general north-east direction, consistent with the general strike of the Precambrian rocks, and although there are marked local disturbances as much as 300 gammas in the magnetic field within one-half a mile from the rim, the variation over the crater is quite uniform. There is however a slight widening of the contours, indicating a decrease in the magnetic intensity in the vicinity of the crater, which may very well be a reflection of the disturbed bed-rock condition under the crater. Although consistent with the magnetic findings at Brent, the widening of the contours is extremely small and the slight decrease in intensity could very well be the result of other phenomena. Several ground magnetic traverses across the crater might be revealing and provide more significant results. While the aeromagnetic data does not provide definitive evidence in favour of an impact origin, the remarkably uniform gradient, and the absence of magnetic disturbances strongly negates the possibility of a structural or geological origin.

Diamond Drilling Program.—Since the geophysical results gave some confirmation to the idea of a crater in the Precambrian basement filled with sedimentary rock it was decided to undertake a diamond drilling program partly to ascertain the depth and shape of the crater and partly to see whether the material under the sediments would turn out to be the broken and fragmented material expected for an explosion crater. Holes were drilled at distances of (1) 1400 ft., (2) 2500 ft., and (3) 3750 ft. from the centre of the crater. The location of Hole No. 3 was chosen so as to be close to the top of the rim while the other two holes were located on the sloping sides at distances favourable for determining a profile. Limitation of funds prevented the drilling of a third hole at the centre.

The first hole drilled penetrated 755 ft. of sediments and at this level rock fragments of a variety of sizes were encountered embedded in a matrix of finely divided materials which upon microscopic examination turned out to be fragments of the Precambrian basement rock. This fragmented material or breccia was drilled to a depth of 1,128 ft., where the drill struck fast

FIG. 8. Drill cores showing sediments and breccia, Holleford Crater.

and had to be abandoned. While it was a disappointment not to be able to penetrate to the undisturbed basement, the 1,128 ft. of drill cores recovered supplied very valuable information and this was supplemented by additional material from Holes No. 2 and 3. In Hole No. 2 rock breccia was encountered after 440 ft. of drilling through sediments. The breccia continued to a depth of 600 ft. where substantially undisturbed rock was encountered. The hole was pushed to a depth of 1,486 ft. in order to secure massive samples of the basement rock. Hole No. 3, bored on the estimated location of the crater rim, encountered a thin layer of breccia after only 65 ft. of sediments had been penetrated. Undisturbed basement rock was reached at 66 ft. and the hole was continued to a total depth of 443 ft. The contrast between the sediments and breccia is illustrated in Fig. 8 showing a selection of cores from Hole No. 1.

and New Quebec craters as well as the theoretical profile of Fig. 2. The information from Hole No. 3 as well as the outcrop of Precambrian rock on the north-east sector of the rim already mentioned gave a definite indication of a rudimentary rim although it is reasonably certain that a large part of the rim was eroded away before the deposition of sediments. No evidence was found that could identify the crater with the processes of erosion, subsidence or volcanism and there appears little doubt that the only reasonable explanation of its origin is that of meteorite impact and explosion (Beals, 1957).

Search for Meteoritic Material.—A search for meteoritic material was conducted making use of two different techniques. First all of the drill cores were studied with the aid of a highly sensitive astatic magnetometer and those which showed indications of greater than average magnetic moment were broken up and searched for magnetic particles. In every case it was

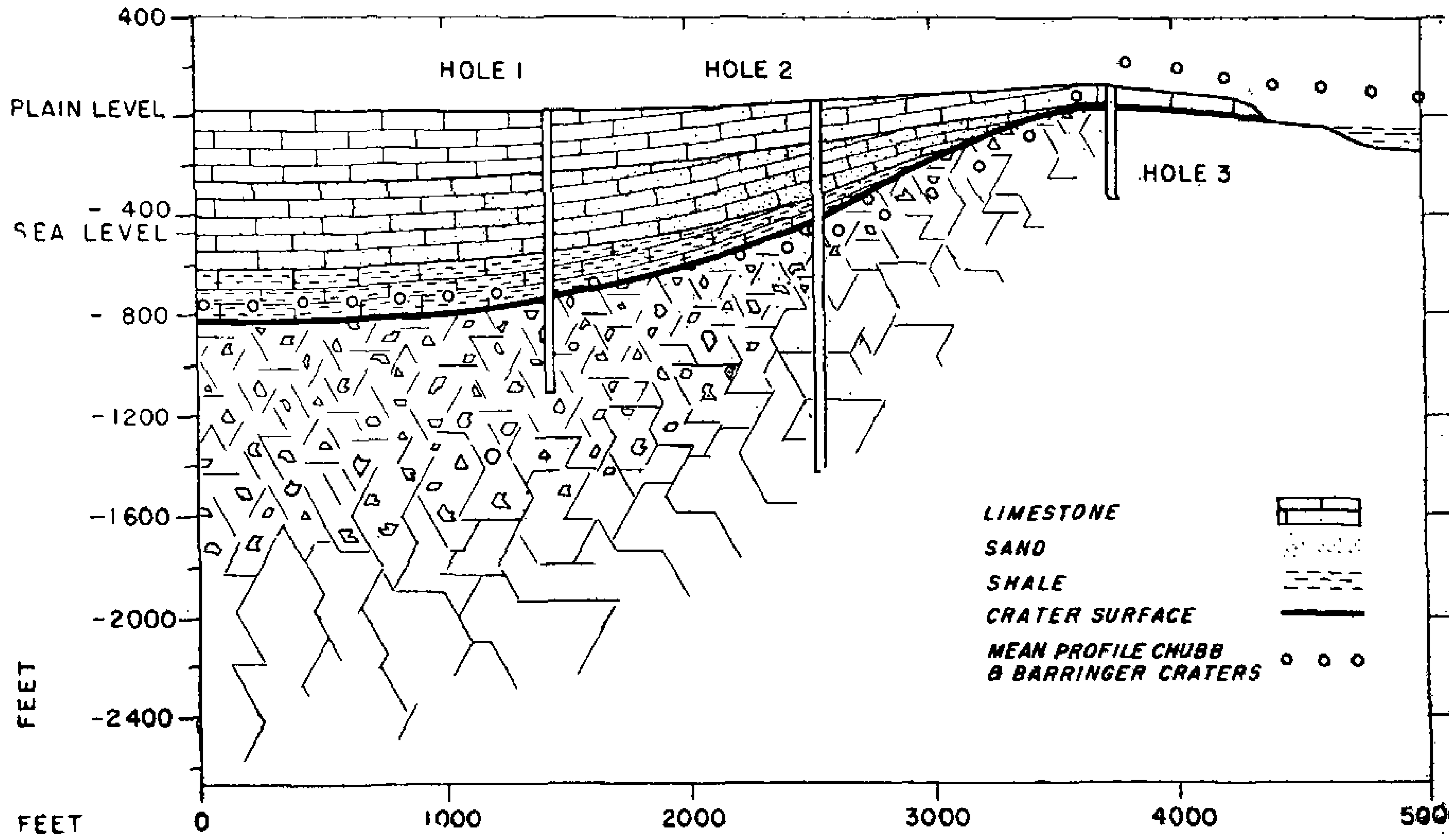

FIG. 9. Profile of Holleford Crater showing comparison with mean of Barringer and Chubb profiles.

The information provided by the drill cores was very favourable to the hypothesis of a meteorite impact origin for the crater. The breccia encountered below the sediments was entirely without bedding planes and gave the impression of being formed *in situ* by an instantaneous event like an explosion or impact. The shape of the crater as may be seen from Fig. 9 is closely similar to that of the Barringer

found that the excess magnetism was due to pieces of basic rock embedded in the breccia or, in some cases, forming the entire core. In no case was anything suggesting the presence of nickel iron discovered.

A second procedure, carried out with the aid of the Geological Survey of Canada, was to take samples of core every five feet throughout the breccia and to subject them to crushing and subsequent magnetic analysis for magnetic particles. In addition to cores from the brecciated layer, numerous cores were taken from the lower layers of the sediments in contact with the breccia since the appearance of these cores suggested that they were formed of finely divided material produced by the explosion and washed back into the crater before the deposition of Palæozoic sediments. Here again the results were entirely negative and although two drill holes of small diameter are admittedly an inadequate sampling, the possibility or even the probability must be considered that the crater was formed by a stone rather than a nickel iron meteorite.

Age of the Crater.—Geological investigations at the surface had indicated the presence of Black River fauna characteristic of the middle Ordovician era. A feature of the core near the bottom of the hole was a layer of whitish sandstone 400 ft. thick which has been identified by Dr. B. V. Sanford of the Geological Survey of Canada as of probably Cambrian age. This would give a minimum age for the crater of 450,000,000 years but it seems probable that it is considerably older. The evidence for the severe erosion of the rim and the absence of Palæozoic fragments in the breccia suggest that the impact occurred in Precambrian time before the area was invaded by the Palæozoic seas. If this inference is correct the age of the crater must be of the order of 500 to 1,000 million years.

The Deep Bay Crater

Following the discoveries of the New Quebec Crater (Meen, 1950), the Brent Crater (Millman *et al.*, 1951) and the Holleford Crater (Beals, Ferguson and Landau) attention was drawn (Innes, 1957) to a large circular water-filled depression known as Deep Bay, which forms the south-eastern part of Reindeer Lake in Northern Saskatchewan. Two separate field investigations of the feature have been completed, the first in August of 1956 during which geological and geophysical observations were carried out and the second in the winter of 1958, during which additional gravity information was obtained by making gravimeter observations over the Bay on the ice. A complete account of the results of these investigations is in preparation (Innes, Pearson, Geuer, 1960) and will appear elsewhere.

Deep Bay, longitude 103° 00′ W, latitude 56° 24′ N, elevation 1,106 ft. above sea-level, is located in the Canadian Shield, midway between the great sedimentary basin of the central plains to the south-west and Hudson Bay to the north-east. Although it lies on the principal route followed by canoes in summer and tractor trains on the ice in winter in freighting supplies to northern outposts, Deep Bay can be reached most easily by aircraft flights from the small settlement at Lac La Ronge, 120 miles to the south, and presently the northern limit of the highway system of Saskatchewan.

Topographically, the Reindeer Lake area is similar to many other places in the Canadian Shield, with flat-topped rock exposures forming hills and ridges above the general level of the lakes, the relief of which seldom exceeds 150 ft. Travelling by canoe, although one might wonder at the wide expanse of Deep Bay (nearly 6¼ miles in diameter), the complete absence of islands and the scarcity of sheltered beaches along its margin, it is unlikely that the near perfect circularity of the bay would be noticed. From an aircraft, flying at considerable height, these unique features are immediately apparent and stand out in marked contrast to the main body of Reindeer Lake, with its numerous islands and irregular bays and shore-lines, which conform in a general way to structural trends of the underlying Precambrian rocks. An aerial mosaic of Deep Bay is shown in Fig. 10.

Although deeply eroded by glacial action, much of the bed-rock portion of the crater's rim remains and stands on the average some 270 ft. above the waters in the bay. To the north-east and east the rim is best preserved. It stands 400 ft. or more above the lake and retains in several places steep and precipitous inner slopes. The original rim diameter is estimated to have been about 40,000 ft. (7·57 miles) or about 1 mile less than its present 8½ miles diameter as marked by the height of land surrounding the bay. As with the Brent Crater the drainage pattern of the Deep Bay area is both concentric and radial, and with the exception of three broad channels into Reindeer Lake along the northern side, the drainage is restricted to short intermittent streams, no greater than two miles in length.

The rocks, which are well exposed in the area, are all granitic in character and are Precambrian in age. Dr. W. J. Pearson of the Department of Mineral Resources of the Province of Saskatchewan has examined the rocks along the shore-line and on the rim and classifies them according to the varying amounts of granitic material they contain. Three main types have been recognized which are as follows: a unit of injection gneisses and migmatites underlying the southern part of the area, a central unit of metamorphic gneisses of sedimentary origin, and a group of intrusive granitic rocks, chiefly granodiorites and pegmatites which occur along the north-western and northern sides of the bay. Careful examination of the structural relations between these rock types in no way suggests a geological origin for Deep Bay. The general trend of the three units is north-easterly and approximately the same on both sides of the crater, while there is evidence that the strike of many local structures are normal to and are terminated at the margin of the Bay.

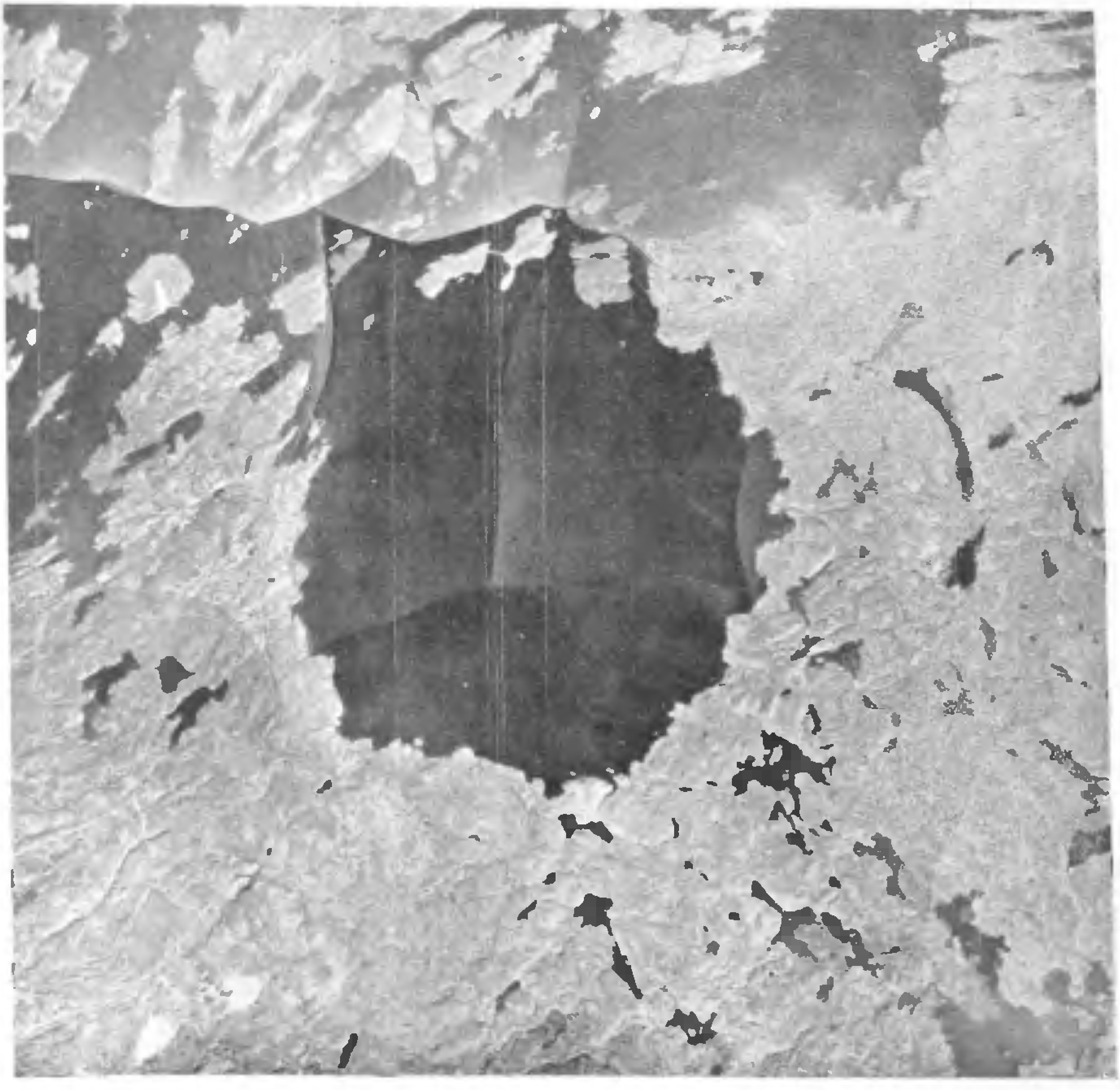

FIG. 10. Aerial mosaic of Deep Bay Crater.

That Deep Bay is the result of a tremendous explosion is clearly indicated by the intense fracturing and shattering of the granitic rocks which is most pronounced in the vicinity of the shore. Large-scale fracture and fault, zones of various widths, now partially obscured by glacial action and deposition, cut radially and obliquely across the rim and persist for several miles from the margin of the bay. A system of concentric fractures is also well developed particularly in that area less than 3 miles from the shore-line. Perhaps the most prominent feature, that may be the expression of such fracturing, is a narrow arcuate lake 3 miles in length located about 3 miles to the east of the crater. There is some evidence from the drainage pattern and dissected topography that this depressed zone is much longer and circumscribes the whole crater and has a diameter of about 12 miles. Within this area lie the rocks which form the now deeply eroded rim of the crater, with the general appearance of having been shattered into huge blocks by a process involving little or no horizontal movement.

Also strengthening the meteoric hypothesis of origin is the great depth of Deep Bay, when one compares its depth with that of Reindeer Lake, which seldom exceeds 150 ft. Numerous depth recordings show that the present floor of the crater lies at an average depth of about 500 ft. with an extensive depression along the eastern margin of the bay that has a maximum depth of 720 ft. Although outcrops of sedimentary rocks are lacking, boulders and pieces of shale, identified as Mesozoic in age from fossil evidence, were discovered on a small beach near the southern end of Deep Bay. The source of this shale is uncertain, but as there are no known occurrences of this rock within hundreds of miles, it is believed to have been carried by ice movement from a lake deposit on the floor of the crater. If so, and as 2,100 ft. is the depth predicted to the original plain for a crater of this size, we may expect to find at least 1,400 ft. of sedimentary strata underlying the waters of Deep Bay.

Geophysical Results.—So far gravity and magnetic studies are the only geophysical investigations that have been carried out in the Deep Bay area. As found at Brent and Holleford, the gravitational field associated with the Deep Bay Crater is negative (Fig. 11), with contours of equal anomaly forming a circular pattern concentric with the feature. The amplitude of the gravity variation is, however, much larger, reaching a minimum value after corrections for terrain and water depths, of about 20 milligals near the centre of the Bay. The

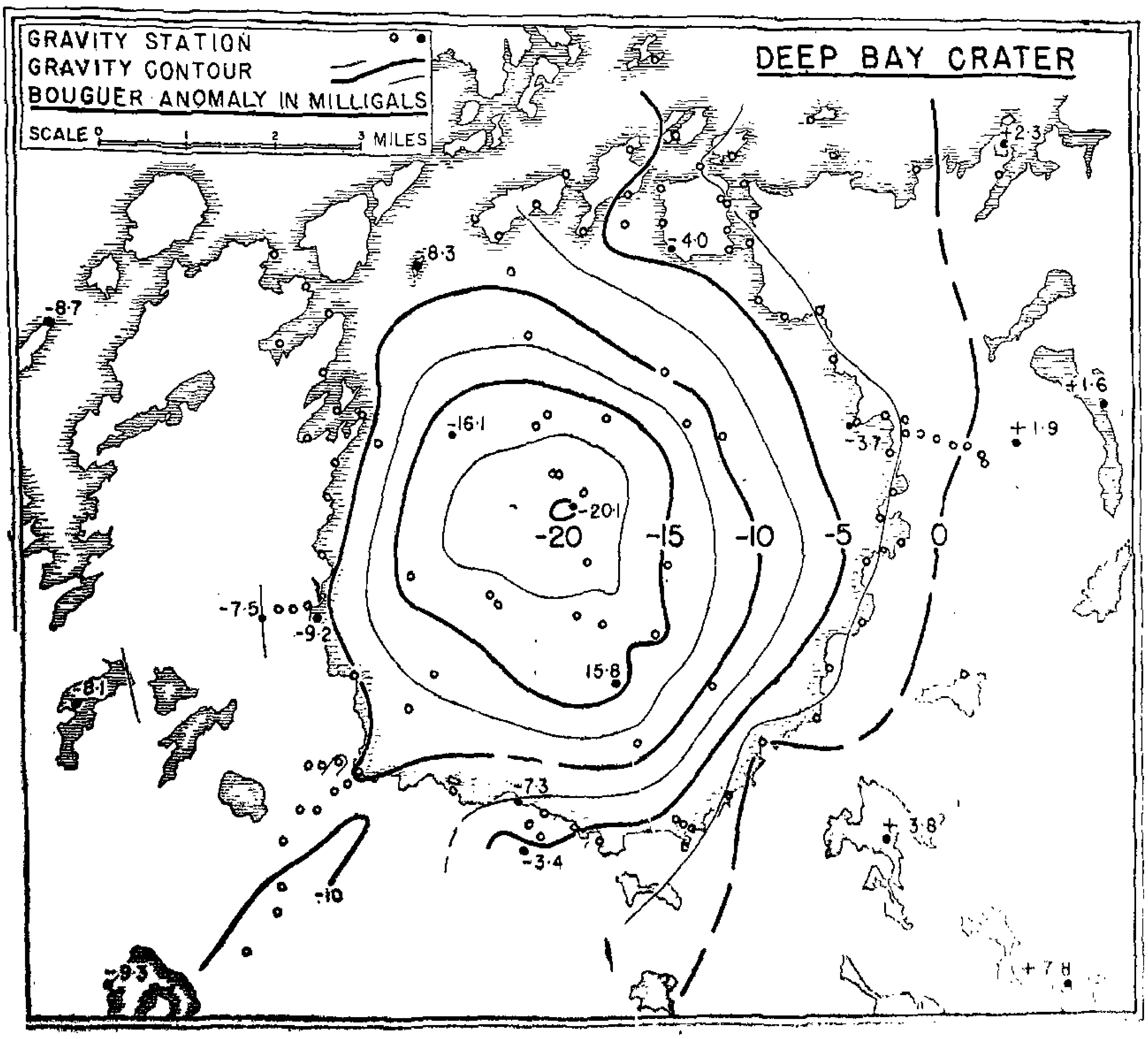

FIG. 11. Gravity contour map, Deep Bay Crater.

1,400 ft. of sedimentary material would account for about 3 to 6 milligals of the total anomaly depending upon its density, leaving the remainder of the anomaly to be explained by the underlying fragmental products of explosion. If the mean density of the latter is similar to the density of the breccia obtained from drill core samples at Brent, which seems reasonable, as the country rock surrounding both craters are granitic gneisses of similar composition and density, it follows that the zone of deformation under the original floor of Deep Bay crater extends to depths which may be as great as 10,000 ft.

An aeromagnetic map of the Deep Bay area has been compiled by the Geological Survey of Canada, giving anomalies in the total magnetic intensity. Because of the more rugged topography the observations were carried out at a flight altitude of 1,000 ft. above general ground level. Although this is twice the height flown during the Brent aeromagnetic survey, the results for Deep Bay are equally definitive and are in qualitative agreement with the results obtained at the other craters.

As before, the most outstanding features of the magnetic map is the small and uniform variation in intensity over the central portion of the crater when compared with the anomalies produced by the surrounding country rocks. As observed at Brent and Holleford the regional field surrounding the crater is highly irregular with local disturbances giving rise to steep gradients and the anomaly contours tending to follow the prominent structural trends of the gneisses. Over the Bay, however, the total variation does not exceed 190 gammas with uniform gradients no larger than 50 gammas per mile, indicative of the great depth to undisturbed basement rocks.

Other Possible Meteorite Craters

The results of the studies of these three craters are in general agreement with suggestions made earlier in this paper, that the underground structure of a meteorite or explosion crater can retain its identity over a very long period of time after the obliteration of its more obvious surface features. This general conclusion emphasized the necessity, in the examination of aerial photographs, for a careful study of every circular feature which did not have some other clear-cut and definite explanation. During the present survey of Canadian aerial photographs, a great many circular or near circular features were encountered but most of them were discarded as not justifying the expense and labour of further study. **Some were fairly obviously old volcanoes. Others appeared to be sink holes while many shallow circular lakes in boggy ground appeared to be due to the erosional effects of wave action. A number of rather small round lakes may most logically be explained as of the nature of pot holes or solution cavities.**

After these more obvious cases had been disposed of (and it is by no means certain that all rejections were justified) there still remained a substantial number of circular features which did not fit in to any standard pattern and for which it appeared legitimate to consider the possibility of a meteorite impact origin. Preliminary studies have been made on the ground for some of these objects but others have been observed only in aerial photographs. Such information about them as is available is summarized as follows :

1. The Franktown Crater, Long. 76° 3·5' W, Lat. 45° 03' N, about forty miles south-west of Ottawa. This feature, about ¼ of a mile in diameter, occurs in Ordovician limestone and may be an example of Type 3, where the buried crater rim, or what is left of it, still influences the attitude of the sediments. The depression is approximately 25 ft. deep and there is a flat area of bog and farm land in the centre which was probably once a lake. The outlines are less clear than at Holleford and in all probability only a diamond drilling program (not yet attempted) would suffice to give a clear indication of the origin of this feature.

2. *Clearwater Lakes*.—Long. 74° 20' W, Lat. 56° 10' N. These lakes consist of two roughly circular bodies of water separated by a screen of islands. The larger of the two components is 20 miles in diameter while the smaller is 16 miles across. These two circular lakes stand out conspicuously in a region dominated by elongated bodies of water which presumably owe their character to the effects of glacial erosion. An interesting feature of the larger lake is an approximately circular ring of islands, 10 miles in diameter, concentric with the circular lake itself. Some of the islands are of considerable height and this, combined with their circular arrangement, makes them a unique and impressive landscape feature. Geological studies of the islands indicate that they are composed of lava. In default of any other explanation it is thus possible that these two lakes constitute an example of Type 8 and were formed by the impact of twin meteorites, the larger impact resulting in a lava extrusion which took the

form of a ring dike. In this connection it is interesting to record that there are several twin craters on the moon roughly corresponding in size to the Clearwater Lakes. Also on the moon there is at least one crater which has a ring dike within it, concentric with the crater as a whole. This crater is 9 miles in diameter, the corresponding figures for the inner ring being 4·5 miles. Apart from size, the similarity to the Clearwater Lake feature is quite striking.

3. *The Manicouagan Lake Feature.*—Long. 68° 37′, Lat. 51° 28′. An approximately circular area, enclosed by Lakes Manicouagan and Mushalagan, is a conspicuous aspect of the map of Quebec and many geologists and other students of this region have speculated as to its origin. The circle is approximately 40 miles in diameter and a mountain approximately 3,000 ft. high rises in the centre. Geological studies of the area (Rose, E. R., 1955) indicate that the central mountain is an igneous intrusion and that otherwise a large part of the area is covered by flat lying lavas of somewhat different character. The possibility has been considered that this may represent an example of Type 8 where a large crater has had its rim removed by erosion leaving the central mountain *plus* a lava floor. Some geophysical studies have been made in the region but the size of the area and the complicated nature of its geology has so far prevented any definite conclusion.

4. *Stratified Circular Features in North-eastern Quebec and Labrador.*—Aerial photographs in this general area have revealed five circular features ranging from 2½ miles to 7 miles in diameter which exhibit a stratified appearance somewhat similar to that shown by the Holleford Crater. The stratified structures in some cases stand up somewhat above the surrounding plain. It is considered possible that they represent examples of Type 5 where an ancient crater has been filled with sediments which have subsequently been consolidated to the extent that they retained their identity when the surrounding rock has suffered severe erosion. The locations and diameters of these features are given in Table I.

TABLE I

Stratified circular features

General area		Longitude	Latitude	Diameter (miles)
Mecatina Crater*	..	59° 22′	50° 50′	2
Lake Michikamau	..	64° 27′	54° 34′	3½
Menihek Lake	..	66° 40′	53° 42′	3
do.	..	67° 10′	54° 19′	2½
Sault au Cochons	..	70° 05′	49° 17′	7

* Illustrated in Fig. 12.

5. *Circular Structure, Carswell Lake Area, Saskatchewan.*—Long. 109° 30′, Lat. 58° 27′. During the geological field season of 1957, Dr. W. F. Fahrig of the Geological Survey of Canada, working in Northern Saskatchewan, discovered a feature approximately 18 miles in diameter bounded on its circumference by co-centric circles of rock outcrops consisting of sandstone and dolomite sediments. These sediments, considered to be of Precambrian age, were deformed and tilted in a manner somewhat reminiscent of those on the rim of the Barringer crater designated as Type 6. According to a sectional diagram provided by Dr. Fahrig, the strata give the impression of having been compressed along a radius and tilted more than 90° away from the centre of the feature. Since this is the kind of deformation expected for a meteorite crater formed in sedimentary rock this feature is considered as having a possible meteorite origin. It is hoped to carry out some geophysical tests of this hypothesis during the 1960 field season. Although the writers consider that the available evidence is best satisfied by the meteorite impact hypothesis, it should be emphasized that there are other explanations which Dr. Fahrig, the discoverer, regards as more probable.

6. *The Nastapoka Islands Arc of Hudson Bay.*—Long. 80° 02′, Lat. 57° 40′. These coordinates represent the centre of curvature of an almost perfectly circular arc on the east coast of Hudson Bay, approximately 275 miles in diameter. This is a conspicuous feature even on a world map and many scientists and others have made the suggestion that it might have been due to the impact of a giant meteorite.

On a moderately large-scale map it is seen that over most of its length the arc is characterized by a screen of off-shore islands of which the most important are the Nastapoka Islands, a chain over one hundred miles long of average latitude 57°. Geological studies of the Islands (Bell, R, 1877-78 ; Low, A. P., 1900; Kranck, E. H., 1950) have indicated that they are composed of Precambrian sediments, which sometimes extend to the mainland and throughout the length of the arc the sediments dip radially inward toward the centre at angles of a few

FIG. 12. Aerial view of Mecatina Crater. This may be an ancient crater filled with sediments later transformed into gneiss.

degrees. Studies of aerial photographs have confirmed the radial direction of dip over the entire length of the arc and they have also confirmed that in many places the sediments extend to the mainland where it is often possible to see the contact between the sediments and the granitic rock of which the mainland is largely composed. When observed from a low flying aircraft, the seaward dip of the sediments is a very striking phenomenon and, considered in connection with the above geological and photographic evidence, suggests the existence of a deep circular basin in which great depths of sediments may well have been deposited. In addition to the off-shore islands already mentioned, there are numerous other islands nearer the centre of the circle of which the most important are the Belcher Islands south and east of the centre. Where geological information is available the islands are composed of Precambrian sediments often capped or interbedded with lava flows. It appears that in contrast to observations on the border of the arc, the sediments on the more central islands are in general either flat lying or folded and do not correspond in dip to those on the arc (Jackson, G. D., Private communication). In addition to the evidence for volcanism on the islands, lava flows are also a feature of certain areas of the mainland near the coastal arc.

On the landward side of the arc, hills normally rise to a height of several hundred feet; in places near Richmond Gulf the elevation is 1,500 ft. above sea-level and this is suggestive of an ancient and eroded crater rim. The incompleteness of the circle on the west is of course a handicap to interpretation and at present there is no evidence of a continuation, under water, of the visible features of the arc. It may be remarked however, having regard to the very great age of the feature (600,000,000 to 1,000,000,000 years) that it would indeed be surprising if it had remained completely intact over such an immense period of time. If this is truly a fossil meteorite crater we are fortunate in having such a substantial proportion of it remaining for study.

There is a rather striking parallel between this feature and the well-known feature known as Mare Crisium on the Moon. Mare Crisium is an oval to circular feature of average diameter 318 miles and depth 8,000 ft. with what is believed to be a lava floor. Although measures of altitude are not available for the rim it is clear that the feature is surrounded by hills which rise to a height of several thousand feet. When the phase of the moon is such that the sunlight terminator bisects Mare Crisium its resemblance to the Hudson Bay arc is quite striking. Unfortunately the size of the Hudson Bay feature and its great age are formidable obstacles to investigation. It would appear logical to look for a lava floor under the sediments but their assumed great depth (3,600 ft. near the coast and presumably much greater further out) would make drilling very expensive. It is also quite probable that consolidation and alteration of the sediments would make it difficult by geophysical methods to establish the existence of a boundary with the basement. In spite of these difficulties it is hoped to undertake gravity, magnetic and seismic work in the area as soon as facilities are available for making measurements of this kind at sea.

7. *Gulf of St. Lawrence Arc.*—Long. 63° 03′, Lat. 47° 00′. A configuration somewhat similar to the Hudson Bay arc though smaller (180 miles in diameter) is outlined by parts of the coast-lines of Nova Scotia and New Brunswick in the Gulf of St. Lawrence. Prince Edward Island and the Magdalen Islands lie within the circle and the somewhat roughly outlined arc subtends a sector of over 180°. Seismic observations within the circle have indicated the presence of sediments of a depth of approximately 6 km. This result is not unfavourable to the meteoric hypothesis but much more extended observations will be required before it will be possible to reach any definite conclusion.

8. In addition to the circular features described above there are a number of circular lakes or bays scattered throughout Canada which for one reason or another (*e.g.*, excessive depth, evidence of shattering around the shore-line or simply unexplained incongruity with their surroundings) are listed as possibilities in the continuing search for old craters. These include Lac Couture, Long. 75° 20′, Lat. 60° 08′, diameter 10 miles; West Hawk Lake, Long. 95° 12′, Lat. 49° 46′, diameter 3 miles; Keeley Lake, Long. 108° 08′, Lat. 54° 54′, diameter 8 miles and Ungava Bay, Long. 67° 20′, Lat. 60° 00′, diameter 150 miles.

In listing these features and the ones described under 1 to 7 above it should be very definitely understood that they represent interesting possibilities worthy of further investigation but cannot yet be presented as probable fossil craters to be included in the statistics of earthly as compared to lunar features. It will no doubt be many years before the true nature of these objects is fully understood. In the meantime it is hoped that publicizing the locations will encourage the necessary investigations by geologists, geophysicists and others interested in meteoritic phenomena.*

Cryptovolcanic Structures.—Any discussion of fossil meteorite craters would be incomplete without some mention of cryptovolcanic structures since it was in connection with these fascinating objects that the actual existence of fossil craters was first suggested. The term cryptovolcanic was first used by Branca and Fraas (1905) in connection with the Steinheim Basin (Long. 10° 04′ E, Lat. 48° 1·5′ N) in Southern Germany. This feature, which is typical of other similar objects of various sizes is a ring-shaped depression 1½ miles in diameter with a present depth of approximately 260 ft. below the surrounding plain. In the centre of the structure is a low hill 130 ft. high on the slopes of which part of the town of Steinheim is located. Much of the feature is obscured by the deposition of sediments (both consolidated and

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* *Lonar Lake:*—Lonar Lake in India (Long. 76° 51′ E, Lat. 19° 59′ N) is a circular feature slightly more than a mile in diameter and 400 ft. deep. Geologists who have examined it have attributed it to a volcanic explosion but specific evidence for volcanism appears to be lacking. Its circular form and raised rim suggest a meteorite impact origin and it may well be due to this cause.

See Medlicott and Blandford, *A Manual of the Geology of India*, Part 1, 1879.
Blandford, *Records of the Geological Society of India*, 1870, 1, p. 63.
Newbold, *Journal of the Royal Asiatic Society*, 1846–48, 9.

unconsolidated) but the essential features seem to be (1) the ring-shaped depression, (2) the central hill, the rocks of which appear on the basis of geological evidence to have been carried some 500 ft. above their normal level in disordered and shattered blocks, (3) intense brecciation extending to the outer edge of the disturbance. In suitable exposures the beds are seen to be broken and tilted in diverse directions and in places are so completely shattered that every trace of original bedding is lost.

Although no traces of volcanic materials have been reported it has been generally assumed that this and similar features later discovered by Bucher (1933) are due to concealed volcanic explosions, hence the term cryptovolcanic structure. Locations and diameters of circular features resembling the Steinheim Basin are shown in Table II.

TABLE II
Cryptovolcanic structures

Name	Location	Diameter (miles)
Steinheim Basin ..	10° 04′ E, 48° 1·5′ N South Germany	3
Ries of Nordlinger	10° 37′ E, 48° 53′ N South Germany	15
Jeptha Knob ..	85° 6·5′ W, 38° 6·4′ N Kentucky, U.S.A.	2
Serpent Mound ..	83° 25·2′ W, 39° 1·7′ N Ohio, U.S.A.	4
Upheaval Dome ..	109° 56·6′ W, 38° 27·7′ N Utah, U.S.A.	3
Wells Creek Basin	87° 39·5′ W, 36° 23′ N Tennessee, U.S.A.	6
Flynns Creek Structure	85° 37·4′ W, 36° 16′ N Tennessee, U.S.A.	2
Decaturville Structure	92° 4·5′ W, 37° 53·8′ N Missouri, U.S.A.	Uncertain
Kentland Structure	87° 23·5′ W, 40° 45·4′ N Indiana, U.S.A.	do.
Crooked Creek Structure	91° 23′ W, 37° 50′ N Indiana, U.S.A.	3

While there is a good deal of diversity among these various objects, investigation of those discovered in the United States indicate that in general they depart somewhat from the circular form and this quality of asymmetry may have something to do with their origin. Another indication which may also be diagnostic is the existence of an outer ring which, with the inner circular depression, has been compared to a system of damped waves associated with an explosion.

The suggestion that the original disturbance which formed what is now the Steinheim Basin was the impact of a meteorite was originally put forward by Rohleder, H. P. T. (1933). Later Boon and Albritton (1936, 1937, 1942) discussed the character of the underground structures likely to be formed by meteorite impact and suggested that cryptovolcanic structures were the remains of ancient meteorite craters. Similar views were put forward by Dietz (1946) and Baldwin (1949) in their classic work on lunar and terrestrial craters. More recently, as a result of geological investigation and drilling at the sites of the Wells Creek Basin, the Kentland structure and the Crooked Creek structure, Wilson (1953), Dietz (1959) and Hendricks (1954) have concluded that some, if not all, of the cryptovolcanic structures find their most logical explanation in meteorite impact. Wilson has called attention to the presence of large quantities of rock breccia and to massive deformations of sedimentary beds around the margins of the Wells Creek Basin and the Flynn's Creek structure in Tennessee, while Hendricks has found similar evidence in connection with the Crooked Creek structure in Missouri. In addition Wilson has had the opportunity to log a diamond drill hole 2,000 ft. deep in the centre of the Wells Creek Basin where he found ample evidence of brecciation and fracturing but no indication of volcanic action. Dietz has examined most of the known cryptovolcanic structures in Europe and North America and has found shatter cones associated with them indicating that the impact which caused them came from above rather than below.

Comparison of Impact and Volcanic Hypotheses on the Basis of Pressures Involved.—Of special interest in connection with cryptovolcanic structures is a comparison of the physical effects from a meteorite explosion and the explosions associated with the build-up of steam and magmatic pressures where volcanic activity is at hand.

The basic fact is that in the meteorite impacts, as in the underground nuclear detonations, the stress wave communicated to the ground starts off with pressures of many megabars (10^6 atmospheres). Such pressures are not attained lithostatically in the Earth except at depth of 2,500 km. or more below the surface (Bullen, 1947). In other words for a steam or magma explosion to build up to the pressures comparable with that of a meteorite striking at a speed of 10-30 km./sec. (Whipple, 1955) would make it possible to lift the whole of the Earth's mantle. It is clear that any such volcanic activity occurring near the Earth's surface would have vented long before the pressure reached these values. (Even at the depth of the Mohorovicic layer the lithostatic pressure is only a few per cent. of a megabar.)

It follows that the identifiable features of a meteorite explosion, *i.e.*, pressures capable of producing physico-chemical phase changes near the point of impact and crushing and fracturing at increasing radial distances from the centre should be distinguishable from those in the neighbourhood of volcanic pipes. In particular it appears that for volcanic explosions both theory and observation indicate that intense brecciation is pretty well confined to the area of the vent where the explosive volcanic forces burst through the Earth's surface and does not as in the case of meteorite impact, extend into the country rock to distances of the order of 10-20 times the diameter of the exploding body. It seems probable therefore that detailed gravity observations combined with diamond drilling techniques should eventually make possible a definite decision as to the origin of cryptovolcanic structures.

Summary

Summarizing the results to date of the search for fossil meteorite craters, the most important advance is clearly the establishment with a high degree of probability of the existence of three fossil craters of large size and sufficiently great age to justify the belief that others are likely to be found if a sufficiently exhaustive search is made for them. Secondly the location of a considerable number of circular features in Canada, for which no other explanation has been found, leads to hopes that at least some of them may turn out to be the result of meteorite impact. Thirdly recent evidence suggesting a meteorite origin for certain cryptovolcanic structures in the United States emphasizes how important it is to make further investigations of these enigmatic objects. While it may be that not every feature classified as cryptovolcanic is due to the same cause, nevertheless, if by diamond drilling and geophysical techniques a definite positive or negative result could be obtained for a representative selection of these objects, it would do a great deal to clear the air in the further search for fossil craters.

Finally the results of the study of aerial photographs has clearly indicated that the best hope of future progress in this field is the extension of a systematic search over as large an area of the Earth's surface as possible. The wide aerial photographic coverage which now exists in many countries, and which is being rapidly increased, represents a golden opportunity to make a decisive contribution to this branch of astronomical-geophysical science. It is to be hoped that astronomers and others interested in this problem will make increasing use of this opportunity to extend our knowledge in a field which is important not only to the early history of the Earth, but also to a clearer understanding of the physical relationships between members of the solar system.

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NATIONAL PHYSICAL LABORATORY (ENGLAND): ANNUAL REPORT FOR 1959*

THE wide range of research topics in modern physics covered by the work of the NPL is described in the latest Annual Report of the Laboratory.

In the new Basic Physics Division the programme has been aimed at investigating different aspects of the Physics of polymers, by means of the most modern techniques for examining the atomic structure of matter. Success in understanding how the atoms are held together in plastics and other polymers, and how these arrangements of the atoms define their mechanical, electrical and thermal properties would have far-reaching consequences.

The programme of the Aerodynamics Division covers many aspects of research of importance to future aircraft and missile design and development. The phenomena of buffeting and aileron buzz, which decrease the safety and controllability of aircraft when they occur, have been studied. As a result means of suppressing these effects have been suggested.

The Standards Division has continued to foster international collaboration in several fields. Determination of the density of mercury has been completed by measurements on samples from the standards laboratories of Australia and the US. A start has been made on correlating UK and US time and frequency services. The scale of temperature between 10° K and 90° K defined by the platinum resistance thermometer has been related to the thermodynamic scale by means of a helium gas thermometer. Comparisons are being made with the US and Russia, with the intention of extending the International Temperature Scale below its present lower limit.

Spectro-radiometric methods have been tried successfully by the Light Division for the first time in the establishment of the standard scale of colour temperature.

The Metallurgy Division which is now equipped with some of the best modern research tools available for the study of metals (including an electron microscope, soft X-ray spectrograph, mass spectrograph and optical spectrograph), is bringing these modern techniques to bear on some of the problems associated with precipitation processes in iron. It is now possible, by using the electron microscope, to see dislocations (*i.e.*, the faults in the atomic planes which weaken metals by one hundred to a thousand times).

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