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EVIDENCE FOR THE IMPACT ORIGIN OF LAC COUTURE

C. S. Beals, M. R. Dence and Alvin J. Cohen

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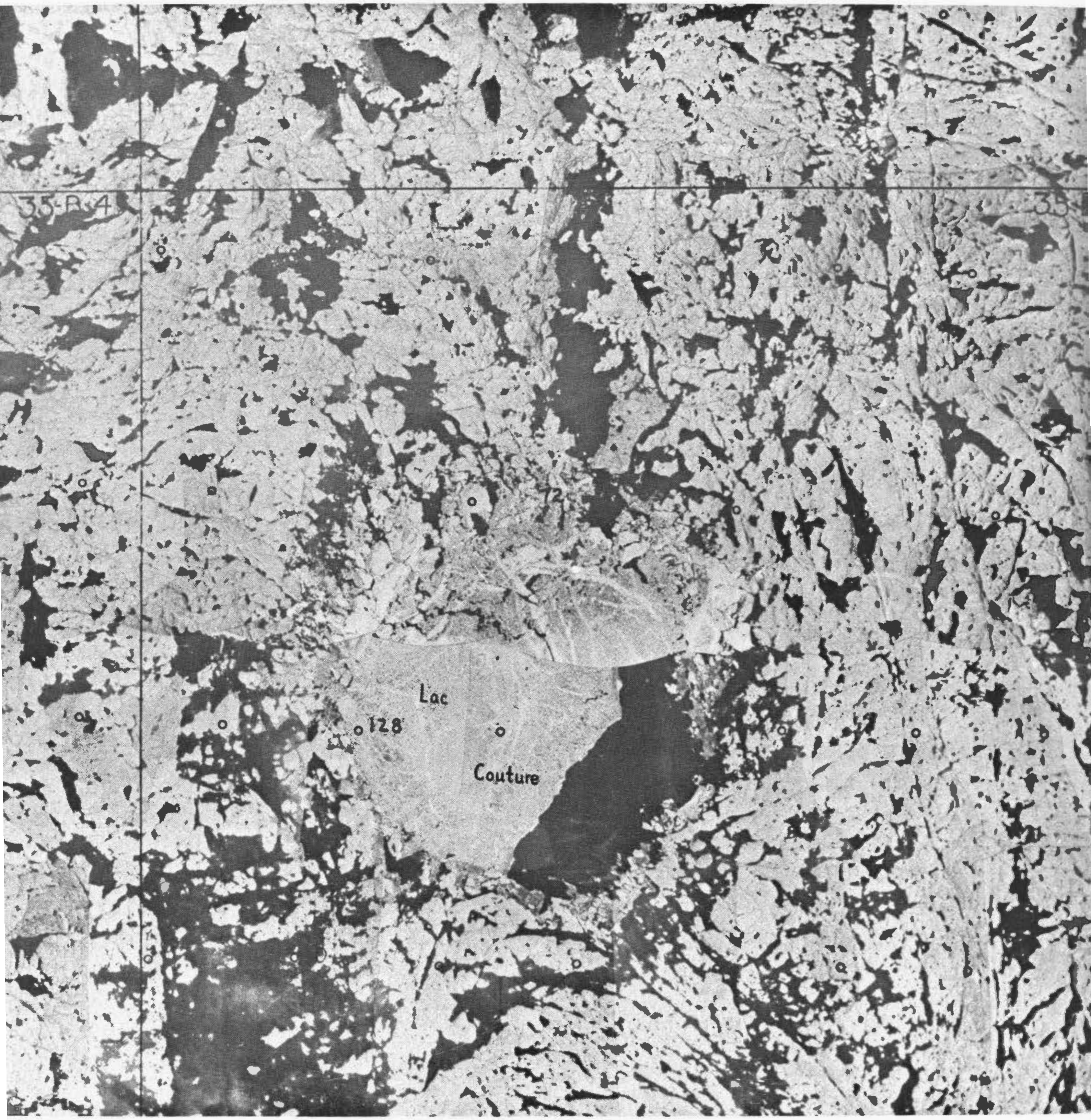

FIGURE 1. Aerial mosaic of Lac Couture; islands partly obscured by floating ice.

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C. S. BEALS, M. R. DENCE AND ALVIN J. COHEN

ABSTRACT:—Lac Couture is a circular lake of diameter 16 km with a central island-free area of 10 km diameter and depth 150 metres. The central deep area is surrounded by a shallower zone characterized by numerous islands and peninsulas all of which show marked indications of glacial action, the direction of ice movement being from east to west.

An examination of the bedrock of the islands showed many locations of heavy shattering and other indications of disturbance with sheeting planes and joints departing from the usual horizontal-vertical pattern common to areas surrounding the lake. Most of the islands and peninsulas examined showed numerous boulders and other types of glacial debris and on a number of islands on the westward side of the lake this debris included large quantities of rock breccia of the type normally associated with meteorite impact. Since the direction of glacial motion was from east to west and since no other explanation could be found for the breccia it was concluded that it had been dredged from the lake bottom by the moving ice.

Mineralogical examination of breccia fragments indicated the presence of numerous crystals deformed and altered by heavy shock. The evidence suggests an ancient and eroded impact crater of 12 km diameter of which the circular fringe of islands and peninsulas represents the remains of the rim, formerly several hundred metres in height.

RÉSUMÉ:—Le lac Couture est un lac circulaire, d'un diamètre de 16 km et dont la partie centrale est dépourvue d'îles. Cette partie, d'un diamètre de 10 km et profonde de 150 mètres, est entourée d'une zone moins profonde, caractérisée par l'existence de nombreuses îles et presqu'îles qui toutes portent les indices évidents d'une action glaciaire, la glace ayant cheminé de l'est à l'ouest.

En étudiant la roche saine des îles, les auteurs ont constaté qu'elle a été fortement fragmentée en bien des endroits. Ils ont relevé d'autres indices d'accidents tectoniques: les plans de structure en gros bancs et les joints n'ont pas pris la position horizontale-verticale qui est ordinaire dans tous les environs du lac. Dans la plupart des îles et presqu'îles, on a vu de nombreux blocs erratiques et d'autres vestiges de l'action glaciaire. Parmi ces vestiges, sur plusieurs îles du côté ouest du lac, se trouvaient beaucoup de brèches rocheuses du genre qu'on attribue généralement à la chute d'une météorite. Étant donné que la glace a cheminé de l'est à l'ouest, et qu'on n'a pu expliquer l'existence de la brèche autrement, on en a conclu que la glace mouvante l'a façonnée par rabotage au fond du lac.

Au point de vue minéralogique, on a constaté que les fragments de brèche renferment de nombreux cristaux déformés et altérés par un choc brutal. Il faut donc croire qu'il s'agit d'un cratère météoritique ancient et érodé, d'un diamètre de 12 km et dont la bordure circulaire d'îles et presqu'îles représente tout ce qui reste d'une margelle autrefois haute de plusieurs centaines de mètres.

Introduction

The possibility that Lac Couture, Quebec (long. 75°20′W, lat. 60°08′N) might have an origin entirely different from most of the lakes in the Canadian Shield was first suggested by an examination of the 8-mile map sheet 35 SE published in 1955*. A more recent edition of this map is contained in the pocket in the back of this publication. On this map it will be seen that the lake is of roughly circular form with a diameter of the order of $8\frac{1}{2}$ miles (13 km) with a shoreline characterized by numerous inlets which extend its dimensions in certain directions from 16 to 18 kilometres. The most striking feature of the lake is a central island-free area of about 10-km diameter surrounded by a fringe of islands and peninsulas which give it a unique and artificial aspect suggestive of some unusual mode of origin.

An aerial mosaic of Lac Couture is shown in Figure 1. This mosaic emphasizes its circular outline but unfortunately the lake was full of floating ice at the time the photographs were taken so that the details of islands and promontories are obscured. Figure 2 shows the same mosaic with the ice blocks painted out while Figure 3 is a map of the lake originally drawn to a scale of one mile per inch. This map shows in considerable detail the islands and the irregularities of the shoreline as well as the numerous lakes in the surrounding country.

*The New Quebec Crater (long. 73°40′W, lat. 61°17′N) Meen 1950, 1957, and Millman, 1956, also appears on this map.

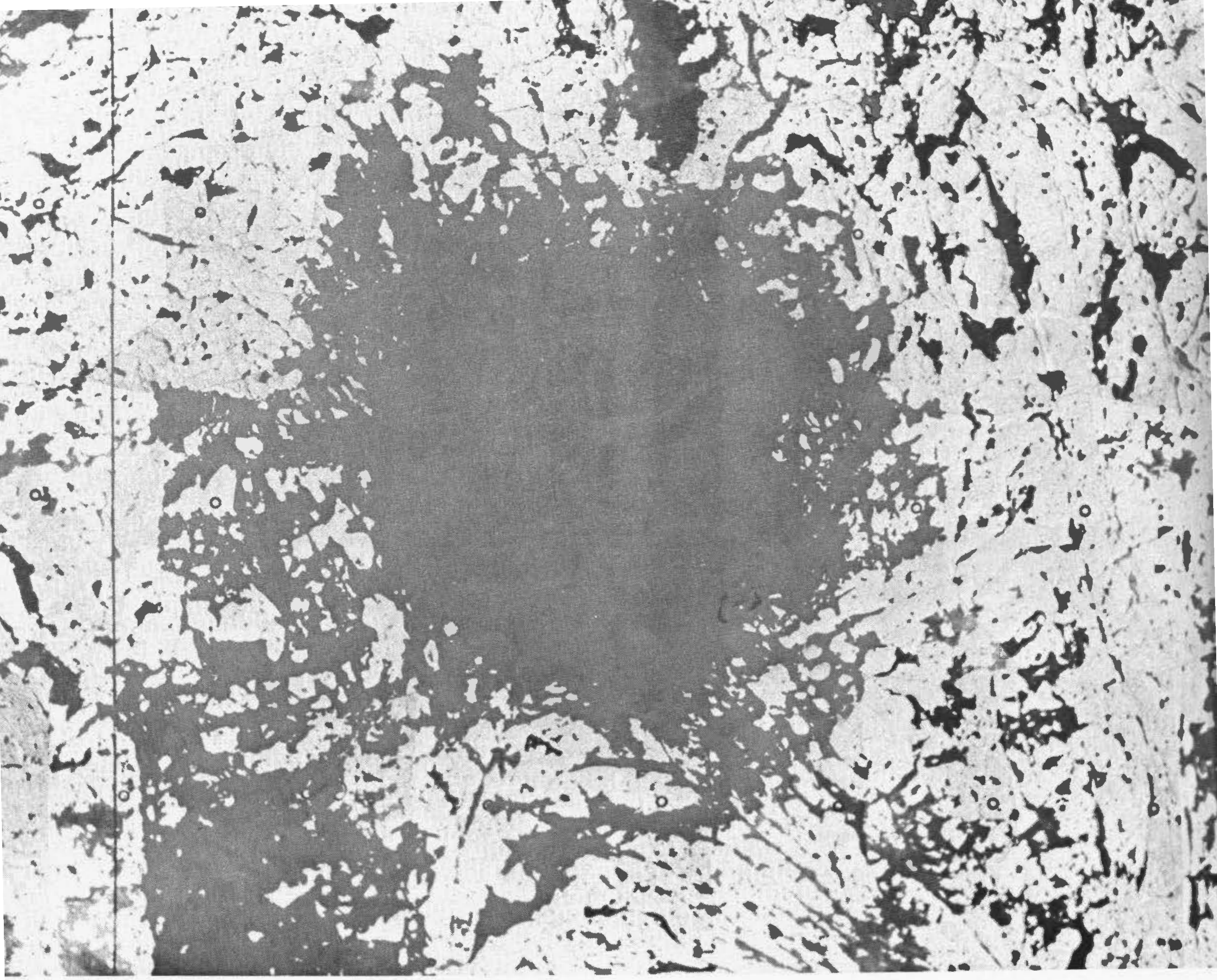


FIGURE 2. Same as Figure 1 with ice painted out to show distribution of islands.

Superimposed upon the map is a depth traverse in an approximately north-south direction indicating maximum depths of 120 metres. The depth traverse was carried out by R. K. McConnell and J. G. Tanner in connection with a gravity survey of this general area in 1959 and 1960. The measurements were made from a Beaver aircraft which was taxied across the lake using a simple mechanical depth sounder and dead reckoning positions. The accuracy was sufficient to show clearly the considerable variations in depth along the traverse and the fact that the greatest depths were not in the centre of the lake. This recalls a similar situation in the Deep Bay Crater (Innes *et al.*, 1964) where the deepest area consisted of a kidney-shaped depression southeast of the centre, possibly gouged out to that shape by glacial action. As in the case of Deep Bay the measured depths of Lac Couture indicate a lake much deeper than is ordinarily found in the Canadian Shield but shallow relative to that of an impact crater of this size. Indications of a rim remnant are found in the islands and peninsulas surrounding the lake, a part of a crater more likely to be subject to erosion than the unshattered mainland area farther from the centre.

The sum total of the preliminary information about Lac Couture outlined above indicates a definite possibility that this lake may be the remains of a very ancient impact crater nearly filled with sediments and/or glacial debris with its rim almost entirely removed by erosion. It was accordingly decided to carry on

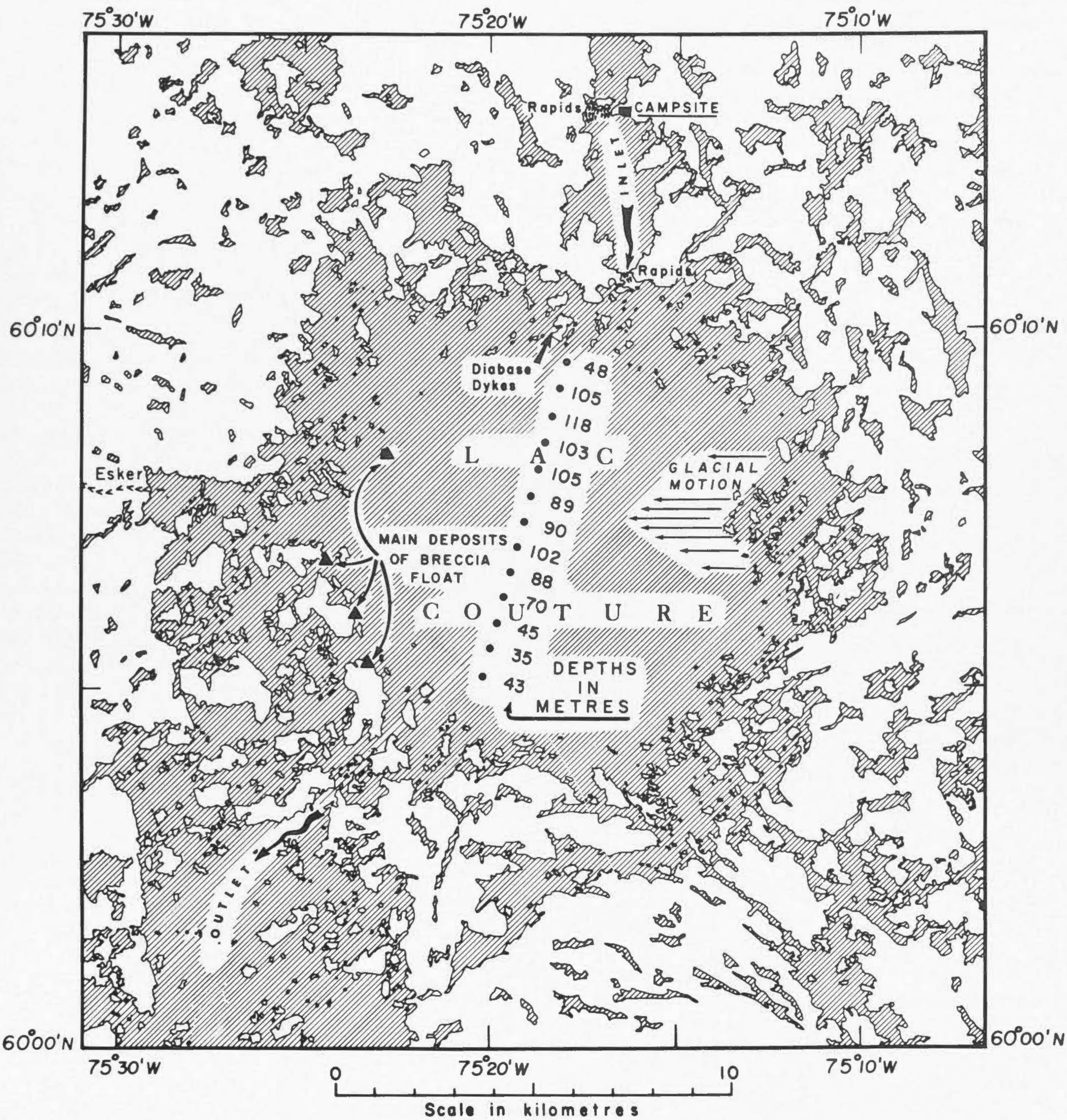


FIGURE 3. Map of Lac Couture showing depths, glacial motion and breccia locations.

further investigations of the crater and to search for additional evidence which might confirm or deny these tentative conclusions.

Field Expedition to Quebec Crater Sites

The first opportunity to do this was provided by an expedition to northern Quebec organized by the Dominion Observatory in August 1963 for the purpose of studying a number of crater sites of which Lac Couture was one. The party consisted of C. S. Beals and M. R. Dence of the Dominion Observatory, Alvin J. Cohen of the Department of Earth and Planetary Sciences, University of Pittsburgh, Geoffrey Charlewood of Heath and Sherwood Drilling Co., and the pilot of the aircraft, Paul Saunders. Transportation was provided by a two-engined Grumman Goose amphibian of Laurentian Air Services with seats for five persons plus considerable additional space for carrying equipment. Arrangements were made for the pilot and the plane to remain with the party throughout the trip and the mobility thus provided proved to be of the greatest value to the whole operation. Although the plane was a little large for some of the numerous island landings required, this was more than compensated for by the skill of the pilot in manœuvering his craft and by the comfort of the seats and the relative quietness of the engines which made possible long flights without excessive fatigue. A feature of the plane which proved very valuable was the window beside the seat of the co-pilot, normally occupied by a passenger. When the window was open there was no draft from the slip stream and while the aeronautical implications of this were not entirely clear to us, we took full advantage of it in taking photographs and making direct visual observations of the ground below.

Leaving Ottawa on August 1, 1963, the party travelled north to James Bay via the Nottaway River and up the coast of James Bay and Hudson Bay to Great Whale River which was reached in late afternoon. Since one major objective of the expedition was to observe the island chain hugging the east coast of Hudson Bay from Long Island in the south to McCormack Island, Elsie Island and Portland Promontory in the north, the trip was resumed the next morning, following the coast as far north as Povungnituk. Most members had not flown this route before and were impressed by the magnitude of the rivers flowing into James Bay and Hudson Bay (particularly the Fort George River or Grand Rivière and Great Whale River) and the scenery on the east coast of Hudson Bay.

From Povungnituk, a flight of about 90 miles east brought the party to Lac Couture where a camp was set up. The site chosen was on a lake, or more precisely the enlargement of a stream leading south into Lac Couture, where there was a good landing beach and an unobstructed stretch of water for landings and take-offs. This location, indicated on Figure 3, was 11 kilometres north of the centre of Lac Couture and about 6 kilometres from the northern border of the island-free area of the lake.

Lac Couture from the Air

The aerial mosaic (Figure 1), its modification (Figure 2), and the large- and small-scale maps already mentioned give a general idea of what Lac Couture should look like from the air. Indeed experience in the study of aerial photographs has proved so valuable and the amount of information which can be gained from them is so great (particularly when suitable sequences of stereoscopic pairs are available) that it might well be questioned whether any additional information could be gained by direct visual observation. It should however be pointed out that the eye used directly does have some advantages over the camera. These include a wider instantaneous field of view, better colour perception and in our case ability to view the subject from a considerable variety of heights and angles. When to these is added the ability of a human observer to integrate, to judge and to make substantially simultaneous comparisons between the subject being studied and its surroundings, it seemed well worth while to spend some time flying over Lac Couture to study it directly from the air.

Most members of our party had had substantial previous experience in the observation of lakes of the Precambrian Shield which was valuable for purposes of comparison with Lac Couture. In addition there were, in its immediate vicinity, a number of bodies of water which might be termed generally characteristic of the Shield area which could be compared with it directly by no more than a turning of the head or a mere re-directing of the glance occupying a small fraction of a second. We flew around Lac Couture twice the first day at an altitude of about 2,500 feet and during the next four days numerous flights were made over the lake at different altitudes in order to reach the various islands and shorelines to be studied from the ground. Some photography was done but in view of the coverage already existing, this was subordinated to direct visual observations.

The first impression of Lac Couture, gained on a day when the illumination was good with light fleecy clouds reflected in the water, was that of a very fine visual spectacle of a kind often met with in the Canadian Shield with numerous islands dotting a broad water area having an irregular shoreline. Looking more carefully, the essentially circular shape of the shoreline gradually separated itself from the irregularly distributed inlets and indentations. One very large extension of the lake to the southwest somewhat interfered with this impression but the massiveness of the peninsulas and islands separating the two units carried the line of circularity around and left it reasonably intact. The next and most vivid impression was that of the broad circular island-free area in the centre of the lake outlined by some hundreds of islands of sizes ranging from a mile or more across to sizeable rocks projecting above the surface of the water. The islands, like the surrounding inlets were rather irregularly distributed, being to some extent bunched together in groups separated from one another by considerable stretches of water. When the distribution was looked at as a whole however, the impression of circularity reasserted itself and it became clear that we were looking at a distribution of land and water that was unique in our experience and probably not duplicated anywhere else in the Canadian Shield.

Once established, the visual pattern struck the observer with a force far greater than any photograph. Any doubts in our minds about the exotic origin of Lac Couture were almost completely eliminated by the impact of the visual observations. Of course we were aware that no general impression, however powerful, could take the place of detailed ground observations of the kind associated with circular objects of confirmed asteroidal impact origin. As a stimulus to further observations however, the direct studies from the air had a profound effect which was of the greatest value in overcoming initial setbacks in the ground studies and encouraging persistence beyond the time which had been initially assigned to this part of the expedition.

Topography of the Islands and Surroundings of Lac Couture

Lac Couture lies in the northern part of the Superior Tectonic Province of the Canadian Shield (Lowdon *et al.*, 1962), and some 60 miles (100 km) south of the southern margin of the Wakeham Bay-Cape Smith fold mountain belt. The regional terrain is generally subdued with local relief rarely in excess of 100 feet (35 metres). Bedrock is well exposed and glacial debris is commonly restricted to a thin veneer of erratics. The main controls on the topography are the strike of the regional gneissosity; linears and steeply dipping joint sets in the gneisses; strong horizontal sheet jointing in typical development; and the last direction of glacial scour. The many small lakes and the general drainage pattern are controlled essentially by the strike of the gneissosity and the jointing, producing elongated to highly irregular, shallow bodies of water in which N-S to NW-SE trends dominate. The last glaciation moved from east to west and was mainly instrumental in moulding outcrops into typical *roche moutonnée* form. Weathering controlled by the horizontal sheeting has later modified some of these forms into step-like terraces, giving blocky profiles to many of the hillocks of the area.

Petrography of the Area

The gneisses which crop out around the lakeshore and peripheral islands are of granodioritic to quartz dioritic composition, the content of mafic material varying from less than 5 per cent to about 20 per cent. Pink, coarse-grained pegmatites of simple mineralogy occur as bands, veins and small, irregular masses cutting the gneisses. A few small diabase dykes also cut the gneisses and represent the latest event in the orogenic history of the area.

At the north end of the lake the gneisses are almost all massive, medium- to coarse-grained leucocratic rocks with less than 5 per cent of biotite and other mafic minerals. They are cut by a small swarm of northwest-trending diabase dykes up to 50 cm wide. To east, south and west the gneisses have a more emphatic foliation due to the distribution of mafic bodies, making up 10 to 20 per cent of the rock, as bands and inclusions. The mafic inclusions are predominantly medium-grained aggregates of biotite, hornblende and plagioclase. Where the banding is most pronounced many minor faults and small shears are defined. The average strike of the gneisses is north-northwest with dips in excess of 60 degrees. The southern margin of the lake corresponds to the northern closure of a major fold which is clearly defined in aerial photographs. The banding is particularly regular in the gneisses forming the fold, the alternations of light and dark material taking place over thicknesses of 2 to 10 cm.

During the late stages of consolidation of the gneisses, pegmatites of quartz, alkali feldspar, biotite and magnetite were injected to form irregular pods and veins up to 1 metre across which crosscut and locally deform the foliation. They themselves are little deformed and orogenic movement must have ceased at the time of their emplacement, save for the late injection of the diabase dykes previously mentioned.

Joints and Fractures

Observations to the north, west and east of the lake show that vertical sets of joints and horizontal sheet joints spaced a metre or more apart are common in the gneissic terrain (Figure 4a). However, on the islands and promontories of the lake margin these regular systems are not found. The joints that are observed dip at a variety of angles. At some localities (e.g. along the northern margin of the lake) regular surfaces which may correspond to the regional horizontal sheeting dip away from the centre of the lake at angles of 25 degrees or more. More severe disturbances are suggested by outcrops along the western side of the lake where joints of similar character dip at angles which approach the vertical. Figure 4b illustrates one location where jointing departs from the usual pattern.

Besides such signs of disturbance of pre-existing structures, more intense fracture zones are common on the outcrops of the peripheral islands. These fractures are less regular than the regional joints, are oriented at all attitudes and in many cases are concentrated in zones 10 to 30 cm across in which the individual fractures are 1 to 5 cm apart. Zones of this character are particularly common in the leucocratic members of the assemblage, notably in the pods and veins of pegmatites. Examples of such fractures are shown in Figures 5 and 6.

FIGURE 4. (a) Horizontal jointing of rocks at location 10 kilometres from lake centre.

(b) Disturbed area 6 kilometres from lake centre.

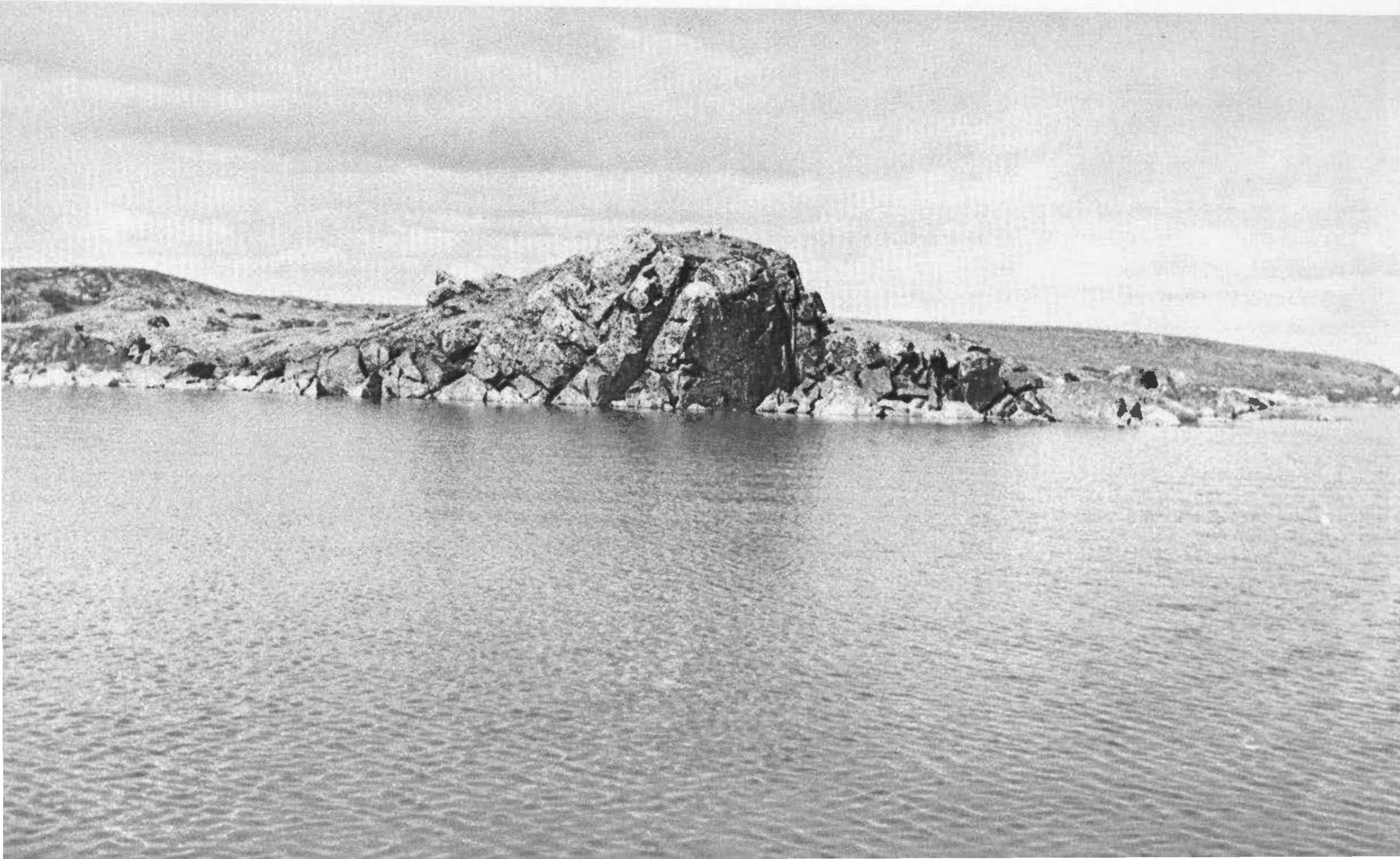
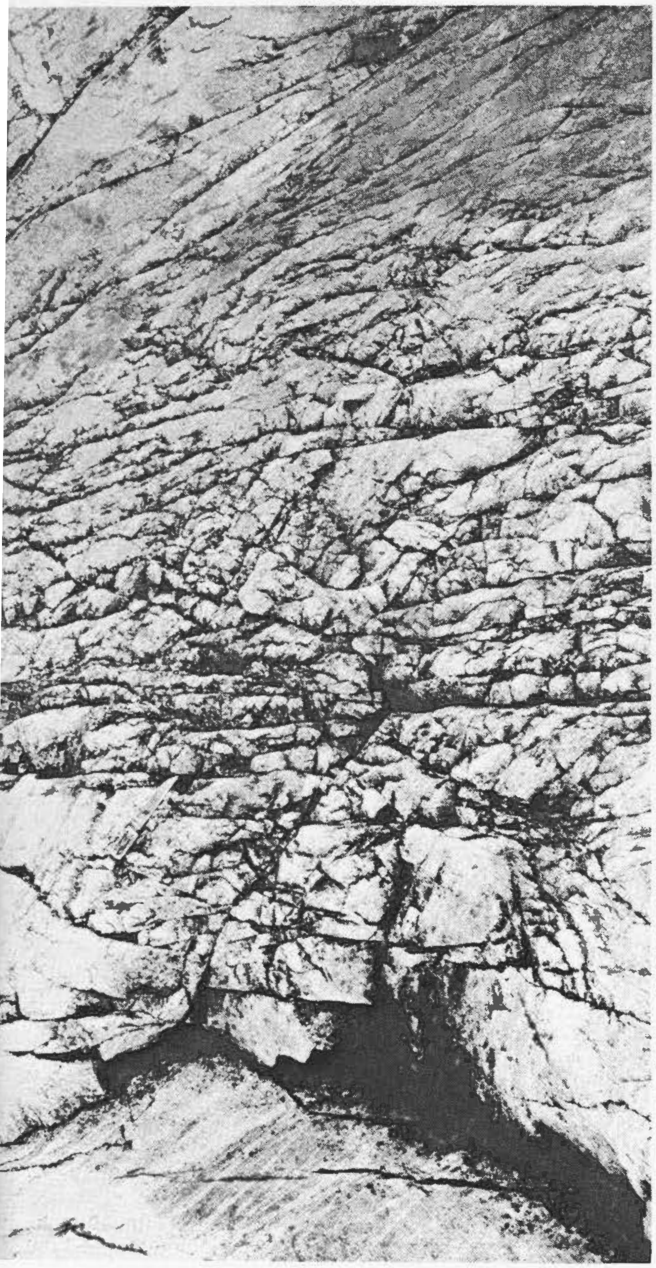
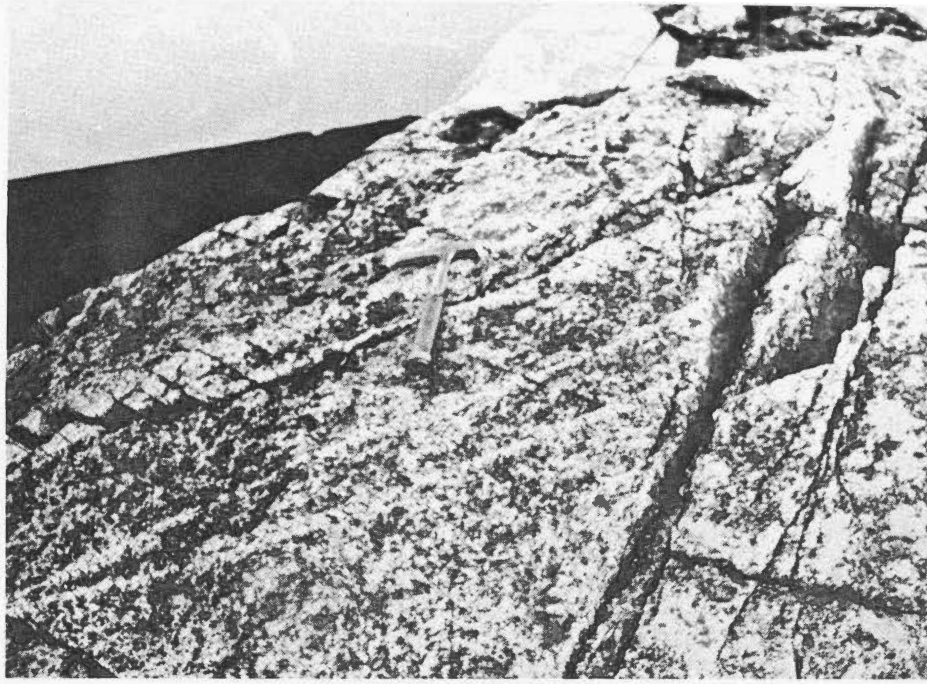
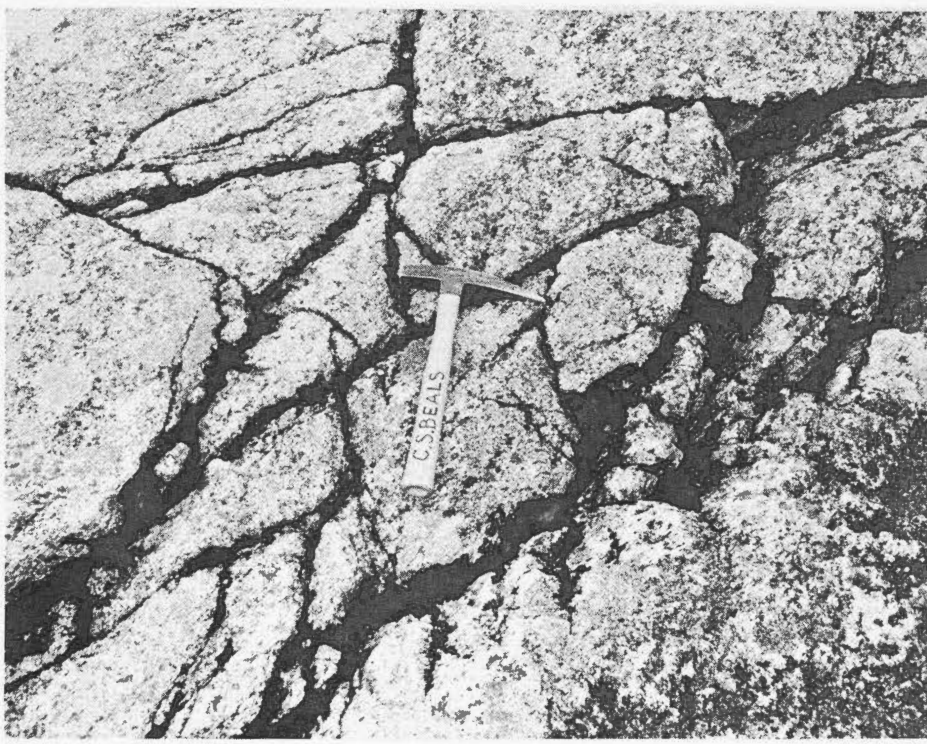
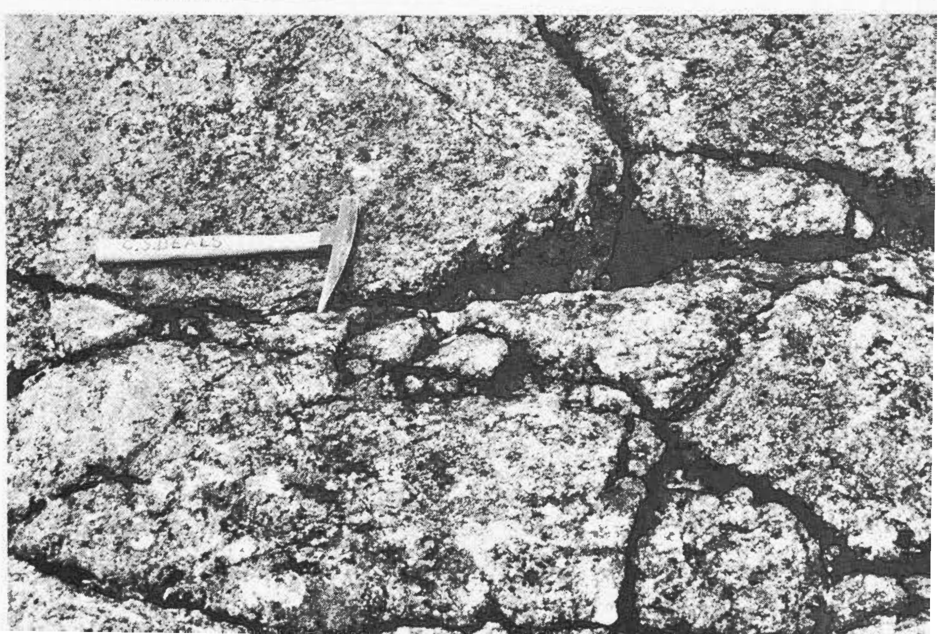


FIGURE 5.
Examples of rock shattering on islands west of lake centre.









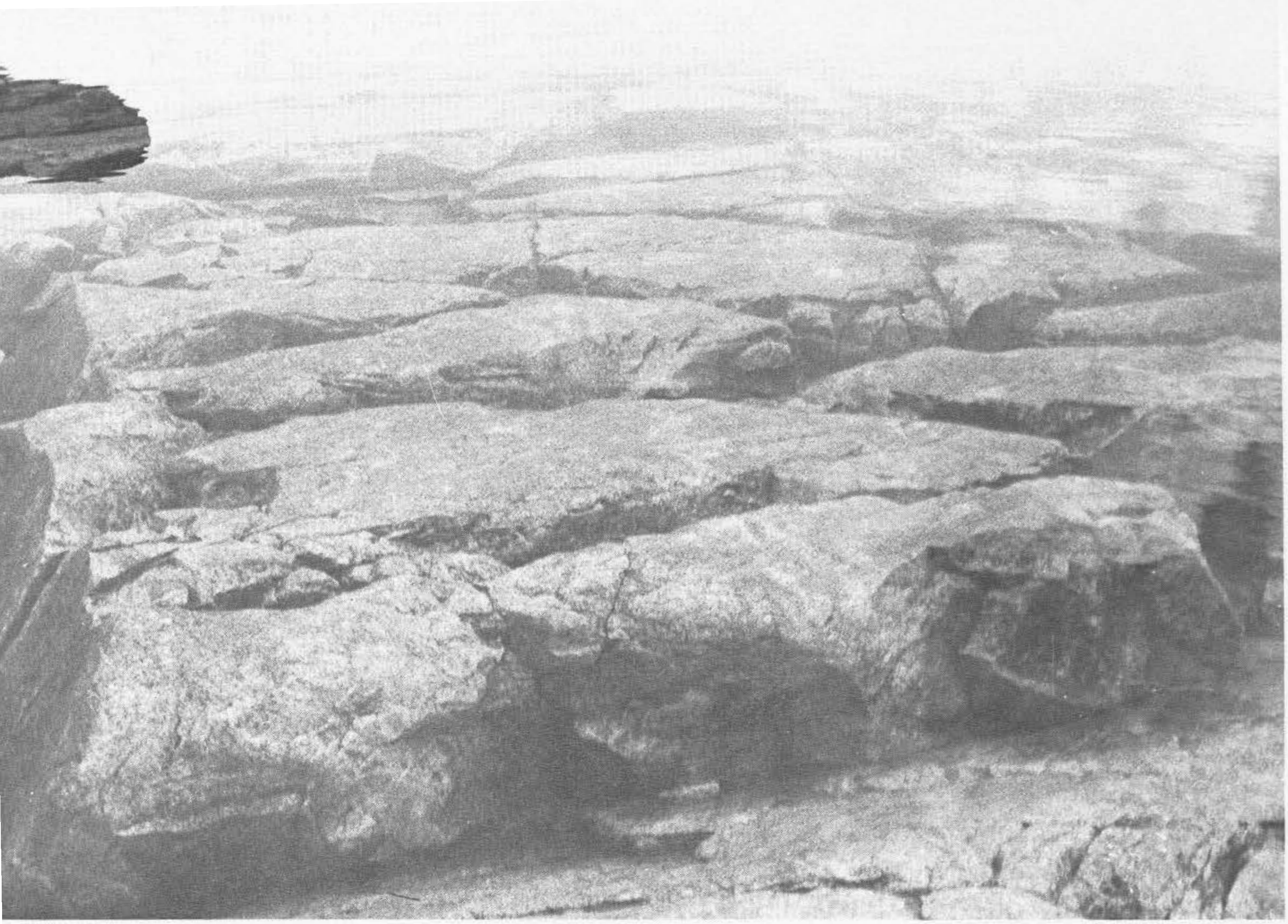


FIGURE 6. Large-scale fracturing in shallow water 5 kilometres west of lake centre.

More detailed and extensive surveys are needed to establish the degree of derangement of primary structures and introduction of later fracturing, but the observations recorded above compare closely with marginal structures from other circular structures for which a meteoritic origin has been advanced, e.g. Deep Bay and Clearwater Lake (Innes, Pearson and Geuer, 1964; and Dence, Innes and Beals, 1965).

Discovery of Breccia on the Western Islands

By analogy with other ancient Canadian craters suspected to be of meteorite origin it was expected that Lac Couture would be at least partially filled with consolidated sediments which would conceal the original crater surface. The presence of such sediments is known both from studies of surface geology and diamond drilling at the Holleford (Beals, 1960) and Brent (Millman *et al.*, 1960) craters. At the Deep Bay Crater (Innes, Pearson and Geuer, 1964) which is filled with water, the presence of sediments was suspected from the presence of Mesozoic shale pebbles and boulders located on the south shore of the lake and presumably dredged from the lake bottom by glacial action. This was later confirmed by diamond drilling near the centre of the lake which turned up shale cores similar to the specimens mentioned above as well as indicating the presence of rock breccia at the expected depths under the sediments (Innes, private communication). A similar situation existed at Clearwater Lake where numerous specimens of Palaeozoic sedimentary rocks were found on the western shores of the lake, presumably transported there by an east to west motion of glacial ice. Again the presence of sediments in this lake was confirmed by diamond drilling which succeeded in penetrating the sediments to the crater surface beneath (Dence, Innes and Beals, 1965). The same general pattern was repeated at West Hawk Lake (Halliday and Griffin, private communication 1965).

At Lac Couture, evidence for fragments of sedimentary rocks on the shorelines was lacking although, as already mentioned, heavy rock shattering and anomalously dipping gneisses were observed. What may well be the reason for the lack of sedimentary fragments was brought to our attention when numerous pebbles and boulders of rock breccia began to appear. The first finds were made at a location on an island southwest of the lake centre and consisted of a few small but very interesting breccia fragments. Later as our party moved to other locations, numerous boulders of all sizes (Figures 7 and 8f) many smaller fragments and a number of "beds" of breccia, presumably due to the disintegration of large boulders by frost action, were found. The breccia was very similar to that found in other ancient meteorite craters. A majority of the specimens showed evidence of crushing and fracturing only but some showed evidence of heating as well, offering a very complete analogy with the Holleford and Brent breccia which has been uncovered by diamond-drilling methods.

Unfortunately the time available for study at Lac Couture was limited by commitments for similar studies at Clearwater Lakes and Manicouagan so that it was not possible to make a detailed study of the distribution of breccia locations relative to their surroundings. Such studies will certainly be made in the future in connection with geophysical and other investigations of this area. However, the very unusual nature of the material, and the difficulty of accounting for it by ordinary geological processes combined with the unusual character of the lake itself already mentioned, make an association between the two highly probable. All the breccia fragments were found west of a north-south line passing through the lake centre and it seems a reasonable conclusion that they had been dredged from the lake bottom by the east-to-west movement of glacial ice. If this is the true explanation it further seems probable that Lac Couture was never filled with consolidated sediments and that this fortunate circumstance has made possible the shoreward movement of the breccia discovered by our expedition.

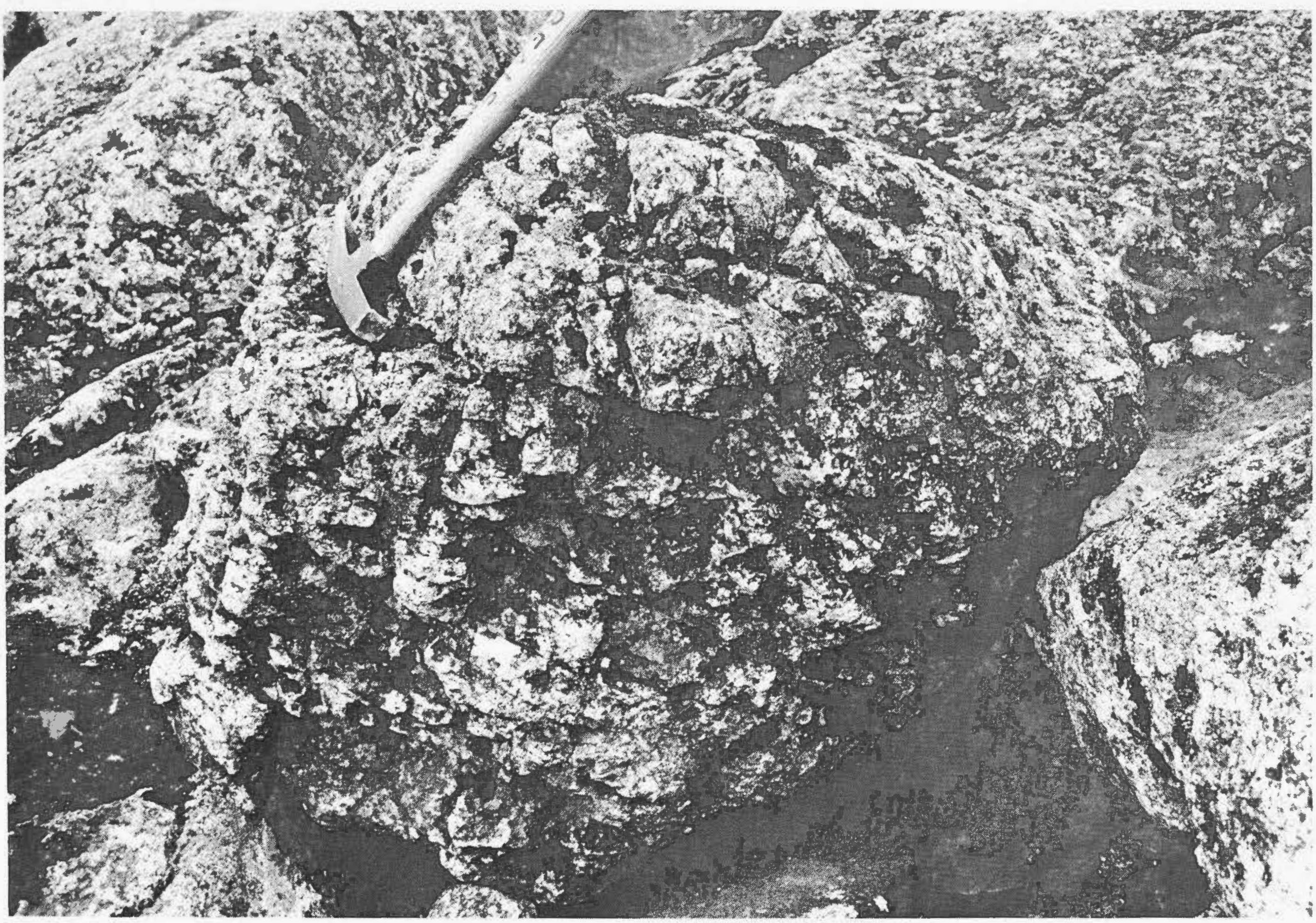


FIGURE 7. Characteristic breccia boulder on island west of lake centre.

The large size (up to 1 metre across) and the generally weak, friable nature of the boulders as shown by their tendency to disintegrate in place, makes it unlikely that they could have been transported more than a few miles and reinforces the probability that they come from the lake bottom. Again, no other possible source is known. Some of the breccia boulders may be derived from crater breccias slightly reworked to form the base of the sedimentary sequence as at Brent and Clearwater East. There is still a possibility that a veneer of basal coarse sediments may be preserved in the centre of the crater even if no representatives of finer-grained sediments remain, if they were ever present.

Petrography of the Breccia Boulders

The boulders of brecciated and altered gneiss observed at Lac Couture ranged from large, subrounded, massive blocks up to 1 metre across to small, soft platy cobbles averaging 5 cm across. It was soon apparent that the large blocks consisted of relatively unaltered fragments of gneiss up to 10 cm across in a grey-green to red-stained matrix, while the smaller erratics, more extensively altered and metamorphosed, were of medium to fine grain-sizes and varied in colour from pale grey-green to yellow and buff-pink shades. In some of the latter the groundmass was of igneous texture with small vesicles lined with quartz clearly visible. Some inclusions were chalky-white, distorted and in some cases vesicular. It was clear that while the material in general was well-consolidated it would not stand up long to continuous mechanical attrition. The boulders with fragmental matrices were generally poorly cemented and hence friable and easily broken apart, while those with partly or completely recrystallized matrices parted readily along curved joints. In many cases large boulders were found to have broken up on standing, presumably through frost action penetrating and parting the rock on planes of weakness. The exceptions were large boulders with a strong framework of well-packed cobbles of gneiss and relatively little fine-grained matrix. These proved tough and resistant to mechanical breakdown.

An effort was made to collect as broad a selection of boulder types as space and time would allow. A rough agreement was maintained between the proportion of the different varieties collected and those observed in the field, although the collection tended to be weighted in favour of the rarer types. The general field classification into massive, coarse, relatively unaltered breccias and gneiss fragments and those of fine grain-size and clearly altered or recrystallized was found on preliminary laboratory examination to be capable of elaboration into two categories of gneisses showing either weak or advanced alteration and metamorphism and five categories of breccias. The latter form a progressive series reflecting ever more severe alteration, deformation and ultimately recrystallization. The sequence is gradational and to that extent divisions are arbitrary. Nevertheless, all specimens examined to date can be assigned to one or another category with little difficulty or ambiguity, so the classification appears adequate for present purposes.

Whereas samples of gneiss collected from outcrop show only minor fracturing and alteration with the introduction of small amounts of epidote, chlorite and sericite, similar but stronger changes are seen in some gneiss fragments. One change consists of limited brecciation with development of fine-grained epidote in abundance, with chlorite and sericite also common; another of a more typically cataclastic texture. Shearing, recrystallization of quartz and deformation of primary feldspar is accompanied by development of epidote, sericite and hematite, as before.

Far-reaching metamorphism is apparent in other specimens of single gneissic fragments, which probably were large inclusions in the more highly metamorphosed breccias described below. The original distribution and relatively coarse grain-size of primary quartz, feldspar and mica is still recognizable in these specimens but original crystals are recognizable only as vague relicts. Primary crystals have been fractured and deformed and boundaries smeared. Original quartz is entirely replaced by fine-grained mosaics of secondary quartz. In a few cases primary twin lamellae in feldspars can be recognized but in general the crystals are now partly vesicular, nearly isotropic mixtures including relicts of primary domains, secondary feldspar of extremely fine grain-size and possibly some glass. Minute inclusions of epidote and iron ore are common. Biotite and to a lesser extent apatite has also been altered.

Breccias of Type I, which include the largest, coarsest and most abundant members of the breccia population, have fragments up to 10 cm across held in a matrix of the angular quartz, feldspar, mica, epidote and iron ore. They are distinguished by the extent to which their fragments bear secondary minerals (epidote, sericite) in similar development to that of the weakly altered gneissic fragments, while showing little evidence of important structural deformation. In some cases the matrix is also extensively altered and may be largely replaced by iron oxide, chlorite and epidote.

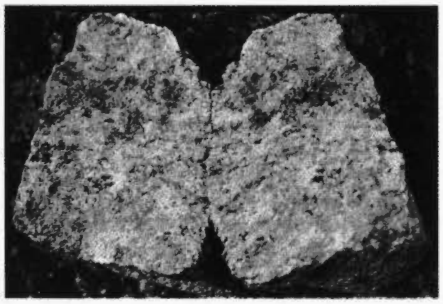
In breccias of Type II, secondary minerals, particularly epidote, are not so important as in Type I breccias, though iron oxide is again prominent. A more significant distinction lies in the more extensive deformation of individual fragments. Some granitic fragments have fracture surfaces of shatter cone type. Under the microscope, deformation of feldspar is seen to involve fracturing along irregular planes, bending of twin lamellae and the development of patchy, undulous extinction. In mica, kinking and

(a)
Grey breccia of Type I. Fragments of weakly altered gneiss in a matrix of comminuted fragments.

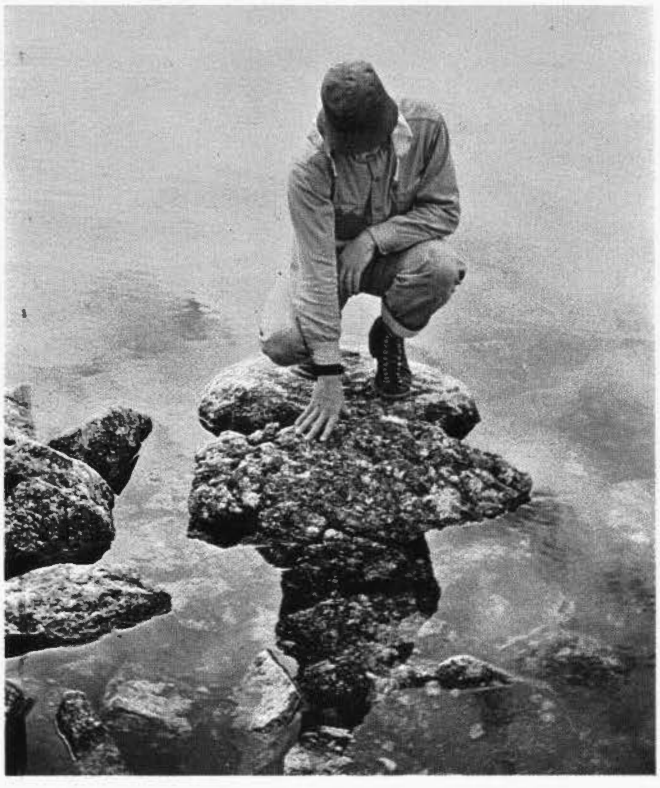
(b)
Red breccia of Type I. Fragments of weakly altered gneiss in an oxidized matrix of comminuted fragments.

(c)
Red breccia of Type II. Some fragments are strongly oxidized as is the matrix. Some quartz grains show microscopic evidence of shock with the development of planar structures.

(d)
Grey breccia of Type III. Fragments finer than in (a) to (c) and include both quartz and feldspar with planar structures and irregular shards of altered glass which weather out to give the rock a vuggy appearance.



(e) Fragment of gneiss about 10 cm across, which has been highly metamorphosed. Quartz (milky) and feldspar (white) are completely recrystallized. The rock is vuggy and porous. Dark spots are due to staining by groundwater.



(f)
Large, partly submerged boulder of breccia of Type I with fragments up to 10 cm across. The knobbly surface is strikingly different from neighbouring smooth boulders of gneiss.

FIGURE 8. Breccia specimens from Lac Couture.

bending deform some crystals. Quartz develops strong fractures, some of which follow rhombohedral crystallographic directions, but even more characteristic of many quartz fragments is the development of fine, closely spaced, parallel sets of planar structures following one or more crystallographic directions. The structures are discontinuous and appear to be fine fractures partly decorated with minute inclusions or cavities. This style of deformation is similar to that found in quartz from other craters (Dence, 1965; von Engelhardt and Stöffler, 1965), as well as in quartz shocked by underground nuclear explosions (Short, 1965). It appears to be a clear indicator of shock deformation.

Breccias of Type III include fragments in which deformation has reached the limits of intensive fracturing, lattice distortion, passage to a near-glassy state and recrystallization to an extremely fine-grained aggregate.

The fine-grained breccias of Types IV and V bear relicts of primary minerals generally less than a millimetre across in matrices of extremely fine grain-size. The inclusions show similar distortions to those of fragments in Type II and III breccias, and are surrounded by narrow coronas of minerals generated by reaction with the matrices. The latter are extensively but not completely crystalline in breccias of Type IV, while in those of Type V crystallization is general and there are numerous quartz-lined vesicles in the groundmass of minute laths of alkali feldspar and irregular crystallites of pale green mica. Part of the interstitial material may be glassy. In Figure 8 are shown colour photographs of specimens of breccias corresponding to the above descriptions. Magnified thin sections of planar features in quartz crystals and other interesting aspects are shown in Figure 9.

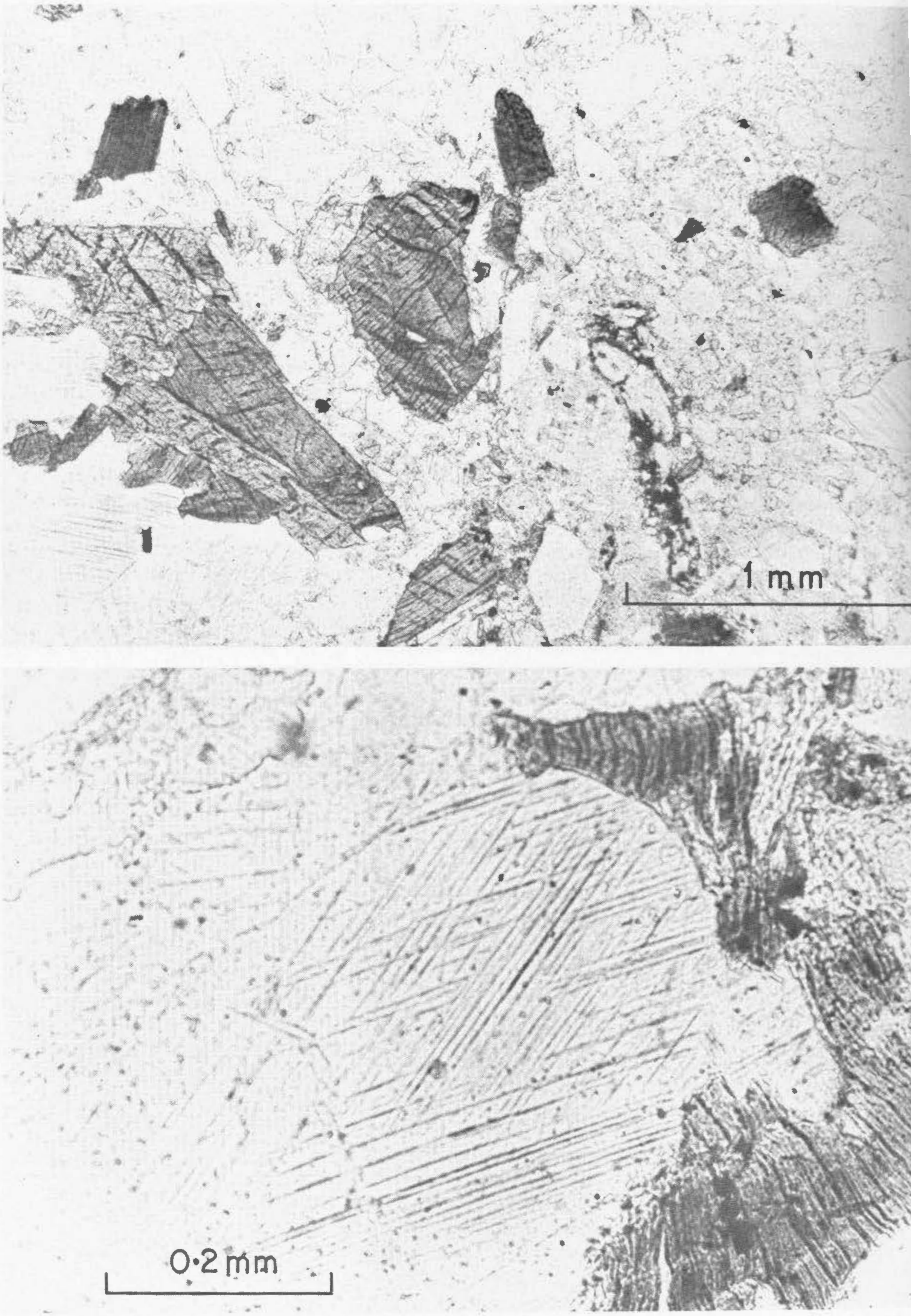
Review of Mineralogical Studies

The character of the metamorphism outlined by the sequence given above is one of progressive deformation of a distinctive style associated with thermal effects which together produce an end product which is almost completely fused and recrystallized. Metamorphism of this type has been recognized in one or more of its stages from a number of craters (Dence, 1964, 1965) including some of undoubted meteoritic origin. Emphasis to date has been placed on the spectacular and distinctive cleavage fracturing in quartz (Bunch and Cohen, 1963; McIntyre, 1961) which is a characteristic of the intermediate stages of deformation observed here. Again some of the advanced stages of feldspar lattice breakdown seen in the Lac Couture material parallel the deformation achieved by experimental shock loading to 250 kilobars and more by Milton and De Carli (1963). The shatter-cone surfaces found in some fragments are similar to surfaces observed in gneisses of similar composition and primary texture from the Carswell Lake structure and Clearwater Lake. Thus while much remains to be done in documenting the effects of shock deformation, the metamorphism at Lac Couture conforms without exception to the patterns observed in other structures formed by shock.

A further similarity to other craters of probable meteoritic origin comes from the alteration of the relatively weakly deformed rocks. Hydrothermal alteration to produce secondary minerals such as chlorite, epidote, iron oxide, sericite, carbonate, quartz and sulphides, is becoming recognized as characteristic of the rim and outer deformation zones of impact craters (Dence, 1964). It is of particular interest that the alteration at Lac Couture is dominated by epidote in the same fashion as the rim-rock alteration at New Quebec which is formed in rocks of the same age and general composition. Far from denying a meteoritic origin, as has been suggested by Currie (1965), alteration of this general character appears to be an invariable outcome of cratering produced by impact.

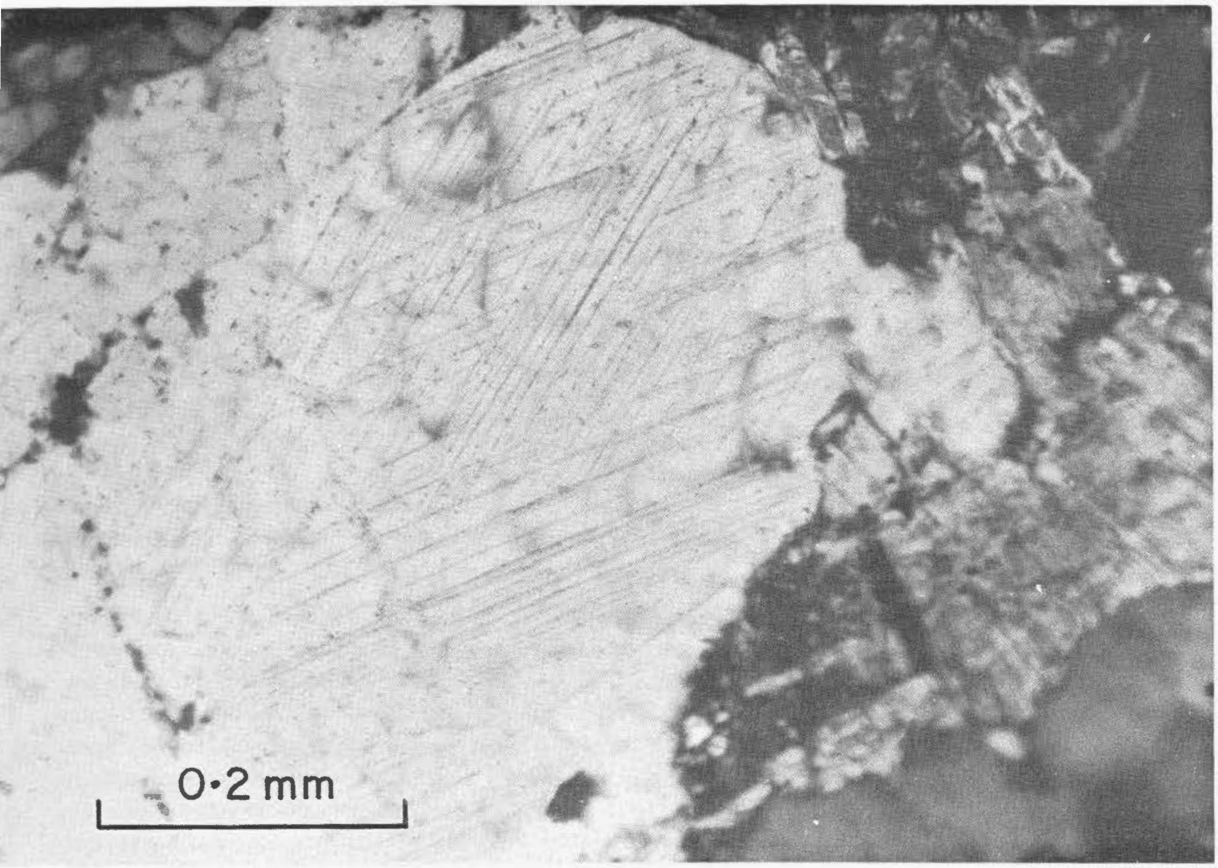
By analogy with the Brent crater (Millman *et al.*, 1961, Dence, 1964, and report in preparation) the structural position of the breccia types can be estimated. The weakly deformed gneisses and breccias of Types I, II and III are from the marginal or superficial parts of the crater. Thorough mixing is indicated by the association of weakly and strongly deformed fragments in Type II and III breccia, which in part may be the result of mixing by slumping or other essentially sedimentary processes after the crater was formed. A rude layering is evident in a few of these gritty breccias, reinforcing this possibility although in no case has significant rounding of fragments taken place. The fine grain-size of the heated breccias of Types IV and V allows comparison with the marginal portions of the vesicular layer at Brent and is an indication that erosion of the crater has penetrated as far as this layer in at least one area. The survey to date, although incomplete, does show interesting variations in the distribution and variety of breccia erratics along the western shoreline of the crater. Relatively little material was found in the immediate vicinity of the east-west diameter of the lake which agrees with the absence of types comparable with the central breccias of Brent. The greatest concentrations were about a mile to the north and south of the east-west diameter, with a particularly varied group to the south. Only there were vesicular fragments prominent. This suggests that glacial action has eroded the lake bottom more deeply in the vicinity of this southern concentration than elsewhere. The topography of the lake bottom may well show a kidney- or horseshoe-shaped depression surrounding a central hill, in similar relationship to the principal direction of glacial scour as the comparable

FIGURE 9. Photomicrographs of thin sections of Lac Couture breccia.

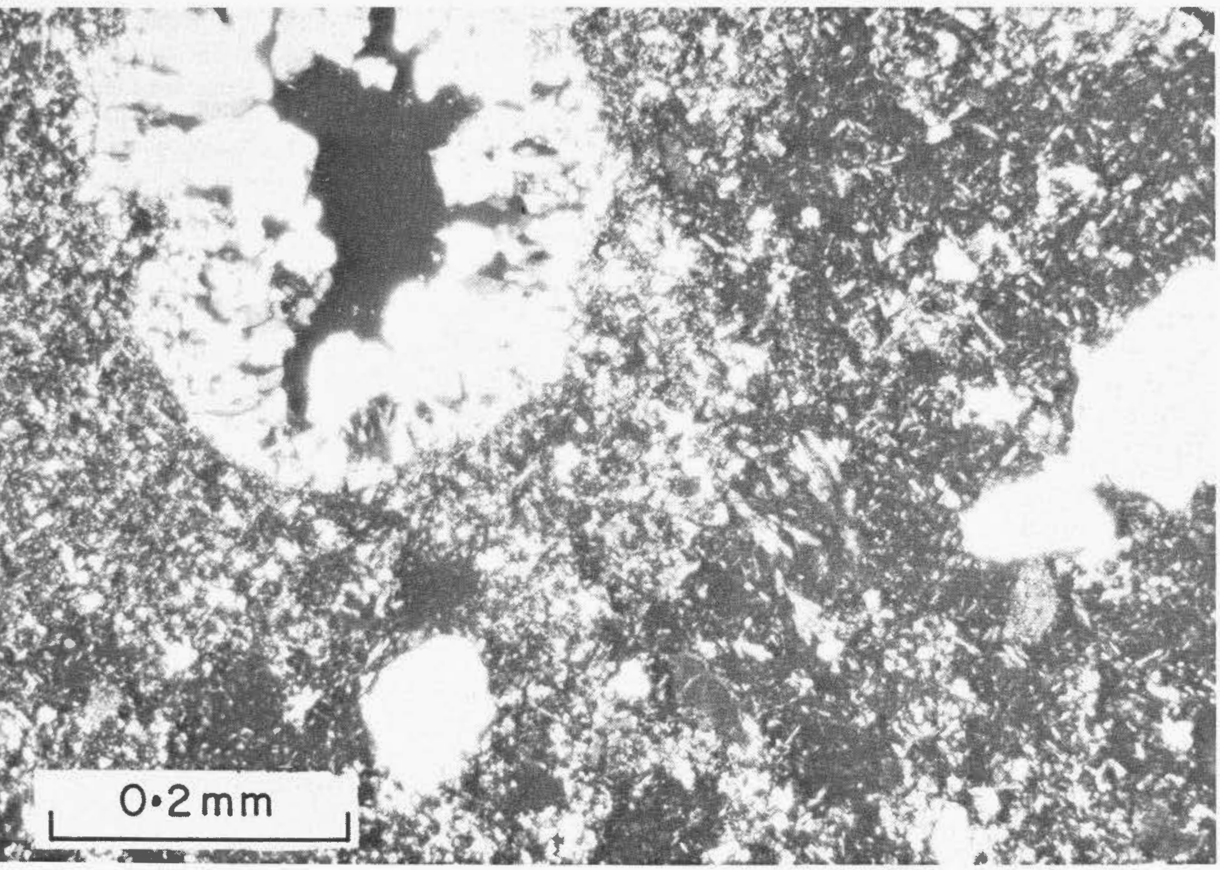


(a)
Thin section in plane light of breccia of Type II. The dark minerals are biotite mica showing well-developed kinking. Bottom left and far right are quartz grains with strong planar structures.

(b)
Detail of (a). A quartz grain in plane light showing two well-developed sets of planar structures. Associated mica is kinked.



(c)
The same as (b) under crossed nicols.



(d)
Breccia of Type V with a few fragments of quartz in a completely re-crystallized matrix of fine quartz and feldspar. The large circular structure is a vesicle partly filled with secondary quartz.

morphology of the Brent, Deep Bay, New Quebec and Clearwater Lake craters.

A further comment concerns the composition of the gneisses. Of all the Canadian craters Lac Couture shows the most restricted range in the composition of its country rocks. With few exceptions these are rocks rich in quartz and feldspar with minor biotite. They therefore have a bulk composition close to that of normal granodiorite or granite and far removed from meteoritic compositions whether stony or metallic. This encourages a particular hope that intensive search may lead to positive identification of meteoritic material even if well mixed, metamorphosed and altered. However, the most favourable site for such a search would be the centre of the crater, which can probably only be investigated by diamond-drilling methods.

General Conclusions

Reviewing the evidence collected in an attempt to ascertain the origin of Lac Couture, it may be pointed out that the initial observations of its circular shape, unusual for so large a lake and the unique distribution of islands and peninsulas around the deep, island-free central area, were suggestive of an unusual origin rather than diagnostic of the actual physical process which formed the lake. This suggestion of an unusual origin was however reinforced by the observation of extensive rock shattering on the western islands and the indications of disturbance presented by the attitudes of sheeting planes and joints on the islands and around the shorelines.

The final conclusion that the lake and its surroundings probably represent the eroded remnant of an ancient impact crater depends mainly on the observation of many tons of rock breccia on the western islands (presumed to have been removed from the lake bottom by glacial action) for which no other reasonable explanation has been found. The validity of the conclusion that the breccia was due to asteroidal impact rather than some other cause depends first on the similarity of its general character to that associated with reasonably well authenticated craters such as Holleford, Brent, West Hawk, and Deep Bay; and secondly, on the microscopic indications of crystals, particularly quartz, deformed and altered by shock in a manner so far encountered in nature only at sites suspected to be of meteorite impact origin. In this connection it is interesting to recall suggestions made by Beals, Innes and Rottenberg (1963) about the comparative pressures to be expected in meteorite impact and volcanic explosive sites. They point out that a meteorite striking the earth at a velocity of some tens of kilometres per second, generates a peak pressure of the order of 10^7 atmospheres, a pressure which is only attained lithostatically at a depth of 2,500 km below the surface of the earth. Even allowing for the attenuation of such pressures as the shock wave moves outward from the point of impact, it would still be expected to be many times greater than that of volcanic gas explosions venting near the surface of the earth. (Even at the depth of the Mohorovicic layer the lithostatic pressure is only a few per cent of a megabar.) It is scarcely surprising therefore to find crystallographic evidence of intense shock at meteorite impact sites and it is becoming increasingly probable that shock-fractured crystals represent a definite criterion for distinguishing between impact and volcanic features.

It is unfortunate that the relatively inaccessible location of Lac Couture has so far not permitted the sampling of the lake bottom itself by diamond drilling or other methods and this is something for the future. Some scattered gravity observations have been made but they are not sufficiently numerous or well distributed for a determination of the subsurface distribution of breccia by gravity methods.

In spite of the obvious lacunae in the observations which can only be filled in by extensive geophysical observations combined with diamond-drilling techniques, we consider it justifiable at this time to add Lac Couture to the growing list of probable meteorite impact sites. The number of such locations for craters over a mile in diameter is now approaching fifty (Beals and Halliday, 1965) and only recently we have received information about new discoveries in Sweden (W. von Engelhardt, private communication) which may bring the total above this figure.

It must of course be acknowledged that many scientists still regard the evidence for the impact origin of some or all of these craters to be insufficient. We would have to agree that in practically all cases a great deal of vital information is still lacking; short of the complete excavation of a crater some miles in diameter, it may never be possible to speak of final proof. In this as in many fields of astronomical and geophysical science it is necessary to rely for our conclusions on considerations of general probability combined with the gradually accumulating weight of evidence for or against a given hypothesis. With regard to the latter, the additions to the evidence for asteroidal impact as an important process on the surface of the earth and moon have been impressive over the past decade. As to the former, it would appear that the general credibility of the asteroidal impact process throughout the solar system has received a considerable impetus from the Mariner IV observations of the surface of Mars (Sky and Telescope, 1965). The remarkable photographs resulting from these observations give clear evidence of a surface dominated by circular features of a kind which is characteristic of high velocity impact. The fact that such features have now been observed on three members of the solar system, Earth, Moon and Mars, is important evidence suggesting that similar processes are probably causing interesting markings of this kind on bodies throughout the solar system at least within the orbit of Jupiter. While it can be argued that the common factor is volcanism rather than impact, the similarity of the lunar and Martian features and their resemblance to terrestrial impact craters is difficult to reconcile with such a view. The appearance of closely similar features on three planets with such widely different characteristics as Earth, Mars and the Moon would at least suggest that the crater forms are characteristic of the mechanism of formation rather than the nature of the surface or the value of gravity on the planet where they are observed. As space exploration proceeds, it will be interesting to see what further evidence turns up on the surface of other planetary bodies unobscured by heavy atmospheres, e.g. Mercury and the satellites of Mars, Jupiter and Saturn.

Age of the Crater

While the absence of any stratigraphic evidence in the data collected so far presents a rather discouraging picture for age determination, it is perhaps worthwhile to compare this crater with Deep Bay, a feature of similar size and with a reasonably reliable minimum age. Deep Bay has a rather precipitous rim rising in places to heights of the order of 100 metres above its surroundings. This at least suggests that Lac Couture, whose rim gives little evidence of even minor elevation above the surrounding plain, is the older of the two. Mesozoic strata penetrated by drilling near the centre of Deep Bay indicate a minimum age of 150 million years and Innes (1964) has suggested, on the basis of surrounding topography, that this may be close to the true age. From this it appears that Lac Couture could be considerably older and might even be Precambrian in age.

While the observations made at Lac Couture suggest that this crater may never have been filled with sediments, this is by no means certain. Until this possibility has been more thoroughly investigated by diamond drilling or other methods, it seems best to reserve judgment on the age of Lac Couture.

Reconstruction of the Original Crater Form

In conclusion it is interesting to make use of the data on terrestrial and lunar impact craters to attempt a reconstruction of the original form of Lac Couture. Following Baldwin (1963) we made use of his empirical equations (7–2A) p. 137 and (7–6A) p. 143 to calculate the apparent depth of the crater and the height of the rim above the surrounding plain.

$$D = 0.0256d^2 + 1.0264d - 2.3461 \qquad (7\text{–}2A)$$

$$Rh = 0.004366D^3 - 0.008506D^2 + 0.9098D + 1.5987 \qquad (7\text{-}6A)$$

Here D is the logarithm of the crater diameter in kilometres measured at the rim summit, and
d is the logarithm of the crater depth in metres measured from the rim summit of the apparent crater to the crater floor.

Rh is the logarithm of the rim height above the surrounding plain. The diameter of the original crater is estimated at 12 km—the diameter of the median line of the circular complex of islands and peninsulas surrounding the central island-free area of Lac Couture.

The resulting value of 1,250 m for the depth of the crater and 378 m for the height of the rim are necessarily approximate but should give a reasonably clear picture of what a crater of these general dimensions should be like. A profile of the crater before erosion compared with present topography is shown in Figure 10. If this model is even approximately correct it is evident either that the crater has been largely filled up by erosional products from the rim and glacial debris or that the Precambrian plain surrounding the crater has itself been eroded by an amount of the order of several hundred metres since the crater was formed. No doubt both processes have been going on but it seems likely that the former would be predominant.

While current ideas about explosion craters suggest that the greatest depth is in the centre, there is increasing evidence that some craters have central mounds or uplifts due to some sort of rebound mechanism associated with the impact process (Beals and Halliday, 1965). The dotted line of Figure 10 indicates this possibility which receives some credence from the depth soundings. If the original crater had a massive central uplift, then the above suggestions, relative to the amount of erosion would have to be modified.

The size of the meteorite which could produce a crater of this diameter has been calculated from Baldwin's equation (Baldwin, 1963, p. 176)

$$D = 0.3284E - 7.9240 \qquad (8-12A)$$

where D is the logarithm of the crater diameter in kilometres and E is the logarithm of the number of ergs of kinetic energy of the impacting meteorite. Assuming a rock meteorite of density 3.4 and a velocity of 20 km/sec, the calculated energy is 2.60×10^{27} ergs and the diameter 901 metres. If the crater were formed by an iron meteorite then the calculated diameter would be 683 metres.

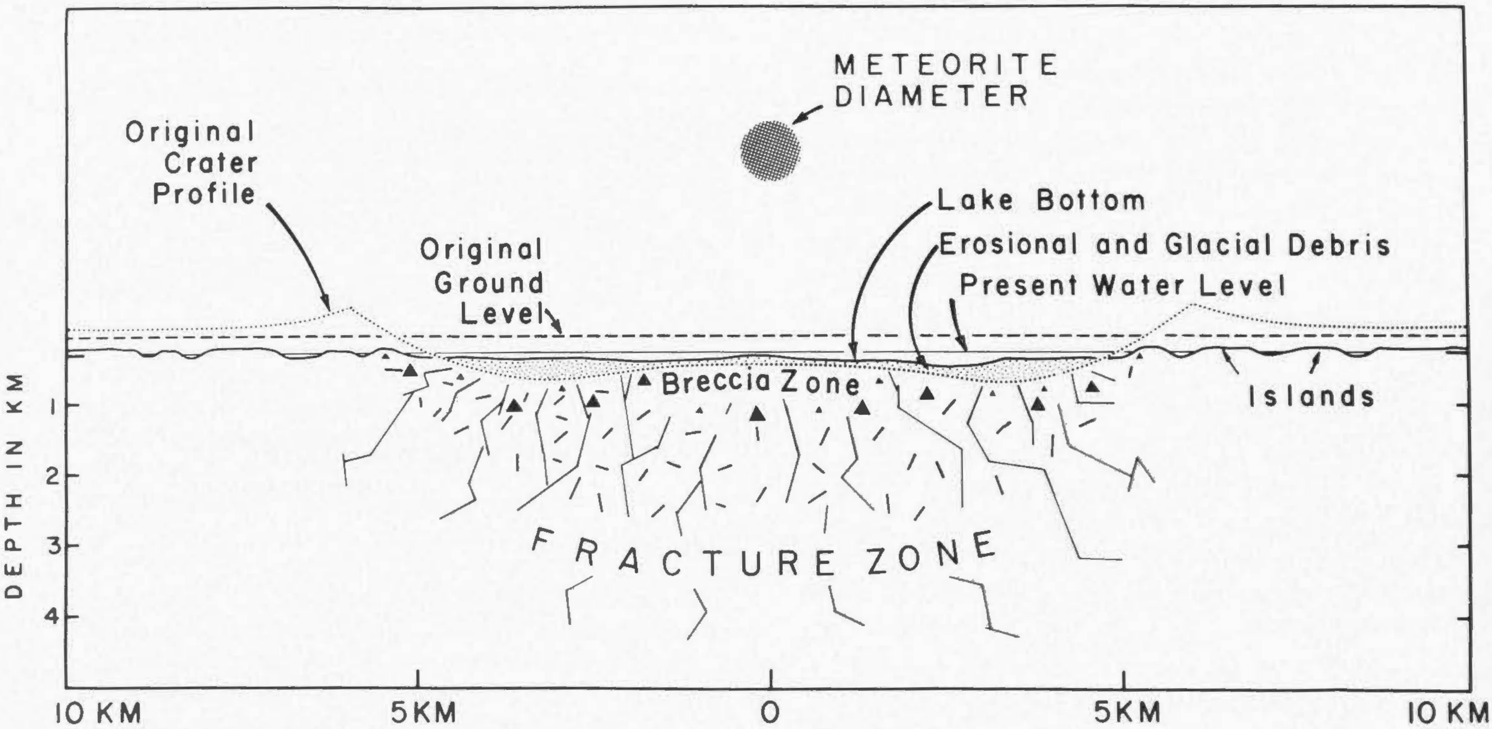


FIGURE 10. Suggested relationship between original crater profile and present topography. Order of diameter of stone meteorite capable of producing crater at velocity of 20 km/sec, 900 m.

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