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GEOLOGY OF THE NEW QUEBEC CRATER

K. L. Currie

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By
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PREFACE

The New Quebec Crater has been examined by many scientists since it was first discovered in 1950. Although definite proof is admittedly lacking, it is widely believed to have been formed by the impact and explosion of a meteorite. The author made a careful geological study of the crater and its surroundings and presents evidence for concluding that an origin by natural geological processes is at least as likely.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, January 13, 1964

BULLETIN 150 — Geologie des Neu-quebec Kraters.

Von K. L. Currie

Die Entstehung des Kraters, von dem allgemein angenommen wird, dass er durch einen Meteor hervorgerufen worden sei, kann vielleicht auf gewöhnlichere geologische Ursachen zurückgeführt werden.

БЮЛЛЕТЕНЬ 150 — Геология Ново-Квебекского кратера.

К. Л. Курри

Кратеру обычно приписывается метеорйтное происхождение но более обычные причины могли быть ответственны за его возникновение.

CONTENTS

Illustrations

GEOLOGY OF THE NEW QUEBEC CRATER

Abstract

The New Quebec Crater is a circular depression in the acid Archaean gneisses of northern Quebec, about 2 miles in diameter and 1,300 feet deep. The regional structure is a complex series of north-trending isoclinal folds cut by four systems of faults. The elevated crater rim shows deflection of curviplanar structure elements, demonstrating that a dome previously existed over the crater. Significant hydrothermal alteration occurs in the wall of the crater but not elsewhere in the region. There is no evidence that the shape of the crater has been substantially modified by erosion. No evidence of meteorite impact or of catastrophic violent origin was found. The evidence is quantitatively consistent with an origin by collapse of a fluid-supported dome. Time of origin of the crater is thought to be late Pleistocene.

Résumé

Le cratère du Nouveau-Québec est une dépression circulaire, dans les gneiss archéens acides du nord du Québec, d'un diamètre d'environ 2 milles et d'une profondeur de 1,300 pieds. La structure régionale est une série complexe de plis isoclinaux à direction nord qui est coupée par quatre réseaux de failles. Le bord élevé du cratère laisse voir une déflexion des éléments de structure curviplane, ce qui indique que le cratère a déjà été surmonté d'un dôme. On trouve une altération hydrothermique significative dans la paroi du cratère, mais non ailleurs dans la région. Il n'y a pas d'indice que la forme du cratère ait été substantiellement modifiée par l'érosion. On n'a trouvé aucune preuve d'une chute de météorite ou que le cratère soit d'origine catastrophique. Quantitativement, tout indique que le cratère doit son origine à l'effondrement d'un dôme soutenu par une matière fluide. L'origine du cratère remonterait au Pléistocène supérieur.

INTRODUCTION

The New Quebec Crater is a circular depression, roughly 2 miles in diameter, in the acid Archaean gneisses of northern Quebec. Its centre lies near latitude 61°17′ N, and longitude 73°40′ W. The United States Air Force first brought the crater to general attention in 1945 when it published a navigation map of the region with the notation 'Crater'. Various oblique aerial photographs were taken by the USAF and the RCAF between 1943 and 1950, from which the crater was recognized as a possible impact scar sometime before 1949 (Millman, 1956).[1] V. B. Meen, whose attention had been drawn to the crater by Fred Chubb, a Whitby prospector, led the first expeditions to the crater in 1950 and 1951 (Meen, 1951, 1952, 1957). Because of the shortness of his visits and the lack of a suitable base map, Meen did not make much progress in elucidating the geology. J. M. Harrison made a brief visit in 1954, and with the aid of vertical aerial photographs taken in 1953 he proved that the crater rim had been glaciated (Harrison, 1954). P. M. Millman (1956), using a topographic map compiled from aerial photographs, and soundings made by Meen, has shown that the topographic form of the crater is roughly compatible with an impact origin, but that the rim is too rounded for an unaltered impact crater. The Dominion Observatory in 1960 and 1961 collected gravity and magnetic data in and around the crater and in the course of this work an excellent topographic map was prepared. In 1961, E. M. Shoemaker (Shoemaker, 1961) spent a short period at the crater searching for evidence of impact origin. G. H. Beal made a few observations near the crater in 1958, in the course of mapping an area centred farther north (Beal, 1959).

In 1962 the author mapped about 50 square miles surrrounding the crater at a field scale 1 inch to 500 feet. By camping on the ice of Lac Cratère, a field season of three months was obtained, most of the time being spent on a painstaking comparison of the structure of the rocks in the rim with those outside.

[1]Names and/or dates in parentheses are those of references in Bibliography.

Physiography

In general, the shape of the crater is a segment of a sphere, with a radius of 2 miles and a depth of 1,300 feet. From the edge of this depression a bedrock rim slopes outward, at first gently then more rapidly, attaining an average width of 1,500 feet and a height above the surroundings of 300 feet. At its outer margin, the rim passes almost imperceptibly into gently rolling tundra.

The crater may be divided into four physiographic divisions: (1) the crater wall, and Lac Cratère, (2) the rim, (3) the outer slope, (4) the hinterland.

1. The crater wall, 400 feet of which is exposed above the central lake, is a steep, remarkably regular slope, averaging 33 degrees inclination. Most of the slope is covered with blocky rubble and partly active talus, intermingled with various amounts of glacial debris (Pl. IV). Many talus streams can be traced upward to outcrops of bedrock (such outcrops are not rare in the crater, even down to and below the waterline), but most of the talus comes from cliffs at the top of the slope that are continuous around the southern and western sides of the crater. Landslip scars with steep concave upper slopes and flat bottoms are a typical feature on the crater wall. A triangular area on the east side of the crater has a distinctly lower slope than the rest of the crater wall, averaging about 25 degrees. The base of the triangle along the lake shore is about 1,500 feet long. Till is obvious in this area, but on examination was found to be a very thin veneer. Otherwise the character of the slope is the same as in the rest of the crater. This similarity and the lack of erosional products on the slope suggest that the low slope is an original feature of the crater.

Lac Cratère is almost circular in plan. However, a pronounced bilateral symmetry about an east-west axis, together with the low slope noted above, gives the crater a distinctly monoclinic symmetry. The edge of the lake is marked by a boulder beach, which reaches a width of 50 feet on the east side of the crater. Behind the beach is a sharp rise of 10 to 15 feet, possibly representing a wave-cut cliff. The same combination of a flat bench terminated by a steep rear slope occurs at heights of 100 and 250 feet on the crater wall, probably indicating old strand lines. The higher of these is above the lowest outlets of the crater, and must represent a transient post-glacial still-stand. Both benches show marked deviations from horizontal, believed to have been caused by slumping of material on the crater wall.

No measurements were made on the lake itself. The marvellous clarity and beauty of the water have been remarked on by every visitor to the crater.

2. The rim joins the wall of the crater with an abrupt change in slope, the wall dipping 33 degrees and the inner edge of the rim dipping 15 degrees towards the crater. The slope of the rim becomes horizontal a few hundred feet from the inner edge, and radially beyond this point the slopes are outward, with values gradually increasing to about 10 degrees. Plate VIII shows a typical section across the rim. In contrast to the rubble-covered inner slopes, the top of the rim is essentially bedrock, with local, thin patches of boulder till. The relief on the rim is considerable, locally amounting to 300 feet, chiefly due to deep steep-sided

valleys cutting more or less radially across the rim. On the east side of the crater these valleys have a broad U-shaped profile typical of glaciation but on the west side the valleys are steep-walled canyons with flat or slightly convex floors. Several rather pyramidal hills occur east and west of the crater. The position and shape of these hills are controlled by structures in the bedrock. The rim is asymmetric in both plan and section such that on the east side it is broad and gently sloping, whereas to the west it is narrow and drops off steeply at its outer edge.

3. The outer slope joins the rim with a discontinuity in slope. The rim dips 7 to 10 degrees outward whereas the outer slope dips 19 degrees. The constancy of this value is as remarkable as that of the inner slope. The outer slope varies in height from 10 to 100 feet; south of the crater it is obscured in places by a till blanket lapping up to the edge of the rim. In places it consists of two or more distinct steps. No bedrock is known on the outer slope; it is entirely covered with boulders, most of which show clear evidence of glacial transport. Some of this material may represent reworked throw-out from the crater.

4. The hinterland of the crater extends well beyond the rim, indeed the effect of the crater can be detected in the bedrock at a distance of at least 2 miles from the centre. The crater rim forms the highest point in northern Quebec. Thus the ground slopes off more or less regularly in all directions for many miles. How much of this broad topographic doming is associated with the crater is unknown, but a rude alignment of topographic features about the crater extends a distance of at least 4 miles from the centre. There is a 'teardrop' symmetry to this doming, with the blunt end facing west and an elongate tail to the east. Outcrop is typical of the Quebec barrens. Rock surfaces of low relief extend over considerable areas, and show very severe frost breakage.

GENERAL GEOLOGY

The exposed bedrock in this area consists of a melange of plutonic rocks of generally granitic aspect, cut by rare basic dykes (Fig. 6). The granitoid rocks are of Archaean age and correlative with many thousands of square miles of similar rocks exposed to the south. Low grade hydrothermal alteration, believed to be related to crater formation, is present on the inner lip of the crater. The bedrock is covered locally with a thin veneer of glacial and recent deposits.

The Archaean Complex

Detailed mapping in these rocks is attended by the difficulties usual to ultra-metamorphic terranes. Rock-units recognizable over areas large enough to be useful are very difficult to define. All rock types except the late basic dykes grade into one another. By a combination of lithological and structural mapping however units can be traced around various structures. The lithological mapping is based on (a) the percentage of basic inclusions in hybrid rocks and (b) the mafic minerals in granitic rocks. In general the rocks were found to be essentially identical with those elsewhere in the region (Stevenson, 1963).

Description of Units

Amphibolite breccia is a spectacular rock (Pl. IX) consisting of blocks of basic material in a granitic matrix. The amount of basic material in these rocks varies from 15 to 75 per cent, occurring in blocks from 6 inches to 10 feet long. The smaller blocks tend to be equidimensional, but the larger ones consist of elliptical masses of hornblende and biotite with various amounts of plagioclase. They show strong gneissosity parallel with that in the enclosing rocks and commonly show trailing streaks of basic material. The basic material in the least altered specimens is a finely banded, black, hornblende-biotite-quartz gneiss. The gneissosity of these blocks is notably straight and undistorted, and the shape of the blocks is rectangular, suggesting boudins. Adjacent blocks show no perceptible parallel orientation of gneissosity. The blocks are locally stretched perpendicular to the strike, in the foliation planes, to lengths as much as ten times the strike length, giving a spectacular rodded structure to the rock.

The matrix is a coarse-grained, mafic-poor, granitic rock. The composition varies in a systematic way over the area. North of the crater, the matrix is pink potassic granite, essentially a quartz-potash feldspar rock with a little green-black hornblende. East and south of the crater, the matrix has a typical yellowish colour (perthite) and contains very black, shiny hornblende and biotite. The texture of the matrix tends to be pegmatitic. Excellent foliation is observed near shears.

The agmatitic appearance of this rock is characteristic and offers no difficulty to identification. The percentage of basic material however varies from 15 to 75 in a few feet, which makes the definition of boundaries a difficult task.

Hybrid biotite gneiss has a characteristic outcrop appearance of alternating green-brown and white stripes about an inch wide. On examination, these stripes are found to be elongate lenses 20 to 30 feet long. Fissility along the foliation is strong, so that outcrops commonly contain much flaggy broken material. Upon examination rocks of the two different colours are found to be surprisingly similar in composition. Both dark and light parts consist of biotite-plagioclase gneiss, the difference in colour being due to the amount of biotite, which varies from 10 per cent in the light stripes to 20 per cent in the dark. The bulk of the rock is made up of plagioclase (An_{35}), perthite, and occasional grains of microcline which have a characteristic red colour. All the feldspar occurs in augen, with the interstices filled with aligned greenish biotite and finely crushed feldspar. The feldspar grains are strongly altered to sericite with rare development of epidote. Some specimens have a few lenses more or less elliptical in shape. These invariably contain a little hornblende crusted with biotite. Southeast of the crater, in massive granites, diffuse shear zones are seen in which biotite has developed at the expense of hornblende. These rocks strongly resemble the biotite gneiss, suggesting that the latter may have developed by shearing of hornblende rocks, possibly the amphibolite breccias.

Granitoid gneisses with abundant basic inclusions form distinct bands as shown on the geological map, and commonly contain amphibolite breccias as lenses or patches. The gneisses have a characteristic rusty appearance – a faint brownish tinge over the pink gneiss. This tint persists to the deepest level that could be sampled. The rock consists of a medium-grained, pink, biotite granite-gneiss with numerous greenish black or rusty, basic inclusions forming 5 to 15 per cent of the volume. The inclusions are generally 4 to 12 inches long, with a few ranging up to 5 feet, are markedly elongate and commonly folded, generally in a Z shape (Pl. X). They are composed of acicular hornblende and some biotite (aligned parallel with the edges of the inclusion), which weathers readily, leaving rusty depressions in the rock and giving the surface a 'buckshot' appearance. In thin section, the basic minerals in the inclusions are highly coloured in shades of green and blue. The appearance of these inclusions is in contrast to the fragments of amphibolite breccia, which are more or less equidimensional, unfolded, and usually stand out above their granite matrix.

The matrix of the rock is a medium-grained, faintly rusty, pink, biotite granite-gneiss. The foliation tends to be uneven and irregular, with many zones of ropy, pegmatitic material, especially around inclusions. Screens of fresh, pink granite-gneiss are common. In thin section, the fabric of the rock is seen to be composed of microcline and plagioclase (An_{30}) both showing some sericitic alteration, with abundant quartz occurring as a mosaic of fine grains, occasionally showing undulatory extinction. The mafic minerals are non-pleochroic, grey biotite in the quartz-rich specimens, plus some weakly pleochroic hornblende in the more mafic specimens.

There appears to be a significant decrease in the amount of sericitization of feldspar and bleaching of biotite with distance from the crater.

Undifferentiated granitoid gneisses include various strongly foliated leucocratic rocks. Two types are of general occurrence. Fine- to medium-grained biotite granite-gneisses, generally grey and with an even, regular foliation defined by alternate bands of biotite-rich and biotite-poor material. The rock is of sugary homogeneous texture, and is composed of microcline, plagioclase (An_{35}), and quartz. The other principal type of granite-gneiss is a pale to bright pink, coarse-grained rock with a weak gneissosity defined by lines of biotite flakes. The fabric of the rock consists of large crystals of microcline and antiperthitic plagioclase with a fine mosaic of interstitial quartz. Sphene is a frequent accessory of this type of gneiss occurring in crystals up to half an inch across, with strong haloes of discoloration surrounding them. In contrast to the inclusion-rich material previously described, the biotite in the granite-gneisses is fresh looking and strongly pleochroic in shades of reddish brown, or rarely, green.

The occurrence of epidote in these rocks is of interest. It was noted in the field that the specimens collected at sites remote from the crater did not contain epidote, whereas those collected in or near the crater had abundant visible epidote. An examination of twenty specimens indicates that rocks of this unit rarely contain epidote at distances from the crater centre greater than 2 miles, indeed specimens of these rocks taken between 1½ and 2 miles contain epidote only if they occur on zones of structural weakness (e.g., the major fracture zone east of the crater). Specimens taken closer than 1½ miles from the centre (i.e., in or near the rim) all contain epidote, although it may not be visible in hand specimens. The degree of development of epidote is inverse to that of sericite, and is dependent on the proximity to fracture zones. The mineral is developed generally in tiny needles along cleavage planes in the feldspars, most prominently in plagioclase but also in microcline. Inside the crater no specimens examined contained less than 5 per cent of epidote, and those with less than 10 per cent were invariably remote from fracture zones and showed strong development of sericite in similar style. The mineral is a characteristic bright green, in contrast to the greasy yellow epidote occurring locally in the granite.

A distinctive pink granite, generally epidote bearing, outcrops across the northwestern part of the area in a northeasterly trending belt at least 2 miles wide and 4 miles long. The boundaries, except the southeastern one, are not established. The rock is a coarse-grained, pink, holocrystalline granite with little or no gneissosity, except at its edges. The rock is composed of microcline, flame antiperthite (An_{35} and potash feldspar) with quartz and biotite in lesser amounts filling interstices in the fabric. The feldspars are severely altered to epidote in a fine needlelike pattern. This alteration is particularly prominent near the edges of the mass. In hand specimens the epidote is greyish or pale yellow, and difficult to detect even where present in substantial amounts. Sphene occurs near the boundaries of the granite in considerable amounts, commonly surrounded by a narrow reddish halo.

The edges of the mass are indistinct. The pink, massive, sheeted rock grades off into buff granite-gneisses, commonly with perceptible shearing. Inside the mass large xenoliths occur. These are relatively unaltered, but their gneissosities do not seem to have any mutual orientation, and upon close examination it is impossible to find any distinct boundary between the inclusion and the surrounding granite.

Sheeting is beautifully developed in this mass and outcrops may appear as neatly sliced as a loaf of bread. Great tabular boulders hundreds of square feet in area, and but a few feet thick, can be found in the granite area, apparently transported intact a few tens or a few hundreds of feet.

Granodiorite and *diorite* outcrop in small masses in the southern half of the area, possibly offshoots of a larger mass to the southwest. The rock has a characteristic yellowish colour in outcrops, occasionally varying to grey. Although the mass as a whole is a granodiorite, compositions of individual specimens vary from quartz monzonite to diorite.

The rock is a coarse-grained, rather friable, grey, granitoid rock composed chiefly of plagioclase, some of it antiperthitic with 5 to 30 per cent microcline in sinuous lamellae. Quartz is present as a fine mosaic of grains between the larger feldspar grains. Biotite, pleochroic in colours ranging from pale yellow to dark grey, is the chief mafic mineral with small amounts of magnetite and hornblende. In the rim of the crater the feldspars show considerable development of sericite and a lesser amount of epidote.

The rock was generally found as coarse, crudely foliated masses, a few acres in extent. Some of the masses are parallel with other gneissic bands, e.g., south of the crater, but most occurrences have the apparent form of stocks. They are clearly older than the pink granite, for southwest of the crater they are cut and altered by veins of pink granite.

There is a vague but significant boundary between pink granitic rocks and yellow-grey dioritic rocks, which crosses the map-area in a northeasterly direction. North of this line the rocks are generally pinkish, and the mafic minerals are greenish black; south of this line the rocks have a yellowish cast and the mafic minerals are a resinous brownish black.

Miscellaneous granitic rocks include a 60-foot-wide pegmatite dyke southwest of the crater and the pegmatite matrix of the various breccias. They are coarse, pink, mafic-free rocks that show little relation to either major mass.

Basic hornblendic gneisses are of uncertain age. They appear to be highly altered basic dykes and thus presumably younger than the terrane they cut. However, they are certainly older than both the granitic masses, which have altered them. Three main bodies occur: (a) a sheared belt a mile long and 500 feet wide southwest of the crater, with a possible extension across the southwest lip of the crater, (b) a narrow belt 200 feet wide and half a mile long on the north wall of the crater, and (c) a body in the bottom of the large valley crossing the northeast wall of the crater. There are two other small occurrences, one southwest of the crater and the other just north of North Pond. It is probable that some of these occurrences represent fragments of a once continuous body.

The rocks are generally fine grained, medium grey to black, and intensely sheared. The heavy shearing is indeed universal, most of the material being reduced to thin plates of rock. Rusting of the surface is also widespread. The material southwest of the crater has developed an incipient gossan, with considerable porosity and the apparent leaching of magnetite. The rocks are composed of plagioclase and hornblende, with varying amounts of magnetite and occasionally a small amount of quartz. Magnetite is sometimes developed along parting planes to such an extent that it resembles a type of iron-formation. Biotite and chlorite are developed at the expense of hornblende to some extent in all the rocks examined. Epidote is very strongly developed in these rocks in and near the crater but not elsewhere.

These rocks invariably occur in shear zones, thus implying that they represent dykes injected along reactivated old zones of weakness. They generally display very thin foliation and strong lineation in the foliation plane.

Hornblendite dykes comprise a group of three spectacular dykes, each about 100 feet wide. These rocks are composed chiefly of tabular crystals of green-black hornblende about half an inch long. The crystals are set in a matrix of feathery greenish amphibole, with a few small crystals of plagioclase (An_{55}) filling interstices. These rocks occur as discrete unbroken dykes with numerous apophyses. However, the edges are broken and engulfed by the surrounding granitic rocks.

Diabase dykes outcrop in two places only. A typical medium-grained, greenish grey pyroxene-plagioclase dyke 40 feet wide cuts granite. Its margins are slightly finer grained than the centre. Trains of angular diabase boulders were occasionally observed in the float and these are believed to represent outcrops in the immediate vicinity. Two varieties of diabase float were observed: one is the light coloured, greenish grey rock noted above; the other is much blacker and consists of labradorite and black augite.

Cataclastic rocks are common. The amount of crushed rock is unusual for this region, but the rocks all appear to be of equivalent age to their surroundings, or at least very much older than the crater. Augen-gneisses occur principally in a broad zone of shearing east of the crater. The augen are potash feldspar and vary in size from barely visible to 3 inches. Some are simple ovoids but most are more or less rectangular and show breakage at the corners where they have been rotated. No other rocks in the area are known with feldspar crystals of this size.

Breccias of peculiar type are also common. These consist of fragments of feldspar set in a matrix of acicular biotite. The feldspar is generally in white to pale pink angular fragments ranging from a quarter of an inch to an inch in largest dimension. The fragments show no regular alignment nor is the matrix strongly foliated. The biotite varies in colour from greenish black to pale brown and commonly shows small radiating structures a few inches across. The occurrence of these rocks is confined to the vicinity of known fault zones, and both types of cataclastic rocks appear to be very much more common in the crater rim than in the hinterland, but this may be due to poor outcrop of these easily weathered rocks. The breccias in places grade into more normal granite-gneisses, but no rocks exposed correspond in composition to the more spectacular examples.

Geological Features Related to the Crater

No bedrock formations were found that are believed to have been formed by the processes that formed the crater. However, some small areas of fractured rock may represent material thrown out of it and one piece of float may be a fragment of melted rock from the crater. Low grade hydrothermal alteration is pronounced in the bedrock inside the lip of the crater.

Throw-out is a characteristic feature accompanying impact craters (cf. Shoemaker, 1963). It consists of angular blocks of fractured but unaltered material from the crater. Under favourable circumstances it may show a reversed stratigraphic order as described by Shoemaker at Meteor Crater, Arizona. The widespread presence of felsenmeer and frost-broken outcrops (Pl. III) makes the distinction between throw-out and indigenous blocks of rock exceedingly difficult in this area. Throw-out should show the following distinctive characteristics: (a) general concordance of planar features, (b) clear evidence of detachment from bedrock, (c) presence of blocks of rock foreign to the locality. The third criterion seemed likely to be easily applied because of the widespread occurrence of epidote bearing rocks in and near the crater. Areas suggested by Shoemaker (1961) were tested by these criteria. All but three were shown to be either felsenmeer or frost-heaved bedrock. One of these exceptions, southeast of the crater (Fig. 2), was studied in detail. It forms the crest of a drumlinoid ridge and is composed of about 500 blocks greater than 15 feet in largest dimension, most of them strongly tabular. The rocks are amphibolite breccia and inclusion-rich granite-gneiss. No epidote bearing blocks were seen. Strikes are concordant in small areas, but there is a pronounced curvature of strike over the area as a whole. A prominent joint set with a strike of about N70°E cuts most of the blocks. Just to the south of the ridge crest several enormous blocks show joints of this trend with dips of 50 degrees compared to the 80 degrees usual in the bedrock. This low dip can be seen on an undoubted outcrop 500 feet to the west. This area satisfies the first criterion, doubtfully satisfies the second, and fails the third.

A somewhat larger patch of similar material occurs northwest of the crater. Some definite outcrops occur on the south end of the ridge, and the north end is covered by felsenmeer. The blocks in the doubtful area are similar in composition to those on other parts of the ridge. Their concordant strike is similar to that on outcrops of bedrock nearby. No epidote bearing boulders occur.

A third possible area of throw-out consists of a single conical hill about 100 feet in diameter by 25 feet high, 4,000 feet west of the crater. This hill juts out of a plain otherwise devoid of outcrops. The strike of the gneissosity and of the joints in this block are anomalous. This outcrop falls into a narrow belt of outcrops crossing the southwest margin of the crater all of which display anomalous strikes and abnormally low dips of joints. It is unreasonable to suppose that this block alone is throw-out; its size and remote location are amazing if it is throw-out.

Shoemaker (1961) argued that these three small localities are remnants of a sheet that once spread around the crater and had a thickness of some tens of feet. The rest of this sheet is assumed to have been destroyed by glaciation. The two remnants to the west were on the upstream side of the crater during glaciation, in an area where evidence of glaciation is more abundant than in any other area around the crater. The third patch occurs just at the foot of a glacially rounded valley. Farther downstream in this valley are large piles of rounded, glacially transported boulders as large as the supposed blocks of throw-out.

In summary, no area can be found that obeys the criteria for throw-out. In fact no area can be found that clearly obeys even two of the three criteria. The mechanism proposed for the preservation of supposed throw-out is implausible in view of the location of the patches. The appearance, petrography, and structure of the blocks are consistent with their being frost-heaved bedrock. Statements such as that of Baldwin (1963) that the surroundings of the crater are littered with material thrown out of the crater are fallacious.

Fall-out is rock blown into the air on high angle trajectories whose fall is retarded by the atmosphere. By its nature this material is liable to contain the melted and highly shocked material resulting from a meteorite impact. An intensive search of the crater area yielded one possible fragment of fist size of such material from an area just inside the wall of the crater, on the southeast rim. The rock has a black, highly vesicular, glassy matrix with many elongate vesicular inclusions, some of them visibly disintegrating into component grains. The inclusions consist mostly of clear glass, locally containing unaltered quartz crystals. Some small fragments of plagioclase (An_{25}), possibly phenocrysts, are also present. The glass shows sharp, intrusive contacts against the matrix. Many of the inclusions are polycrystalline. The matrix is a brownish colour with a groundmass of glass charged with a myriad of plagioclase microlites (An_{30}) in trachitic texture. The vesicles are completely unfilled, and it is still possible to see the original glassy crust on most of them.

Examination of the fragment suggests that it is not fall-out but a fragment of fresh vesicular volcanic rock; this conclusion is supported by chemical analysis (*see* page 46). Examination of the Geological Map of Canada shows that transportation of a fragment of this kind from some other source is unlikely. The nearest known volcanic rocks of Phanerozoic age are more than 300 miles away.

Rock alteration is a noticeable effect near the crater. Epidote is developed in all types of rocks in the rim. It is a relatively common accessory in certain types of granite in this region, but is very uncommon in rocks of a more basic composition. The epidote in the granite is a dull yellow, whereas that in the rim is a bright green. Inside the rim it is present as thin green seams in joint faces, as diffuse greenish patches in the rock, and most spectacularly as sheaves of large green crystals with individual prisms an inch long. In gneiss units that can be traced from the rim into the hinterland, epidote occurs in abundance in the rim but not in the

PLATE I

KLC, 2-10-62

Typical outcrop on the rim of the crater. Note slightly rounded edges of rock and sheeting dipping left (east).

PLATE II

KLC, 2-8-62

Typical outcrop outside the crater. Note low relief, glacial fluting, and good sheeting dipping right (southwest).

PLATE III

KLC, 1-20-62

Felsenmeer outside the crater. Note the outer slope of the rim in the background, descending in two distinct steps. An area of supposed throw-out can be seen as a very low prominence on the horizon at the centre left.

PLATE IV

KLC, 2-17-62

Felsenmeer inside the crater. The firn banks mark a line of cliffs around the top of the inner slope. The thin white line down the rim marks the site of a major rock slide June 27, 1962.

PLATE V

KLC, 2-2-62

Large firn bank with core of ice. This firn bank extends several hundred feet to the right, down a fracture-controlled valley. Freshly broken material can be seen on the finger of rock crossing the valley, which indicates that this fracture has been active recently.

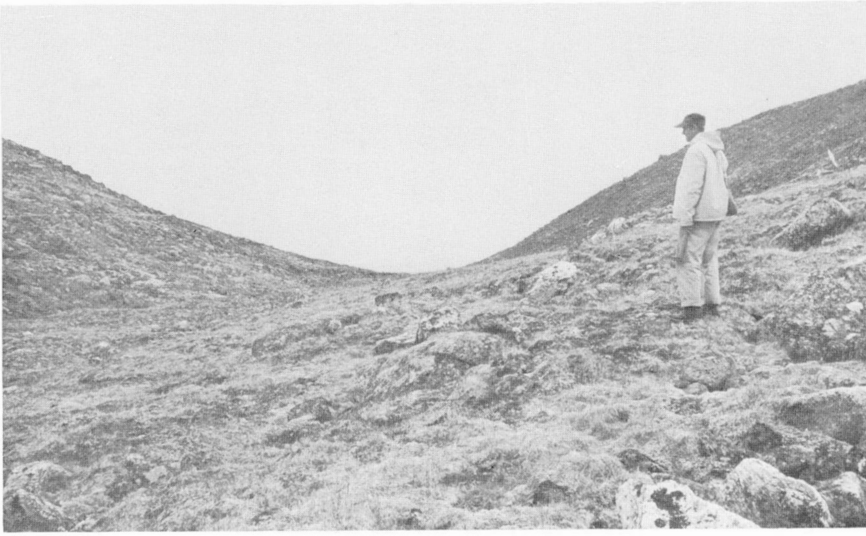

PLATE VI

KLC, 2-19-62

U-shaped valley crossing the northeast rim of the crater. This valley is thought to have been a major outlet for ice leaving the crater.

PLATE VII

KLC, 7-6-62

Moderately upturned sheeting in the rim. Note the two boulders in the foreground; these have been wedged out of the outcrop and represent incipient development of felsenmeer.

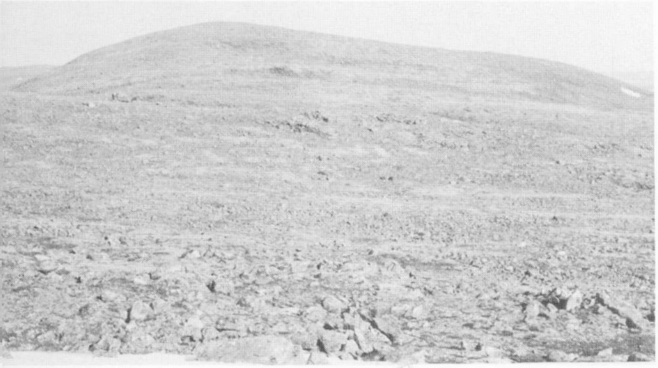

PLATE VIII

KLC, 2-7-62

Cross-section through the rim. At left (west) is the 33 degree slope of the inner wall; in the centre is the gently curved rim; and at right is the 19-degree slope of the outer rim.

PLATE IX

KLC, 2-4-62

Agmatite (amphibolite breccia). Note the blocky, discrete appearance of the inclusions.

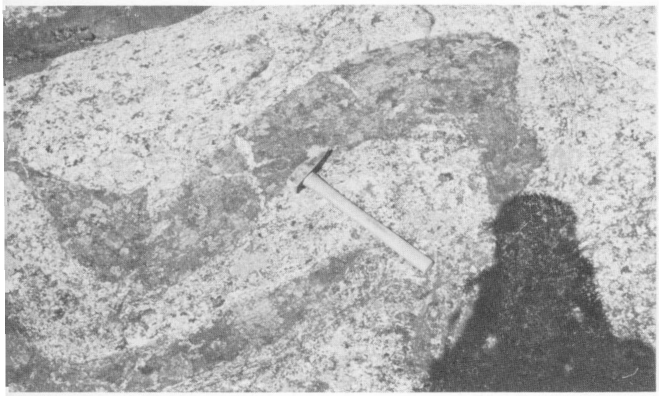

PLATE X

KLC, 2-5-62

Inclusion-rich granite-gneiss. Note the folding and the vagueness of some of the contacts of the inclusion.

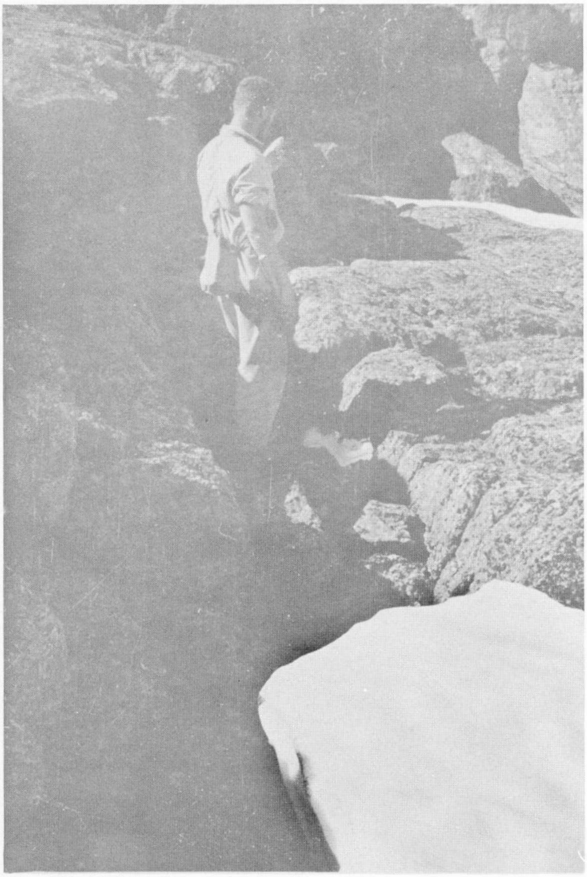

PLATE XI

KLC, 2-21-62

Down-dropped block on west side of crater. Man is standing on a narrow graben with the bounding faults visible.

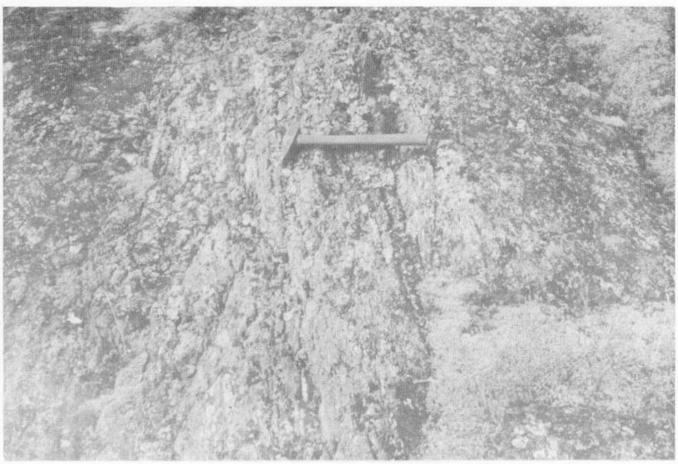

PLATE XII

KLC, 2-6-62

Gouge and crushed rock of post-Proterozoic age in fracture zone on east rim of crater.

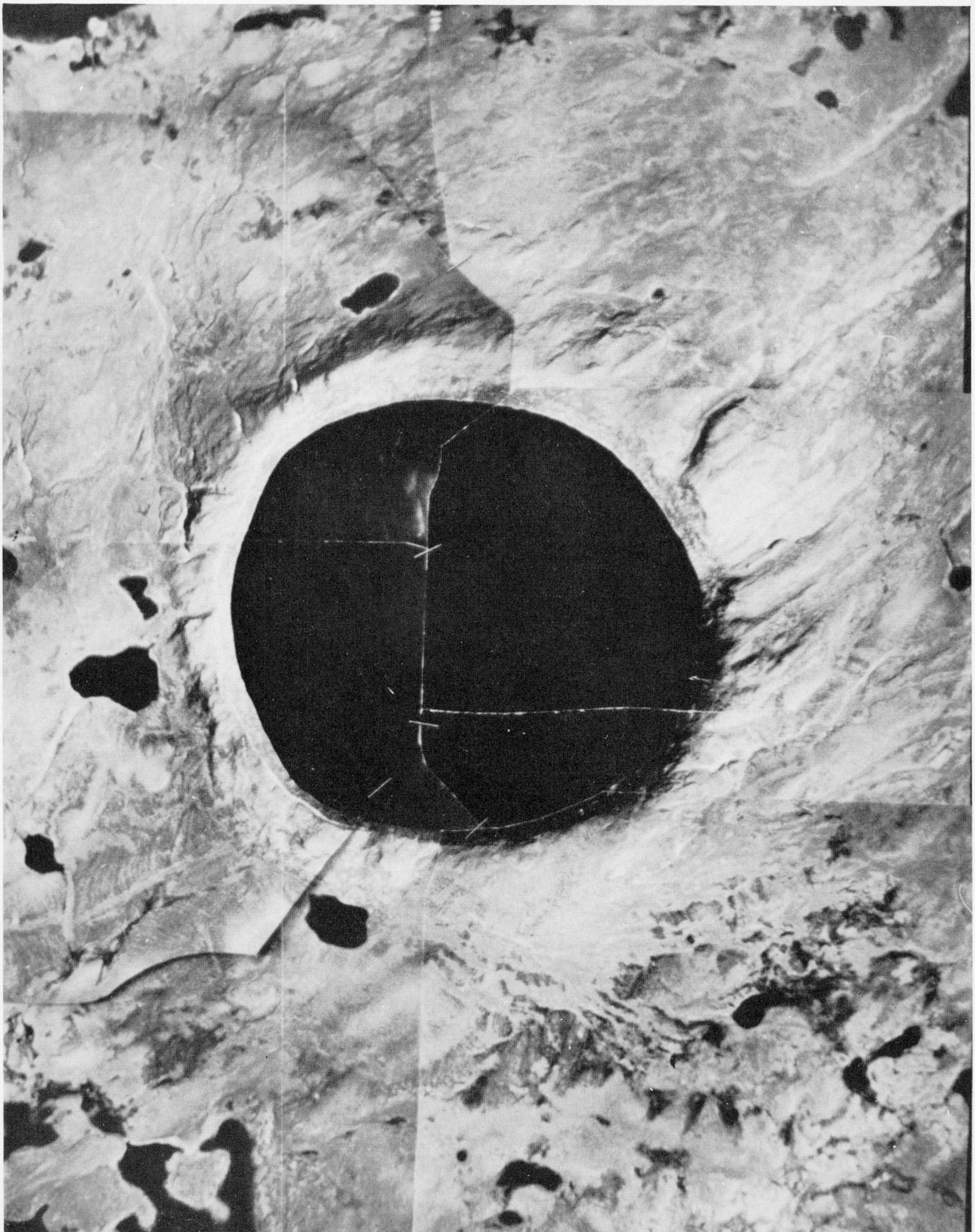

PLATE XIII Mosaic of vertical aerial photographs of the New Quebec Crater.

same rock outside the rim. This indicates that the formation of the rim and the process of hydrothermal alteration are closely connected.

White and Sigvaldson (1962) have investigated the formation of epidote under hydrothermal conditions in natural hot springs. They have shown that epidote forms under minimum pressure of 120 atmospheres, and minimum temperature of 240°C. In the occurrences examined the crystals were extremely small, presumably because the rate of flow of the saturated fluid was too rapid for optimum growth conditions. The size of the crystals in the New Quebec Crater occurrence indicates that these crystals grew very slowly under almost static conditions. The temperatures and pressures required show that they can have grown neither in their present location with respect to the atmosphere nor under any plausible thickness of post-crater sediment. The size of the crystals makes it quite incredible that they grew under the transient conditions of impact. But the perfect correlation of pistacite occurrence with the rim shows that they must be genetically connected with the rim. The only plausible explanation is that the rim must have been underlain by hot, quasi-static fluids during its formation.

Considerable amounts of red hematite are found in the crater, generally as red stained joint faces but occasionally in the matrix of a fine-grained rock, particularly augen-gneiss, partly replacing the silicates.

On the south wall of the crater several gash veins about 8 inches long composed of calcite and quartz were discovered. The occurrence of these minerals, associated in rocks of this metamorphic grade is surprising and it is tempting to relate the veins and the formation of the crater.

Glacial and Recent Geology

Glacial striations and flutings are moderately abundant on the rocks outside the crater rim. Striations indicate movement at S70°E with later ice-advance in the direction N45°E. Outcrops are as a rule extremely flat (Pl. II) making it difficult to judge the degree of glacial rounding. Rare boulders of Wakeham Bay belt rocks presumably were transported by ice advancing in the earlier direction. None of these boulders was seen on the crater rim. In general, transported material is not common. The ground is covered mostly with felsenmeer (Pl. III), i.e., fields of ice-broken blocks in situ or slightly transported by creep. Locally these blocks occur in definite 'streams' which appear to be actively in motion at present. Rounded, glacially transported boulders tend to occur in discrete belts (*see* Fig. 6). These belts consist mostly of rounded boulders with lenses of clay or sandy material forming open patches, commonly marked by the formation of polygonal ground. With the exception of half a dozen Proterozoic boulders from the Wakeham Bay belt, all the transported material appeared to be of local origin. Trains of boulders could be traced in the boulder till downstream from basic dykes. Despite a careful search, none of the epidote bearing rocks typical of the rim was found downstream from the crater. In a general way, there seems to be a vague boundary between the areas of till and those of felsenmeer which crosses the mapped area in a north-east direction.

The net of meltwater channels visible on aerial photographs (Pl. XIII) suggests that the glacier may have halted for some time in its retreat, possibly just west of the crater. These channels contain abundant sandy material, across which the channels braid and intertwine in intricate fashion. Near Lac Laflamme and Laflamme River lensoid sand deposits suggest raised beaches.

The appearance of the rim is distinct from that of the hinterland. The outcrops are notably angular and unrounded (Pl. I), and no glacial striations have been found on rocks of the rim. These facts were interpreted by Meen (1951) as showing that the rim had not been glaciated. Harrison (1954) however recognized that the rim had been glaciated and suggested that the crater might have been an independent centre of glaciation with its own ice-cap. Neither suggestion is plausible in the face of the typical scouring in the latest glacial direction (N70°E) evident on the rim (Pl. XIII). The lack of glacial striations and the angular appearance of outcrops can be explained by more rapid erosion on the rim due to its topographic eminence. On the other hand it seems likely that the crater might passively fill with ice and snow in advance of glaciation, as it does now during the winter, and that the interior of the crater would thus be protected from continental glaciation.

Plate XIII shows clearly that the northeast-trending valleys crossing the rim have been scoured, but that the northwest-trending valleys have not. The latter are steep-walled, flat-bottomed canyons. This suggests that the rim originated in the period between the two recorded directions of ice-movement, probably a few tens of thousands of years ago.

An attempt was made to judge the depth of glacial abrasion in the rim. If the considerations of the last paragraph are correct, the rim was abraded only during the latest period of glaciation. Examination of basic rocks in the hinterland showed that boulder trains extended downstream about 1,000 feet suggesting that this was the most likely distance the base load of the glacier was carried. Easily identified units on the rim were selected (those with a high content of green epidote) and an attempt was made to trace their boulder train, but no such trains could be found. On the contrary, boulders of these rocks were randomly distributed within a few hundred feet of the outcrops, suggesting downhill creep as the principal transporting agent. It has already been remarked that none of these distinctive boulders was found in the belts of transported glacial boulders. As the trains of boulders occur outside the rim, the most plausible conclusion is that very little material from the rim was transported in the downstream direction. Unfortunately this is a negative conclusion which is almost impossible to prove, but it does seem more in accord with the rather meagre evidence than Millman's (1956) conclusion that several hundred feet of solid rock were removed from the rim by glaciation.

Recent landforming processes at work in this region are not of the type found in moderate latitudes. Solifluction and frost heaving are the two principal agents. The main valleys are at present filled with streams of slightly rounded boulders. These boulders appear to represent a downhill creep of felsenmeer, the recent flowage being indicated by the growth of lichens on the lower side of the boulders. The slopes on which these boulders flow are low, not more than 4 degrees. Most of the streams had a minute amount of water flowing at the bottom, but it seems likely that the transporting medium is ice during the winter and spring.

Solifluction in till areas gives rise to a curious phenomenon resembling a stone dam. This results from the broad scale flowage of fine silt and cobbles until it is arrested by several large boulders. The silt flows through and the small boulders are wedged into interstices, forming a remarkably solid structure. These dams form radial to the local drainage direction and may reach several hundred feet in length. They are common to the northwest of the crater (Pl. XIII) and seem to be the structures interpreted by Meen (1957) as damped waves resulting from the formation of the crater.

Frost breakage is probably at present the main cause of the breakdown of solid rock. All stages of the formation of boulder fields can be seen (Pls. VII, II, and III). Felsenmeer, fields of frost-broken blocks, is one of the main forms of land cover in this region. A misinterpretation of these boulder fields seems to be responsible for the widely published but erroneous statement that large areas are covered with ejectamenta from the crater (cf. Baldwin, 1963).

The Arctic nature of the climate in this region is emphasized by the short ice-free season, about 45 days, and the number of firn banks existing on the rim. One in particular on the east rim (Pl. V) occupies a cirque-shaped valley 300 feet long and 60 feet high, and is composed of blue ice. It could be called an incipient glacier. A considerable line of firn occurs on the steep north-facing cliffs inside the crater. Ice action is presently spalling material from the steeper slopes, resulting in cliffs at breaks in the slope and replenishing the felsenmeer fields.

STRUCTURAL GEOLOGY

Three distinct structural styles are superimposed upon one another in the vicinity of the crater. The oldest, a series of complex, vertically dipping, isoclinal folds, is cut by four systems of fractures, all of much the same age. Superimposed upon these old regional structures is intense local deformation centred on the crater. The older structures are typical of large areas of granitoid Archaean rocks. The younger structures are unique in this region and appear to be associated with the crater.

Folds

Mapping of folds in the Archaean rocks is rendered difficult by the lack of suitable marker horizons and by the uncertainty of the significance of the gneissosity. Inclusion-rich granite-gneisses were used as horizon markers with local success. Several north-trending isoclinal folds were delineated by tracing out these markers. The small structures are all of chevron type, and from the total absence of low dips, it may be inferred that the large structures are also. Axial plane cleavage is strongly developed in the hinge zones. Generally the gneissosity parallels this cleavage. The axial planes of small folds trend north and dip vertically, or steeply, east. Plunges of the minor structure are generally south and less than 10 degrees. Characteristic aberrations of strike and plunge occur in the rim of the crater; these are discussed below.

The interpretation of the fold pattern in this area is shown in Figure 4. The inclusion-rich rocks are interpreted as all belonging to one horizon. This interpretation is speculative, but it is certain that the general effect of the folding is the development of a strong parallelism in the gneissosity. The strikes of the gneissosity rarely deviate more than 20 degrees from north in areas remote from the crater, and tend to be almost perfectly parallel in areas of a few thousand square feet.

Fractures

On a practical scale there is no distinction between joints and faults in this area. 'Joints' invariably show minute displacements, probably due to frost heaving; 'faults' rarely if ever show any large displacement on a single fracture, but instead consist of a large number of closely spaced fractures, each with a small displacement. Fractures appear in systems: widely spaced, planar fractures are mapped as joints; closely spaced fractures are mapped as 'faults', especially when accompanied by shattered rock. Strongly sheared and slickensided material is uncommon.

A pervasive fracture system trends N65°E to N75°E, causing the 'grain' of the topography obvious in Plate XIII. The strike of these fractures is remarkably constant over large areas, and their trend was commonly used to determine if frost-heaved bedrock had been substantially rotated. Dips are 80° to 90° N. Zones of augen-gneiss and brecciated feldspar-biotite rock occur along major fractures of this system, showing that recrystallization took place after the fracturing. Right-hand movements on these fractures can be measured at a number of places on the east side of the crater, particularly on the large fracture just at the southeast corner of the crater. Displacements rarely exceed a few tens of feet. Occasional slickensides suggest that the vertical and horizontal components of the latest movement were about equal. A major fault zone of this system covers most of the east rim of the crater. As shown on the geological map, recrystallized breccias and augen-gneisses occur in at least five different zones.

A second major fracture system trends N15°W to N5°E; dips of these fractures are generally within five degrees of vertical. The western rim of the crater terminates against a major fault of this set (Pl. XIII). Unlike the northeast-trending faults, which are diffuse and branching, these faults are narrow, intensely slickensided belts of shearing, containing contorted biotite schist. Slickensides indicate that the latest movement on these fractures was west side south and up. A rather poorly defined granite-gneiss contact west of the crater appears to show about a 500-foot offset in the left-hand sense.

Two major fault systems appear to intersect at the western edge of the crater. The intersection is marked by spectacularly shear folded and deformed schists. Faults of the northeast trend have not been observed west of this area.

A few joints have a trend of N25°E to N40°E. They are uncommon, and appear to represent a feathering fracture diverging from the east-northeast fractures. Fractures trending N85°W to N60°W appear sporadically, but are particularly well developed on the south and southeastern part of the rim. Unlike the fractures mentioned above, they have jagged surfaces and no development of sheared rock or augen-gneiss.

These four systems of fractures can be explained by assuming a northwest-southeast compression. The two main fracture systems are principal shear directions, the northeast-trending fractures are secondary shears, and the jagged southeast-trending joints are tension fractures. This scheme can be improved slightly by assuming a simultaneous counterclockwise couple to explain the intense shearing on the north-trending fractures, compared with the more diffuse shear on the east-northeast-trending fractures. The assumed direction of compression is in accord with that assumed to have folded the Wakeham Bay belt to the north. The assignment of a Wakeham Bay (Proterozoic) age to the fracturing is speculative, but plausible. In any case, all the ground-up material in these fractures has been recrystallized and appears as augen-gneiss, biotite schist, recrystallized breccia.

Sheeting in this region consists of smooth parallel fractures 2 to 6 feet apart (Pl. VII), with low to moderate dips. Sheeting is particularly well developed on the massive granitic rocks and on the granitoid rocks in general. Some minor structures occur in the form of small domes with a generally northeast trend, but over any considerable area the dips are random. The strikes tend to be close to that of the most prominent local joint set. There appears to be no way of telling when the sheeting developed. The domes do not coincide with present topography.

Deformation of the Rim

Rocks in the topographic rim of the crater and the immediately adjacent hinterland have suffered deformation different in both style and intensity from that of the rest of the region. This deformation can conveniently be measured by deflections of three planar structures: gneissosity, fractures, and sheeting.

In order to plot variations in the trend of gneissosity the outcrop map was divided into squares 3,000 feet on a side, and all the strike measurements in each square were averaged. In all squares where more than one measurement was made deviations from the average strike were less than 25 degrees. This is a consequence of the general parallelism of gneissosity previously noted. The results are plotted in Figure 1 in such a manner that the averaged strikes in contiguous squares could be joined to form continuous lines representing continuous trends on the ground. Strikes on the rim of the crater are radial to the crater. This effect is achieved by a marked inward bend of the gneissosity east and west of the crater. Comparison with Figure 4 shows that fold axes are disposed in the same sense, and in addition, folds in the rim tend to plunge away from the crater at angles of about 30 degrees. The dips of gneissosity tend to be abnormally low in the rim rocks.

The principal fault zones in the crater area are plotted in Figure 2. A deflection similar in sense and magnitude to that of the gneissosity is apparent. The deflected parts of the fractures are indicated by dashed line. This deflection is plainly visible in the photo mosaic (Pl. XIII), especially on the east rim where all the prominent valleys, which represent old fracture zones, show a distinct curvature towards the crater.

In addition to the deflected ends of old fractures mentioned above, young fractures appear in the rim. These are easily distinguished from the older faults by the presence of fresh looking goudge and crushed rock (Pl. XII). In some places these faults follow older fracture zones and contain crushed augen-gneiss and schist. These young fractures are associated in pairs that parallel the old fracture sets, but dip in opposite directions; small down-dropped blocks are caught between them (Pl. XI). The faults cross the rim in a more or less radial direction, and hence indicate an enlargement of the circumference of the rim.

Sheeting patterns in the rim rocks fall into two parts, those in the outer rim and those in the crater wall. More than 500 measurements have been made on the former (Currie and Dence, 1963). On the crest and outer part of the rim the dip of the sheeting is systematically outward. The boundary of this outward dip is approximately the boundary of the crater rim. The cutoff is abrupt to the west but very gradual to the east. The pattern of sheeting in the rim crest is shown in Figure 3. A crude symmetry axis trends northwest, with the steepest dips occurring northwest of the crater. The average dips in this area approach 90 degrees. Some steep dips occur *towards* the crater, but seem to be localized on fault valleys. A few tens of feet away from these valleys the dips are much lower.

Sheeting inside the rim crest appears to dip at very low angles, almost at random. Unfortunately only 17 localities were found where dips inside the crater could be measured, but these outcrops are scattered around the crater and there is little doubt that the low dips represent a genuine difference between the outer and inner parts of the rim.

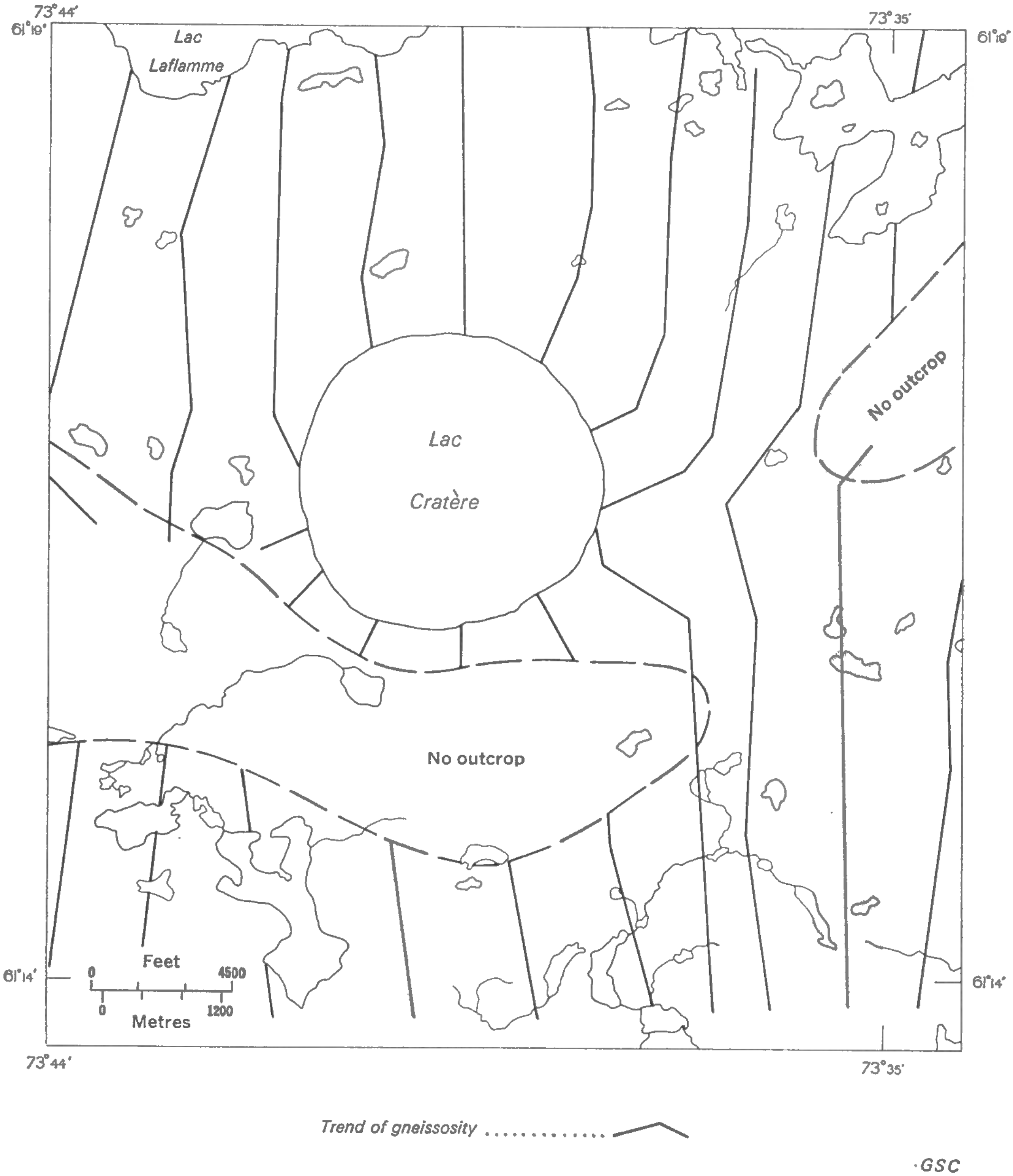

FIGURE 1. Strike of gneissosity near the New Quebec Crater. (Line segments are average strikes in 200 acre squares. Average strikes connected to show trend of gneissosity. Dashed line bounds area of no outcrop.)

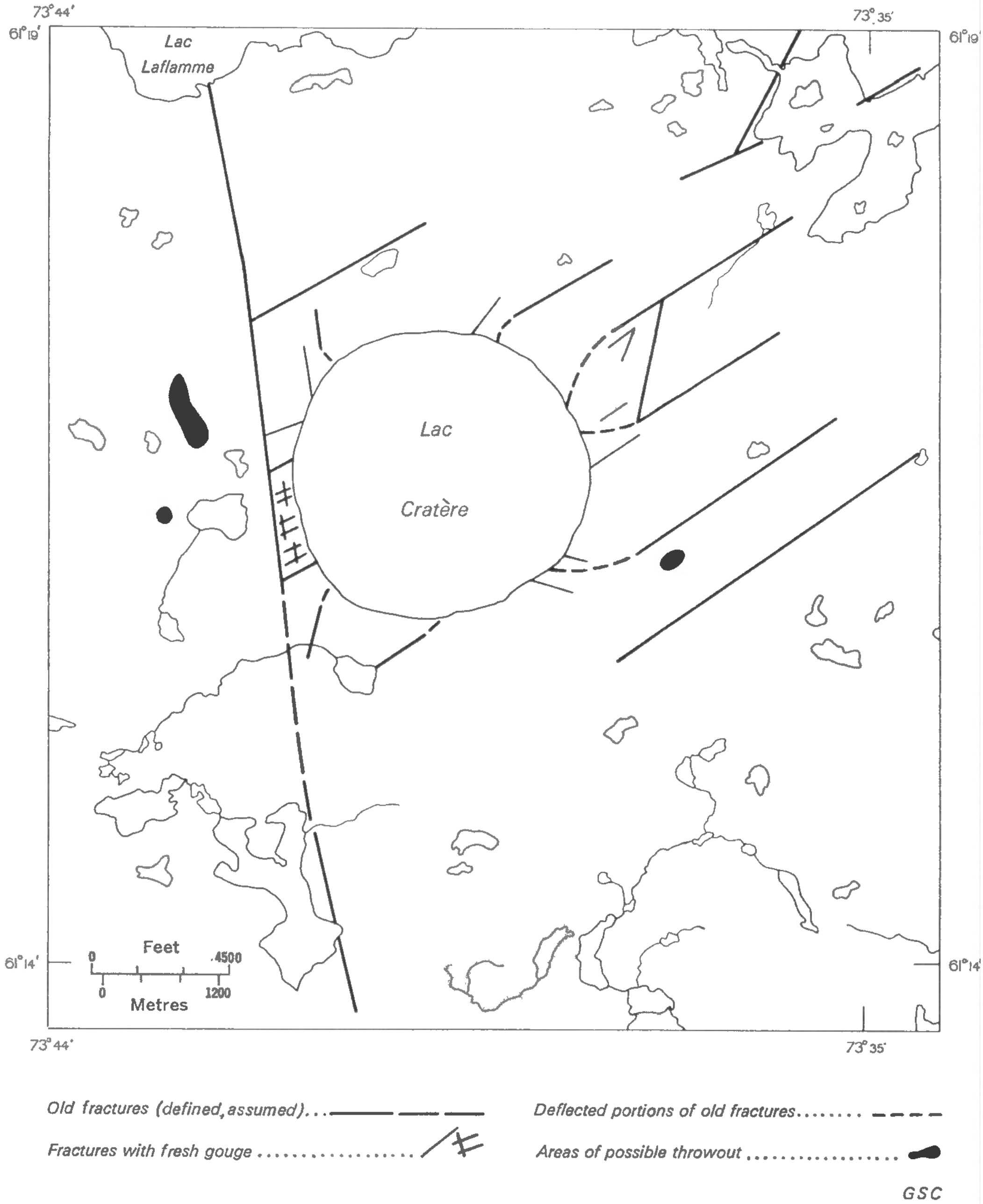

FIGURE 2. Fracture zones near the New Quebec Crater.

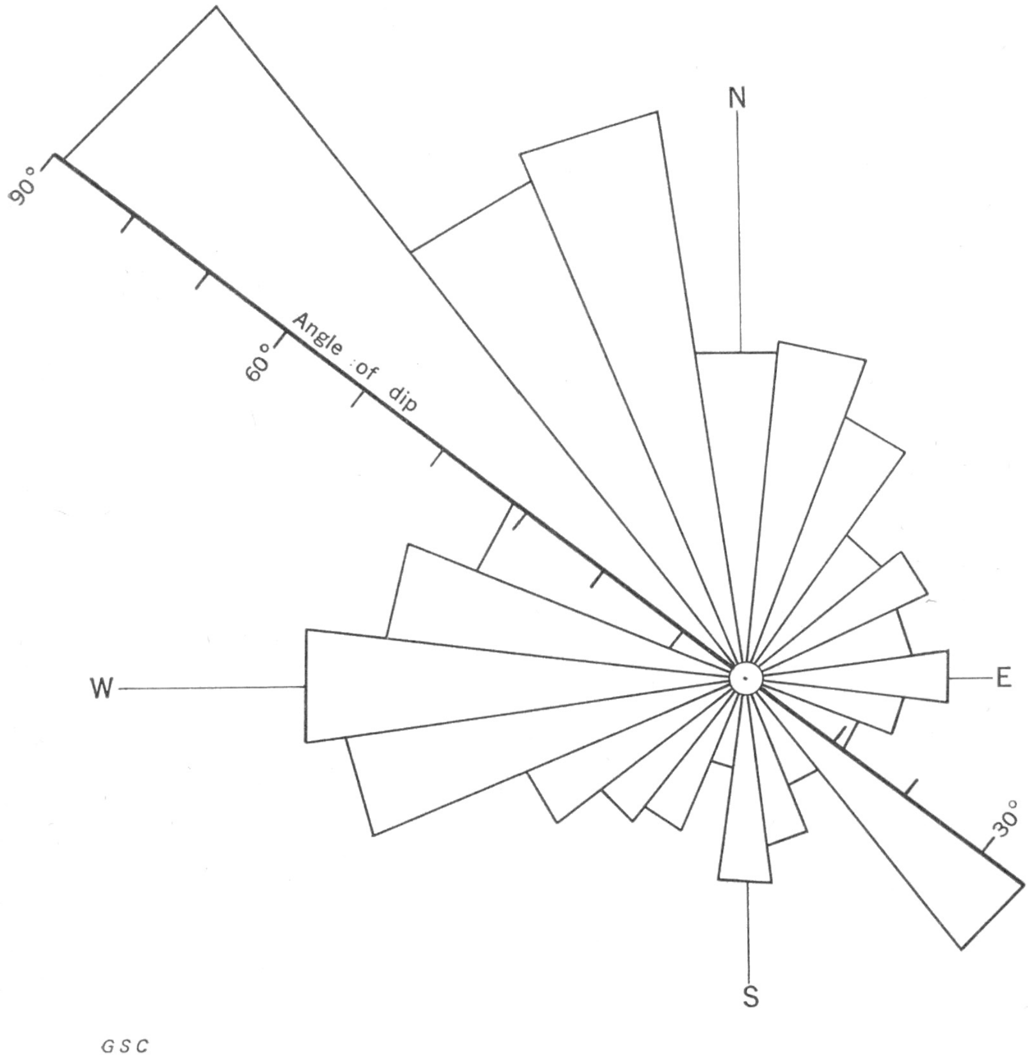

FIGURE 3. Outward dip of sheeting in the New Quebec Crater plotted against bearing.

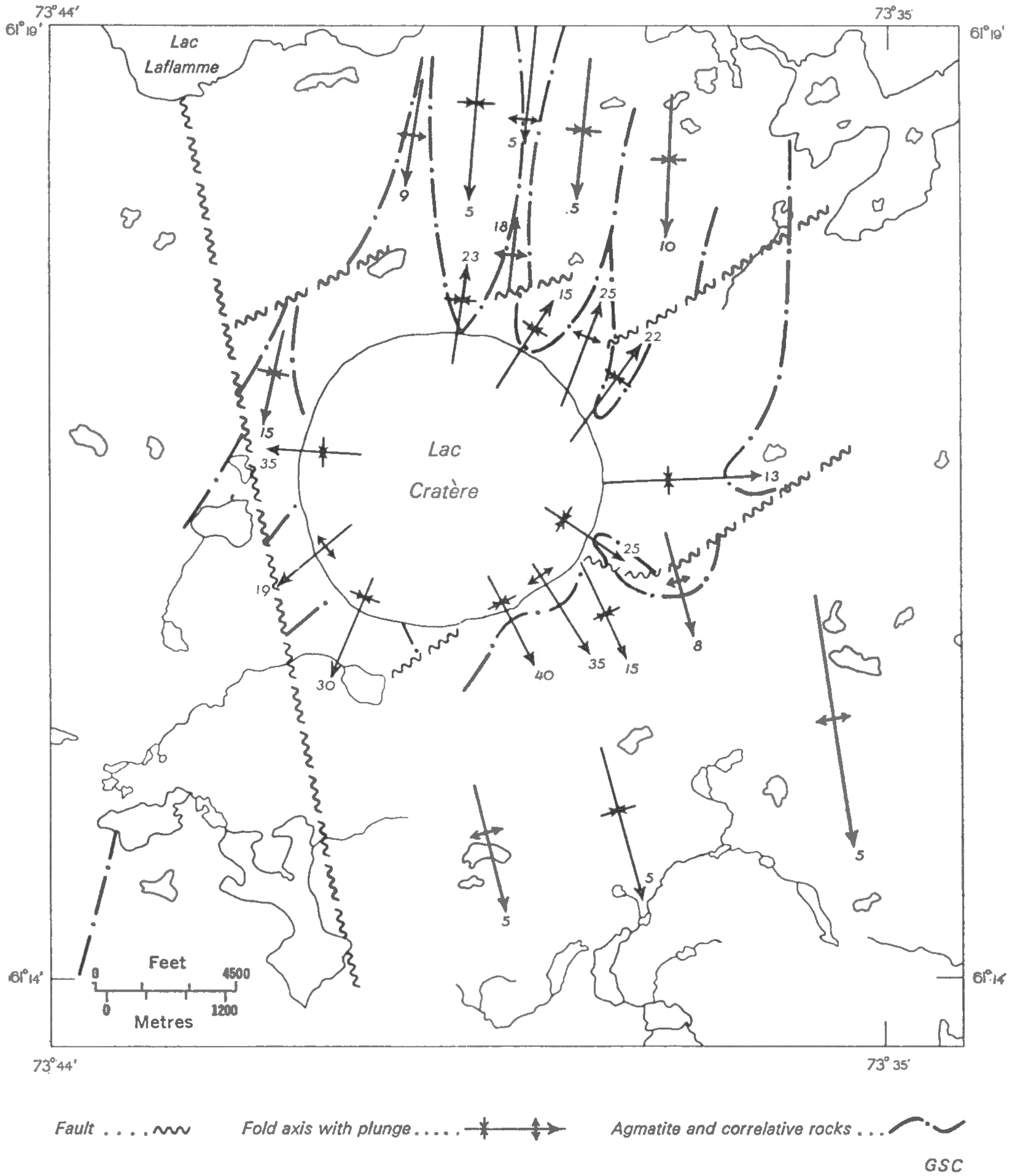

FIGURE 4. Fold axes in the region of the New Quebec Crater.

Interpretation of the Rim Structures

The congruent deflections of gneissosity and fracturing indicate a local displacement of the rock subsequent to the Proterozoic(?) faulting. The regional trend of the gneissosity suggests that the disturbed region originally had a north-trending gneissosity. If this be assumed, the displacement can be measured by comparing the original structural trend, obtained by extrapolating the trend from undisturbed parts across the disturbed area, with the present position of the trend line. The trend lines when plotted (Fig. 1) indicate that the distance between two points on opposite sides of the crater is now 2,500 feet less than it was prior to the latest deformation; 2,000 feet of this deformation occurs on the east side of the crater and only 500 feet on the west.

This considerable shortening, together with the attitude of the sheeting, suggests that at one time a dome may have existed over the crater. It will be shown that such a structure is consistent with the structural data from the rim. If the dips of sheeting in each sector on Figure 3 be averaged, the average angle of outward dip obtained is 32½ degrees. Assume the supposed dome to be a spherical cap of radius a, subtending an angle θ (Fig. 5). The chord S is taken to be 2,500 feet greater than 2a in order to explain the inward displacement of the gneissosity. Elementary trigonometry yields

$$S\text{-}2a = R(\theta - 2\sin\theta/2).$$

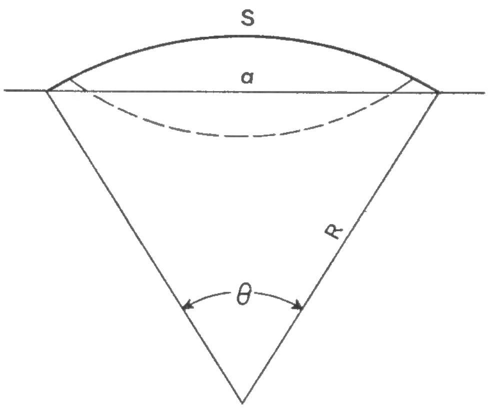

FIGURE 5
Cross-section of the spherical dome approximation to the former shape of the New Quebec Crater. (S, arc length; a, chord length across dome; R, radius of dome; Θ, angle subtended by dome, dashed line shows shape of crater approximated by spherical cap 10,000 feet in diameter and 1,300 feet deep.)

2a is known to be 18,000 feet (the maximum diameter of the deformed area), $\theta/2$ is 32½ degrees, and R is $a/\sin\theta/2$. These values yield S-2a of 2,600 feet. The concordance with the observed value is excellent, any excess being attributed to lengthening by tension faulting. Of course the non-symmetrical attitudes of the sheeting show that such a dome could not have been exactly spherically symmetrical, but the close approach of the whole structure to radial symmetry suggests that the calculations are reasonably accurate.

The observed graben faulting of the rim and the radial plunge of folds away from the rim are natural consequences of the formation of the assumed dome. In short, all of the structural peculiarities of the rim can be explained by assuming the formation of a large rounded dome over the present site of the crater. It is impossible to construct any other simple structure that will explain all the data.

The date of formation of the dome was post-Proterozoic (deflected faults) and preglacial (glaciated rim). In view of the deduction that the existing crater rim was glaciated only by the latest ice advance, a young age seems likely. A near surface deformation of 2,500 feet in 18,000 feet (13 per cent) without wholesale fracturing may seem implausible. Billings (1954, p. 301), discussing the intrusion of laccoliths, stated:

> The overlying rocks are elongated. . . . The amount of elongation depends of course on the shape of the laccolith but in some cases it is as great as 10 per cent and even more. . . . Tension cracks may form . . . but even where the roof is preserved such fractures are rare – apparently because the rocks were sufficiently plastic to yield without rupture.

Figure 5 shows that the dome at one time rose about 2,000 feet above its present surroundings (compared to a maximum relief of 500 feet for the present rim). The crater occurs on the culmination of the former dome. The formation of a depression of this size requires the disposition of a considerable volume of rock. This problem is considered in the next section.

ON THE ORIGIN OF THE CRATER

There is something fascinating about science. One gets such wholesale returns of conjecture from such a trifling investment of fact.

—Mark Twain—

This crater has in the past been considered to be of impact origin (Krinov, 1963; Baldwin, 1963). The principal evidence advanced is the shape of the crater and the lack of volcanic material associated with it. Baldwin (1963) considered seven criteria for recognition of impact craters: (1) elimination of terrestrial crater-forming mechanisms, (2) presence of meteoritic material, (3) presence of high pressure polymorphs (coesite, stishovite) characteristically occurring in impactite, (4) presence of ejecta from the crater (throw-out), (5) the shape of the crater, (6) presence of crushed material, either in the rim, or as a lens of breccia below the crater, (7) presence of shatter cones.

Let us consider these points. Meen (1952) failed to recover meteorite material by magnetic separation. The author repeated the attempt, likewise without success, and examined thousands of boulders. Nothing resembling meteoritic material was seen. If any meteorite material exists in this region, it must be so dispersed that it is virtually undetectable. Fall-out and throw-out do not occur around this crater, although conceivably they may occur below Lac Cratère. Shatter cones have not been observed near this crater. Crushed material does not occur in the rim. It will be shown that a breccia lens of about the same size must exist below the crater no matter what its manner of origin. Thus the only evidence of impact is the shape of the crater.

In general, the crater is the shape expected for an impact crater, that is, a depression surrounded by a raised bedrock rim. In detail, the height of the rim, the total depth of the crater, and the width of the rim all agree well with Baldwin's latest curves (Baldwin, 1963), suggesting that the crater, if it is of impact origin, is essentially unaltered. The structure of the rim however is completely unlike that of other closely studied meteorite craters. Shoemaker (1961) suggested that it might resemble the Meteor Crater, Arizona, but there is no overturned 'flap', so characteristic of the Arizona crater, no radial scissor faults, and little or no breccia in the normal faults that do exist. The most remarkable feature of this crater is the absence of any sign of violent upheaval. What deformation there is appears to have taken place slowly, so that the rocks have adjusted themselves with little or no fracturing.

From this analysis it is apparent that the impact theory for the origin of this crater is heavily dependent on the implausibility of a geological origin, and that if a plausible geological origin could be advanced the impact theory would suffer heavily.

It has been shown above that the structure of the rim and its topographic shape can be explained by assuming that the rim is the remnant of a large dome. Further, the absence of boulders of rim rocks in the hinterland has been remarked upon; in the author's opinion, this lack has a genetic significance. If the material from the crater is not outside the crater, it must be inside it or have escaped from beneath it. This is possible if fluid of somewhat more than the volume of the present crater has so escaped. It must have been more than the crater volume in order to allow for the expansion of the rock on brecciation. The presence of fluids is indicated by the widespread hydrothermal alteration inside the crater. This theory proposes that the crater resulted from up-doming of the country rock by hot fluids or possibly by a fluid-charged magma, followed by the escape of the fluid through the surface resulting in the collapse of the central part of the dome. It explains the fragment of vesicular volcanic rock and also offers a satisfactory explanation of the very local overturning of the sheeting (steam blasts directed along fissures) and of the low dip of sheeting inside the crater (down-bending of steeper sheets due to collapse).

The theory of collapse of a fluid-supported dome explains all the geological evidence and is at least as plausible as the impact theory. The geological evidence, although favouring the collapse theory, is inconclusive, because of the invisibility of the material hidden under the lake or removed by glaciation. Other possible lines of evidence must therefore be examined.

It has been remarked that on the collapse theory, the base of the crater must contain a large amount of breccia. If the crater and the collapsed part of the overlying dome are treated as segments of spheres with radius 5,500 feet and heights 1,300 and 1,500 feet respectively, the volume of this breccia may be calculated. Innes (1961) has shown that in the Brent crater the density of the breccia averages 10 per cent less than that of the solid rock. Assuming that this is so for New Quebec, the volume of breccia is 1.1 times that of the solid rock from which it formed. This latter volume is 1.36×10^{11}, so that the volume of breccia is about 1.47×10^{11} cubic feet. This is practically the same as that obtained by Innes (1961) for the Brent crater (1.91×10^{11}), which is almost identical in size with the New Quebec Crater. This coincidence suggests that gravity measurements designed to ascertain the amount of breccia beneath this crater are unlikely to distinguish between a collapse origin and an impact origin.

If heated gases have escaped from this crater in the recent past, it is possible that an abnormally high geothermal gradient may still exist. Dietz (1963) has recently argued that large impact craters must also display an abnormal temperature gradient for considerable periods of time. This matter needs more quantitative investigation, but at present it seems unlikely that heat measurements can offer conclusive proof of either method of origin.

Magnetic surveys near the crater have shown no significant anomalies (Meen, 1957). This observation is in accord with either possible origin. On the whole, it does not seem likely that geophysical measurements will offer any conclusive evidence of the mode of origin of the crater.

The critical evidence lies concealed beneath the crater lake and the rocks will have to be drilled before the origin of this crater is definitely known.

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Appendix I

PETROGRAPHY OF A VOLCANIC FRAGMENT FROM THE NEW QUEBEC CRATER

Hand specimen. The specimen was roughly ovoid, about 6 inches in long dimension and 3 inches in diameter. The external surface is slightly rusted, but not abraded or spalled. In places a very thin skin of black, glassy, scoriaceous material adheres to the outer surface. On a fresh surface, the rock is dull grey, with 15 to 20 per cent of the surface occupied by white to pale buff inclusions. The matrix is extremely vesicular, with vesicles ranging in size from microscopic to about 5 mm. The bulk specific gravity is 2.240 whereas the powder specific gravity is 2.731, indicating that vesicles occupy about 18 per cent of the volume. The inclusions range in size from 0.5 to 5 mm. They tend to be round, or lensoid, but a few are elongate. In some inclusions, a core of clear glass is surrounded by finely powdered material.

Thin section. Under the microscope, the matrix is seen to consist of brownish, glassy or cryptocrystalline material charged with plagioclase microlites and lesser amounts of opaque dust. The plagioclase microlites (An_{33}) comprise one third to one half the matrix, whereas magnetite grains and unidentifiable opaque dust occupy 5 to 10 per cent. The remainder is translucent to transparent, brownish or greenish brown, isotropic material, which locally has a poorly defined lath-like structure. This material is isotropic and without crystal boundaries under the highest magnification available.

The inclusions range from rather fresh single crystals of plagioclase to blobs of clear glass. The crystals are generally partly recrystallized and show irregular internal areas of low birefringence. In some cases there are sinuous lamellae of clear glass in the crystal. The outer edges of the crystal appear to be reacting with the matrix. The contact is rather diffuse, and small parts of the crystal are recrystallized into microlites. The crystals rarely show any plagioclase twinning but have a $2V = 85°$ and refractive index 1.547 which correspond to An_{33}. Most of the inclusions consist predominantly of clear glass with minor amounts of partly melted fragments. The contact between the melted and unmelted parts is sharp. The clear glass generally has an unfilled vesicle in the centre, the larger the amount of glass, the larger the bubble. The glass has a refractive index averaging 1.542, which is substantially higher than might be expected for a glass of this composition. (The expected value would be about 1.534.) The contact of the glass with the matrix is sharp, and its shape (smooth curves), suggests that the glass formed small liquid drops that are held together by surface tension. Around the inclusions the plagioclase microlites are well oriented, bending around the inclusions in well-defined flow textures. Such texture is imperceptible or absent elsewhere[1].

Chemical Analyses

	I	II	III
SiO_2	68.6	65.3	67.37
Al_2O_3	15.8	15.7	15.28
Fe_2O_3	2.1	1.5	1.13
FeO	4.0	3.5	3.86
MgO	1.8	2.0	1.20
CaO	3.2	4.2	4.46
Na_2O	3.7	4.9	4.67
K_2O	0.8	2.7	0.92
TiO_2	0.42	0.93	0.72
MnO	0.06	0.05	0.15
	100.5	99.6	99.76

I. Analysis of volcanic fragment from the New Quebec Crater; analyst Mrs. T. D. Dawes (analysis by rapid methods).

II. Analysis of composite sample of country rocks from the region of the New Quebec Crater; analyst S. Courville (analysis by rapid methods).

III. Analysis of augite hypersthene-andesite, Hakone volcano, Japan (from H. Kuno "Petrology of Hakone Volcano and the Adjacent Areas, Japan"; *Bull. Geol. Soc. Amer.*, vol. 61, pp. 957-1020; analysis No. 23 (1950)).

If the impact hypothesis is correct, the 'volcanic' fragment must result from impact melting of the country rocks. Column II shows that this is a qualitative possibility, although it is hard to see why the melted product contains only half as much titania and alkalis as the host, and substantially more silica. Column III shows that the rock has close chemical affinities with volcanic rocks elsewhere. Kuno (1950, p. 993) deduces that magma of this composition can arise by simple crystallization differentiation from olivine basalt.

[1]Basal deformation lamellae have been discovered in an inclusion of quartz examined by M. R. Dence (M. R. Dence, pers. com.). Quartz has not been observed in sections examined by the author, but inclusions of plagioclase commonly show a peculiar swirling fracture pattern reminiscent of a fingerprint. These unusual deformations make it highly probable that the fragment came from the crater, and is not an exotic transported boulder.

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