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# CLEARWATER COMPLEX, NEW QUEBEC

(Report and figure)

H. H. Bostock

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## ABSTRACT

Clearwater Lake, centred at 56°10'N, 74°20'W, consists of two circular basins roughly 19 and 16 miles in diameter respectively. A concentric ring of islands 10 miles in diameter and a low broad central reef area lie in the west lake. The smaller east lake is slightly more than 500 feet deep, but the west lake is considerably shallower.

The hinterland and islands are underlain by Precambrian plutonic rocks. These are intruded by diabase bodies, more abundant on the island ring than in the hinterland. Local remnants of Middle or Upper Ordovician limestone are preserved on the island ring. Precambrian rocks and diabase of the island ring are intruded by a sequence of rocks progressing from friable volcanic breccia through coherent volcanic breccia to massive dacite. Argillization of plutonic rocks is associated with the friable breccia, whereas partial fusion and recrystallization are associated with the later intrusions. Two K-Ar whole-rock age determinations on massive dacite yielded 285 and 300 million years.

Feldspar, particularly plagioclase, in some plutonic rock fragments in the friable breccias, and on the surface of the small islands of the central reef area is partly or entirely converted to glass (maskelynite) so as to preserve mineral textures such as antiperthite. Mafic minerals are only slightly affected and cleavage is commonly developed in quartz.

The order of emplacement, and the petrographic details of the rocks of the Clearwater Complex and the alterations that accompanied them do not support an hypothesis of meteorite impact. The structure is thought to be of volcanic origin, transitional between cauldron subsidence and cryptoexplosion. A local intrusion of hot gas into diabase magma at depth is advanced as a tentative working hypothesis to account for the features observed.

# CLEARWATER COMPLEX, NEW QUEBEC

## INTRODUCTION

Clearwater Lake is centred at 56°10'N, 74°20'W, or some 80 miles east of the arcuate coastline of Hudson Bay at Richmond Gulf. The lake consists of two roughly circular basins separated by a fringe of islands. The larger west basin contains a prominent concentric ring of islands some 10 miles in diameter and six small islands near the centre. Field work for the present report was carried out in 1963 while the author was attached to Operation Leaf River. The hinterland in the vicinity of West Clearwater Lake was examined on a single flight by helicopter at a radius of 11 miles from the centre. Sixteen equally spaced landings were made. At the time of the flight, June 21, 1963, ice had left the marginal bays but was still solid on the main parts of the lake. The author returned to the west lake on July 11 and remained until July 25, during which time all the islands of the ring and in the centre of the west lake were visited by boat.

Interest has been focused on the Clearwater structure by the staff of the Dominion Observatory (Beals, Innes, and Rottenberg, 1960)[1] who have included it in their list of possible meteorite impact scars. In order to compare the Clearwater structure with a theoretical model for impact structures the Dominion Observatory drilled four diamond-drill holes under the direction of Mr. M.R. Dence during the winter of 1962-63, three in the west lake (see map) and one near the centre of the east lake. Through the cooperation of the Dominion Observatory and Mr. Dence the author was able to examine the drill core and obtain samples from it. The description of the drill cores has been published elsewhere (Dence, Innes and Beals, 1965); the author's observations however confirmed his general ideas on the origin of the Clearwater feature. Mr. Dence also kindly provided the recent bathymetric data included in this report. Dr. A.C. Turnoch of the Mines Branch undertook the partial fusion of blocks of plutonic rock in an attempt to reproduce some of the alteration textures found in rocks from Clearwater Lake.

## PHYSIOGRAPHY AND PLEISTOCENE GEOLOGY

Clearwater Lake consists of two roughly circular basins separated by a fringe of islands. The broader west basin contains a prominent concentric ring of islands some 10 miles in diameter, reaching maximum

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[1]Names and/or dates in parentheses refer to publications listed in the References.

elevations roughly 350 feet above lake level. Within this ring, near the centre of the lake, are six small flat islands reaching only a few feet above lake level. At lake level (780 feet above sea-level) the basins are roughly 18 and 12 miles in diameter; however, about the western basin the land surface rises to a poorly defined and interrupted rim some 3 to 8 miles back from the shore. Maximum elevations of this rim are close to 1,400 feet. Beyond the rim the land merges with the gently westward sloping, rounded, dissected surface of the surrounding shield. In recent soundings most of the western lake was found to be less than 150 feet deep, and depths approaching or slightly exceeding 500 feet were found in the east lake.

Glacial striae on the northeast islands of the ring suggest an early ice-movement of S50 to 70°W. A later ice-movement of S80°W to N80°W is suggested by striae and crag-and-tail deposits found in most parts of the west basin. Pebbly to silty drift with scattered boulders forms most of the overburden. Wave-cut benches and prominent raised beaches suggest that water level stood 25 feet above the present lake level for some time after the ice retreated. It is not known, however, whether these represent an early lake level or the east margin of the post-Pleistocene marine overlap.

## GENERAL GEOLOGY

The oldest rocks (1) of the area comprise gneissic, foliated, and massive granite to gabbro of early Precambrian age. They form the hinterland around, and the basement beneath, Clearwater Lake. These rocks are overlain by at least four small remnants of middle or upper Ordovician limestone (2) found only on the island ring. The Precambrian rocks are intruded by dykes and irregular bodies of diabase (3) not observed in the immediate hinterland, and hence believed to be post-Precambrian and related to the Clearwater Complex. Following the diabase, a sequence of rocks progressing from friable volcanic breccia (4) through coherent volcanic breccia (5) to massive dacite (6) was emplaced during the Pennsylvanian.

The terms "friable volcanic breccia" and "coherent volcanic breccia" are coined to distinguish between the early soft, crumbly, porous, deeply argillized breccias, and the later fresher, less porous, resistant, tough, cohesive breccias. The adjective "volcanic" is used above because, in fact, these breccias more closely resemble volcanic breccias than tectonic or sedimentary breccias. This resemblance does not imply that a meteoritic origin is not possible. The term "volcanic" will be omitted from here on but the reader should bear this resemblance in mind where the terms "friable breccia" and "coherent breccia" are used.

## Table of Formations

| Era | Period | Formation | Lithology | Associated Alteration |
|---|---|---|---|---|
| Palaeozoic | Pennsylvanian(?) | Clearwater Complex | Dacite | Partial fusion and recrystallization |
| | | | Coherent volcanic breccia | |
| | | | Friable volcanic breccia | Argillization<br>Maskelynitization |
| | | | Intrusive contact | |
| | | | Diabase | Internal brecciation |
| | Intrusive contact | | | |
| | Middle or Upper Ordovician | | Limestone, slightly recrystallized | |
| Unconformity | | | | |
| Precambrian | | | Granite, quartz monzonite, granodiorite, diorite, gabbro, granulite; massive foliated or gneissic | |

## Precambrian Rocks (1)

The hinterland about West Clearwater Lake is, so far as is known, entirely underlain by fresh medium- to coarse-grained plutonic rocks of the Superior Province of the Canadian Shield (age 2,350 million years or greater). Mostly these rocks consist of massive to slightly foliated granodiorite, quartz monzonite, minor granite, and amphibolite, with a variable proportion of foliated to massive inclusions more mafic than their host (1a). Olive-green, chiefly massive granulite (1b), containing bodies of light pink-grey granitic rock, outcrops on the islands between the two basins. North of these islands, banding and foliation appear to be better preserved (1c) than in the rocks to the south and west.

Gneisses, and massive to foliated granodiorite and quartz monzonite, similar to those of the hinterland, are exposed along the shores and locally in the central parts of the islands of the ring. Massive to slightly foliated gabbro-diorite (1d) forms most surface exposures on the islands and shoals in the central part of the west lake and on some of the smaller islands to the west. Though these rocks (1d) appear to be more basic than many of the Precambrian rocks outcropping in the hinterland, this feature is believed to be a coincidence of exposure. A small exposure of granodiorite-quartz monzonite is present on one of the centre islands. Minor granite-pegmatite dykes are present cutting the basic rocks, and structures such as foliation and inclusions typical of the Precambrian rocks of the hinterland, though not abundant, have been found on the central islands.

Locally on the island ring Precambrian basement rocks (1e) have been intensely fractured and brecciated, or intruded by numerous small dyke-like bodies of coherent breccia. Other areas on the island ring consist of basement rocks (1f) which have been fractured, intensely argillized, and intruded by small veins of friable breccia. A few exposures (1g) show Precambrian rocks that have been recrystallized in proximity to massive dacite or coherent breccia.

Structural trends in the Precambrian rocks, though strongly suggested by the parallel alignment of many ridges and valleys of the hinterland in a west-northwest direction, are not strikingly apparent on most outcrops. The dominant direction of intermittent foliation and banding appears to be northwesterly in the western and northern parts of the west basin and more northerly in the central, southern and eastern parts. Such foliation is commonly not closely parallel with the ridges and valleys. The pronounced grain of the country seen on maps and air photographs is therefore probably a reflection of glacial scouring, principally along fractures rather than parallel with foliation in the rocks. Such fracturing of surface rocks on a regional scale must have been later than the development of foliation which in most outcrops has been partly or completely destroyed by deep-seated recrystallization and intrusion. The possibility that much of this fracturing may be very much younger than the rocks in which it occurs, and may reflect the tectonic environment into which the Clearwater Complex was emplaced, should be considered in further more-extensive studies of this area.

## Ordovician Limestone (2)

Dark grey and blue-grey to white limestone, showing varying degrees of recrystallization, outcrops on two islands in the eastern half of the ring. Locally the limestone appears to lie unconformably on the Precambrian surface in windows through the younger massive dacite. Elsewhere it may be partly engulfed in dacitic rocks. On Volcano Island, at the only contact exposed, the limestone is altered along the contact with dacite and is therefore inferred to be older.

Limestone drift, commonly somewhat less recrystallized than that in outcrops, is found on many of the islands in the ring. Fossils from this drift have been identified as Middle or Upper Ordovician (Kranck and Sinclair, 1963).

Limestone does not appear as fragments in the breccias of the Clearwater Complex, nor does it appear at several localities where the unconformity between Precambrian rocks and coherent breccia or dacite is exposed in bluffs. From this it may be inferred that the limestone cover deposited in the Ordovician was thin and had already been partly removed by erosion before the dacite was emplaced.

## Clearwater Complex

The Clearwater Complex comprises early diabase intrusions followed by a sequence of rocks progressing from friable breccia through coherent breccia to massive dacite. The time interval between emplacement of the diabase and the breccias is unknown. Distinctive alterations that accompanied their emplacement produced rocks that form an important part of the complex; these are described in a later section.

### Diabase (3)

Numerous small dykes and irregular bodies of aphanitic, fine- and medium-grained diabase cut the Precambrian rocks of the island ring.

The diabase is considered to be older than the volcanic breccias and dacite because it is cut by dykes of coherent breccia, and a few fragments of altered rock similar to the diabase have been found in the friable breccia. The diabase is thought to be post-Precambrian and related to the Clearwater Complex because, although numerous on the island ring, no diabase bodies were found in the immediate hinterland around the west lake. Furthermore, the structure of the Clearwater diabase bodies, which appear notably discontinuous and irregular in shape, is different from that of the Precambrian diabase dykes common in the Shield which can be traced for great distances along strike.

The diabase bodies on the surface are commonly brecciated and everywhere contain moderate to large amounts of metamorphic hematite. Where diabase dykes have been brecciated, as little as 50 per cent of the rock may be made up of recognizable diabase fragments, the rest being fine-grained hematite-rich material. Such dykes do not appear to contain any foreign plutonic-rock fragments; where plutonic fragments are associated with diabase bodies the rock appears to be diabase-rich agglomerate. This brecciation and alteration of some diabase dykes may have occurred during emplacement of the volcanic breccias or dacite, but the possibility that these dykes were in part emplaced as a gas-rich mush of fragments and magma should be considered.

The principal minerals in the diabase, exclusive of alteration products, are augite [(+) 2V=48°, beta 1.686], plagioclase ($An_{58}$), magnetite, minor quartz, and trace amounts of apatite. The plagioclase and augite are similar to their counterparts in the dacite.

## Friable Volcanic Breccia (4)

Breccias composed of fragments of fresh to severely altered plutonic rocks and minerals in a friable, light grey-pink or red matrix containing hematite and montmorillonite were found in the northeastern three quarters of the island ring. Locally these breccias appear to grade into recrystallized, argillized granodiorite by increase in proportion and size of fragments and decrease in the amount the fragments moved. Elsewhere they may be gradational to more coherent breccia by decrease in porosity and alteration of the matrix, and by change in the type of alteration of the included fragments. The more coherent breccias commonly consist of two phases, slightly different in colour and porosity. The earlier breccia, which itself occurs as fragments in a matrix of a younger breccia, is typically more dense and coherent than the younger enclosing breccia. In places fragments of the older breccia are distorted into lenses to give the appearance of flow banding. These features however should not be regarded as conflicting with the general trend of breccia intrusions to become more coherent as intrusion progressed, as shown by coherent breccia dykes cutting friable breccia. If emplacement of these breccias occurred in pulses then the more-coherent, less-porous inclusions may represent a slightly earlier pulse emplaced close to the wall-rocks when the vent was perhaps narrower. Chilling of such material may have increased its viscosity enough to prevent further evolution of volatiles. Fragmentation and incorporation of this earlier breccia may then have occurred during later pulses. Alternatively, if slight variations in volatile content of material injected during the transition from friable to coherent breccia emplacement be assumed, the age relations suggested by the complex breccias may merely reflect the greater explosiveness of the material that formed the more friable porous phase.

Friable breccia at the southeast end of the large double-tailed island locally contains black glass as rounded distorted blebs and as coatings on some altered white to brown plutonic rock fragments. This glass (refractive index 1.551, specific gravity 2.62) contains corroded fragments of clear white glass with a refractive index ranging from 1.461 to 1.531, suggesting that the clear fragments may consist in part of fused quartz.

The structure of the friable breccia bodies is largely unknown. Locally traces of flow banding (described above) suggest that some are flow breccias. Others may equally well occupy large dyke-like or neck-like fissures. In some instances (4a), where the plutonic fragments are commonly large, only slightly altered, and constitute the greater part of the rock, the friable breccia resembles a volcanic agglomerate.

Small masses of breccia have been found with glassy to aphanitic matrices and containing vesicles partly filled with chabysite, calcite, and clay minerals. One of these is a breccia dyke (4b) about a foot thick; two others appear to be crevice fillings in the Precambrian rocks nearby. Rare boulders of similar material have been found on the beaches. The relationship of these rocks to the rest of the complex is not known but they are thought to be related to the friable breccias.

## Coherent Volcanic Breccia (5)

The coherent breccia is found in all parts of the island ring and appears to be gradational between friable breccia and massive dacite. It consists of variable proportions of angular basement blocks in a pink, red, purple, or grey matrix that is commonly finer grained than that of the massive dacite. Locally it is noticeably vesicular. Dykes of this breccia intrude the basement rock and irregular masses penetrate the friable breccia.

Coherent breccia bodies transitional to friable breccia form masses reaching 200 feet in thickness on Volcano Island. On two of the smaller islands similar rocks are well enough exposed to suggest that they form major necks or dyke-like structures. Several small coherent breccia dykes are exposed for as much as 15 vertical feet along the shorelines of the islands but exposures are not good enough to trace these inland. Coherent breccia also commonly appears at the base of massive dacite bluffs where it is gradational into the massive dacite.

In thin section, coarser-grained specimens show grain sizes near 0.01 mm but the matrix of finer-grained samples is commonly hematite rich and opaque. Dyke rocks are commonly microlitic. Fresh angular plagioclase crystals and fragments with compositions between $An_{25}$ and $An_{45}$ are common and are thought to be inclusions. Augite inclusions are less common. Quartz inclusions are almost invariably surrounded by pyroxene haloes which are in turn commonly surrounded by a zone of quartz and potash feldspar interlaced with apatite needles and slightly coarser than the matrix. More rarely, quartz alone may form the outer haloes and this quartz is commonly of parallel optical orientation to the grain within. Many quartz inclusions show 'dusty' brownish cores with cleavage-like fractures.

## Massive Dacite (6)

Massive, light red to grey dacite forms the cappings of most of the higher islands, but the thickest sections are in the southern and eastern islands of the ring. All gradations between very fine grained inclusion-rich coherent breccia and massive fine-grained dacite may be found. The larger exposures of dacite are thought to be remnants of flows, as nearly horizontal contacts between dacite and plutonic rocks are commonly exposed at the base of the larger bluffs. A variable zone of dacite transitional to coherent breccia is commonly present along contacts. Higher zones of dacite transitional to coherent breccia, which might suggest upper contact zones, have not been found and the possibility that the major dacite bodies are sills is therefore unlikely.

No dykes are known to cut the massive dacite, and in view of this and its apparent stratigraphic position it is considered to be the youngest member of the Clearwater Complex. Fleischer and Price (1963), using the uranium fission track method have dated glass from the Clearwater Complex at 34 million years. K-Ar whole-rock age determinations[1] have been completed on two samples of massive dacite which yielded ages of 300

[1]Argon extraction, mass spectrometry, and age calculation, by R.K. Wanless, J.A. Lowdon, and R.A. Stevens.

and 285 million years respectively. The date of emplacement is tentatively considered to be Pennsylvanian.

Locally small fragments of Precambrian rock are included in otherwise massive fine-grained dacite. Such fragments are irregular in shape and are commonly associated with yet smaller fragments, consisting of one or more grain aggregates from the original plutonic rock. These inclusions leave the observer with the impression that they were frozen in the last stages of disintegration into dacite magma. At one locality on the western islands of the ring, dark green, pyroxene-rich nodules containing some plagioclase and accessory sphene and calcite were found. Rare small inclusions similar to these nodules were observed in thin sections of massive dacite elsewhere.

Under the microscope the massive dacite is seen to be fine grained, allotriomorphic, and essentially equigranular with a granophyric texture. Plagioclase (twinned central zones $An_{55}$), potash feldspar [(-) 2V=20 to 50 degrees], quartz, and augite [(+) 2V= 50 degrees; beta 1.695] are the major minerals present. Plagioclase crystals commonly show outer zones gradational through more sodic components to potash feldspar. Patches of quartz and potash feldspar interstitial to plagioclase and pyroxene are common. These patches are laced with extremely acicular crystals of low birefringence and negative elongation thought to be apatite. Such crystals penetrate at least the outer part of plagioclase crystals. Minute quantities of zircon crystals constituting roughly ten millionths per cent by weight of the sample examined are present. Red dacite contains augite partly altered to hematite, whereas grey dacite contains augite partly altered to chlorite and minor biotite. Grain size averages about 0.4 mm and, though essentially equigranular, most specimens contain somewhat larger augite crystals and a few distinct subhedral to anhedral plagioclase crystals averaging close to 0.8 mm. The latter are commonly intensely antiperthitic, like the plagioclase in some rocks altered by the dacite (see next section: "Rock Alteration"). In view of this, and the intimate disintegration of plutonic rock fragments in some dacite already inferred from megascopic observations, it seems logical to interpret these larger plagioclase crystals as late inclusions rather than phenocrysts. It should also be noted however, that some of the smaller plagioclase crystals in the massive dacite are also antiperthitic, though commonly to a lesser degree.

## ROCK ALTERATION

Alteration of the Precambrian basement may be divided into three categories which may be intergradational. These consist of:

(1) maskelynitization
(2) argillization
(3) recrystallization

Milton and DeCarli (1963) have proposed to restrict the term maskelynite to "A noncrystalline phase that in a pseudomorphous way preserves the external features of crystalline feldspar." Maskelynitization therefore involves the alteration of feldspar in rock to feldspar glass with minimal destruction of mineral textures. At Clearwater Lake, maskelynitization has affected the rocks at the surface on the islands at the centre of the west lake, and some of the included fragments in the friable breccias on the island ring.

On the central islands plagioclase in the gabbro-diorite is partly converted to glass without distinct boundaries between the crystalline and noncrystalline plagioclase. Polysynthetic twinning passes into glassy areas by gradual loss of birefringence. Locally, partial devitrification has followed maskelynitization. Pyroxene amphibole and biotite, except where later argillization has occurred, may be very little altered. Where granodiorite has been altered by this process, plagioclase is converted to glass but blebs of potash feldspar (antiperthite) maintain their optical orientation and birefringence, although they are surrounded by a selvedge of glass of low refractive index (1.490). Quartz shows development of cleavage and a brownish dusty alteration.

A thin section of a plutonic rock fragment surrounded by black glass in the friable breccia showed feldspar almost entirely converted to glass and subsequently partly devitrified. Small areas with low wavy birefringence yielded a low negative optic angle suggesting that sanidine may be present. Numerous crescent-shaped to annular cavities were observed throughout quartz crystals and some of these appear to be filled with a clear colourless glass of low refractive index. Rounded embayments of brownish devitrified glass penetrate along grain boundaries. Magnetite, hematite, and altered biotite were also observed.

Argillization at Clearwater Lake involves the partial alteration of feldspar, principally plagioclase, or glass to montmorillonite with minor illite. Mafic minerals except magnetite are partly or completely altered to hematite. This type of alteration is widespread on the island ring and is perhaps best developed in some of the plutonic rock fragments included in the friable breccia. It is noteworthy that severely argillized Precambrian rocks are clearly overlain by apparently unaltered coherent breccia on one of the northwestern islands in the ring, though the contact itself is inaccessible on the bluff face. On the southwest end of the long island in the north sector however, the contact between argillized rocks and massive dacite, though again inaccessible, appears from a distance of 25 feet to be indistinct and possibly gradational. The indistinct zone does not appear to follow fractures in the fresh dacite above and it is therefore probable that this feature represents contamination of the dacite through assimilation of argillized rubble rather than argillization of the dacite itself.

Recrystallization here comprises partial or complete recrystallization of one or more constituents of the Precambrian rocks without formation of appreciable glass or clay minerals. Hematite is generally present in sufficient quantity to give the rock a red colour. Recrystallization is evident in a wide variety of textures that do not all appear together. Some plagioclase in recrystallized rocks is intensely antiperthitic, like some of the larger crystals in the massive dacite. Other grains may contain patches of intergrown feldspar laths of refractive index similar to their host. Plagioclase crystals may be surrounded by one or two zones not found in rocks of the hinterland. For example, a central subhedral twinned plagioclase grain may pass gradationally outward into a euhedral untwinned distinctly more sodic zone. This latter zone may in turn be partly or completely surrounded by an outer zone of distinctly lower birefringence and refractive index in optical continuity with the zone within, but containing masses of minute acicular to radiating crystals. The outer two zones may be penetrated by apatite (?) needles. Locally, textures suggest that quartz pseudomorphous after tridymite is present. In some specimens recrystallization appears to have taken place mostly along fractures and grain boundaries between sialic minerals. In extreme cases most of the sialic minerals are converted to a mosaic or small equant grains.

Locally, and chiefly in altered rocks bearing some amphibole, patches visible in thin section of black opaque material may be found in embayments along grain boundaries and penetrating along cleavage in pyroxene. In reflected light this material appears to be composed of hematite and a light grey material. A black opaque glassy material showing similar textures has been produced experimentally by the author and A.C. Turnock. Rectangular blocks of amphibole-rich Precambrian rock from the hinterland were heated to the point of melting at one end. Thin sections cut across the interface between glass and unmelted rock showed textures comparable to the above. Textures similar to the above but involving finely divided magnetite, hematite, pyroxene(?), and a small amount of feldspar(?) instead of the black opaque material described above, have been found in some recrystallized rocks. It is considered that such rocks have been involved in partial fusion followed by recrystallization.

A texture that may be transitional between recrystallization and argillization was found in a fragment of plutonic rock from the coherent breccia. In hand specimen this fragment was mottled red-brown and creamy white, and had a slightly fused distorted appearance. In thin section the sialic minerals were seen to be altered to a very fine grained mass showing first-order birefringence. Remnants of mafic crystals similarly recrystallized could be distinguished. Rounded distorted patches of mosaic quartz were locally present as well as a few patches of fine microlitic plagioclase.

Recrystallized rocks are found chiefly in association with massive dacite. Most commonly they appear at or near the edges of dacite flows but locally they form outcrops surrounded by massive dacite.

## DISCUSSION

Widespread interest in the Clearwater Lake structure has arisen through the suggestion that it might represent a fossil meteorite scar or astrobleme (Beals, Innes, and Rottenberg, 1960); (Dence, personal communication); (Fleischer and Price, 1963). Other authors (Kranck and Sinclair, 1963) have considered the structure to be of volcanic origin. Although research now in progress may provide a clearer picture of the development of the structure, some lines of thought toward comparing these hypotheses are already clear.

### Meteoritic Hypothesis

An hypothesis of simple meteorite impact requires that the available energy peak must pass within minutes after impact and thereafter energy available for melting and alteration of the impact area must decrease. The observation that penetrating argillization of part of the Precambrian rocks of the island ring was essentially complete before emplacement of the coherent breccias or massive dacite renders the simple impact hypothesis unlikely, for such alteration of silicates throughout large blocks of rock could not take place within seconds by any known mechanism. It is necessary to assume therefore, that some mechanism for storing impact energy in the crust was available and that this resulted in a considerable time lapse between impact and the emplacement of the dacite.

An impact-volcanic hypothesis implies the existence of two types of products; one consisting of impact products and one of volcanic materials. Since no limestone fragments were found in the friable breccias, and since intermediate rock types are present in the friable breccia — coherent breccia — massive dacite sequence, none of these is ejecta from an impact explosion and all belong to the suggested period of impact-induced volcanism. Only the maskelynitization effect remains to bear witness to supposed impact. Though similar textures have been found in shock-induced glass in gabbro (Milton and DeCarli, 1963), the limiting conditions of temperature and "shock" under which maskelynitization can occur are not known and as yet no conclusion should be drawn from the occurrence of such textures. Determination of the thickness of this glassy alteration will therefore be of particular interest.

Finally it should be recalled that the friable breccias were preceded by diabase intrusions. The peculiar concentration of these intrusions on the island ring suggests that the west lake basin had already become a unique structural environment before emplacement of the friable breccia and probably before maskelynitization. If the diabase bodies are of Precambrian age the probability that a Pennsylvanian meteorite would choose such a concentration of them as an impact site is remote. On the other hand the interpretation of the diabase bodies as part of the Clearwater Complex, intruded after maskelynitization but before the friable breccias, may, in a sequential sense, admit the generation of diabase magma indirectly by meteorite impact. In so doing, however, it confirms the later volcanic origin of the breccias that are usually advanced as the most telling evidence of impact. Generation of the Clearwater Complex through meteorite impact therefore seems unlikely.

## Volcanic Hypothesis

The alternative hypothesis, that the rocks are of volcanic origin, is indeed favoured by the author. It is true that without knowledge of their chemical composition and variation it is premature to draw comprehensive conclusions as to the course of development of the magmas that produced the Clearwater Complex. It has been argued indeed, that rocks like the dacite and breccias, and their associated alterations, are not found among rocks of known volcanic origin, implying that volcanic processes might not be capable of producing some of the characteristic features of these rocks. For the latter reason it is desirable to show that a reasonable hypothesis for the volcanic origin of these rocks may be devised.

From the point of view of volcanism two features of the complex appear especially significant. The mineralogical similarities between diabase and dacite, and the apparent concentration of diabase dykes on the island ring, suggest that diabase magma played an important role in the development of the complex. The lithologic gradation from friable breccia through coherent breccia to massive dacite with accompanying changes in alteration is thought to reflect a progressive transition from gas evolution to extrusion of hot, gas-charged magma. This gas may have been injected into diabase magma from below and would provide the energy necessary to drive the diabase and its contamination-assimilation products to localized expression at the surface.

The following paragraphs are devoted to reviewing pertinent aspects of these features, speculating on their origin, and briefly suggesting other geological phenomena with which the Clearwater Complex might be compared.

The kinship of the diabase intrusions to the later breccias and massive dacite, though perhaps not definitely established, is indirectly indicated by the concentration of diabase on the island ring. Furthermore, it is a remarkable fact that the plagioclase of the diabase ($An_{58 \pm 5}$) is very similar to that in the core zones of plagioclase of the dacite ($An_{55 \pm 5}$), and nearly the same degree of similarity appears to be shown in the optical properties of the augite contained in each. The remaining prominent minerals of the dacite are those that might be expected from partial assimilation of the Precambrian rocks in the hinterland. At this stage therefore, it may be suggested that diabase magma, perhaps potentially present at depth over broad areas beneath the shield, has been locally energized to produce a magma system capable of forming the Clearwater Complex.

Before further speculation, some details of the intrusion sequence and associated alterations that make up the Clearwater Complex may be reviewed in tabular form.

Lithology and Associated Alterations of the Clearwater Complex

| Lithology | Alteration |
|---|---|
| Diabase (?) | Peculiar brecciation of some dykes. |
| Friable porous breccia | Early maskelynitization of angular to subrounded fragments of country rock included in the breccia, with later argillization of fragments. |
| Coherent less-porous breccia | Local partial fusion of country rock (?). Recrystallization and distortion of some included fragments. |
| Massive dacite | Recrystallization of country rock with disintegration and assimilation of included fragments. |

The progressive decrease in porosity from friable breccia to massive dacite suggests a progressive decrease in the content of dissolved volatiles in the magmas of this sequence. Maskelynitization of plutonic rock in the friable breccia is perhaps indicative of some degree of intense shock and heat (Milton and DeCarli, 1963). The development of unusual fusion and recrystallization textures with tridymite (?), and the absence of prominent phenocrysts in the dacite suggest that dacite and coherent breccia magmas were particularly hot; and the presence of black glass in some of the friable breccias suggests that they also reached magmatic temperatures at some stage in their development. The progression from argillization to partial fusion and recrystallization suggests that materials reaching the surface became hotter as intrusion progressed. With these features in mind one may consider the injection of proto-materials of the friable breccia at depth into fractures leading to the surface and the subsequent evolution of the injected material to dacite magma.

Suppose that early, local, and limited volatile release at the base of the diabase magma had resulted in local intrusion of diabase at Clearwater Lake. Injection of some diabase and dissipation of gas may have initiated the development of a ring fracture just outside the island ring. If then volatile release at the base of the diabase magma were resumed and accelerated, gas would rise through the diabase magma yielding a part of its substance to solution in the diabase magma on the way. If subsequently, the resistance of the overlying rocks along the ring fracture were overcome by the accumulating volatiles below, a series of violent explosions would result.

As a consequence of release of volatiles from the magma chamber the wall-rocks in the lower reaches of the conduits leading to the surface would be subjected to violent high-temperature compression and their surfaces fused. Fragments would be torn from them and rapidly carried to the surface. The rapid transit to the surface would be accompanied by severe chilling due to adiabatic expansion of the surrounding gases as they rose in the conduit. Such conditions may be consistent with the formation of maskelynite in some of the fragments in the friable breccia and could also account for the local appearance of glass selvedges on these fragments. On reaching the surface, the volatiles could have cooled sufficiently to produce penetrating argillization of the surface wall-rocks. Continued injection of volatiles from the magma chamber might be expected to result in enlargement of the conduits to produce breccia pipes.

Diabase magma through which the volatile material rose from depth would, in effect, receive super heat from the solution of added volatiles, and assimilation of roof rocks in the upper parts of the magma chamber would begin. After the initial gas explosions it is therefore likely that material progressively richer in contaminated, energized diabase magma would be ejected, and that eruptions at the surface would become less explosive. However, the decline in the absorption of heat by adiabatic expansion of volatiles (resulting from the increase in the proportion of magmatic materials ejected) would result in an increasing temperature of materials reaching the surface. The progression from friable breccia through coherent breccia to largely inclusion-free dacite, and the accompanying change from argillization to partial fusion and recrystallization of surface rocks may thus be explained.

At the centre of the complex, early volatile injections sufficiently energetic to fracture and dilate the country rock may have taken place. Possibly, a nearly horizontal fracture opened at the level now exposed at the surface, into which the expanding gases were injected from a major fracture now covered by the lake. If the overlying rocks were unable to contain these gases, an explosion, which shattered these rocks and predisposed them to erosion, would have occurred. Momentary concentration of intensely hot compressed gases along the fracture plane followed by explosion and inrush of surface water could have resulted in the maskelynitization of a skin of rock along the basal fracture plane and subsequent local devitrification.

In comparing the Clearwater Complex with possibly similar structures, one recalls the association of limited intermediate volcanism with large roughly circular depressions and ring structures found in some areas of cauldron subsidence (Williams, 1941). The presence of a crater-like structure with central uplift and external ring depression combined with peculiar glass and breccias in the west lake suggests a comparison with some cryptoexplosion structures (see Bucher, 1963). It is therefore possible that Clearwater Lake represents a transitional form between these two types of structure.

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