DPV 432

MANICOUAGAN IMPACT STRUCTURE AREA (SAGUENAY COUNTY)

EXPLORATION GÉOLOGIQUE

MINISTĒRE
DES RICHESSES
NATURELLES

DIRECTION GĒNĒRALE
DES MINES

MANICOUAGAN IMPACT STRUCTURE

by

J. G. MURTAUGH

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Frontispiece -- The Manicouagan Impact Structure photographed from NASA's ERTS Satellite. Lakes are white. Diameter of structure to median of bounding lakes is 65 km.

FOREWORD

The map which accompanies this report is a retouched version of map 28-1967 (Lac Manicouagan, Québec) produced by the Geological Survey of Canada in 1968 to accompany Preliminary Report 583 published by the Québec Department of Natural Resources in 1969 under the title *Preliminary study of the Manicouagan structure* and bearing the following authors names: J.G. Murtaugh, Quebec Department of Natural Resources, and K.L. Currie, Geological Survey of Canada. Redrafting of the map was not deemed necessary as Murtaugh's final map shows changes in the definition of rock units rather than new boundaries for these units. Accordingly corrections were applied to a lithographed copy of map 28-1967 and the French and English legends accompanying it were replaced by the legend provided by Murtaugh to accompany his final map.

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INTRODUCTION

GENERAL STATEMENT

The Manicouagan Impact Structure is one of the largest such structures known. The diameter of the polygonal, nearly circular, structure (frontispiece), is about 65 km. The structure-forming event affected rocks as much as 15 km beyond the present rim. The structure was formed, apparently in Triassic time, at the junction of geologic units that represent most of the major rock types of the Grenville province of Quebec. The metamorphic grade of the Precambrian rocks ranges from amphibolite facies to granulite facies. There are a few outcrops of unmetamorphosed igneous rocks. Precambrian rock types include metagabbro, charnockitic rocks, grey biotite-hornblende gneisses, tan gneisses and melanocratic gneisses that mark a transition between the granulite and amphibolite facies, granitic gneisses, rocks of the Gagnon Group (iron formation, marble, quartzite, paragneisses), anorthosites, and metamorphosed and unmetamorphosed basic and ultrabasic igneous rocks. Many of the rocks have been affected by more than one period of deformation and metamorphism. Iron formation and graphite in gneisses associated with the iron formation, sulfide mineralization in the metagabbro, and zeolites on Mount de Babel are the only known possible mineral resources.

Fossils in outliers of Ordovician limestone indicate that the area was covered by a shallow sea at that time. The event that caused the Manicouagan Impact Structure, probably in Triassic time, produced a large crater that has since been deeply eroded. The crater-producing event happened after Ordovician time, as indicated by inclusions of Ordovician limestone in breccias formed during the event. The event occurred during or before Early Triassic time as indicated by absolute age dates on igneous rocks that overlie and intrude these same breccias. These igneous rocks have been dated by the K-Ar whole rock method at 225 ±30 m.y. (Wanless et al., 1969), and 210 ± 4 m.y. (Wolfe, 1971), and by the fission track method at 208 ± 25 m.y. (Fleischer et al., 1969). In addition, the igneous rocks have Lower Triassic paleomagnetic poles (Robertson, 1967; Larochelle and Currie, 1967). I interpret the igneous rocks as crystallized impact melt, and conclude that the crater was formed in Early Triassic time.

The area is unique for its *in situ* display of features associated with impact structures, and for its diverse assemblage of rocks of the Grenville province. The present study is divided into two distinct parts: (1) mapping, description, and interpretation of rocks older than the impact structure; (2) mapping, description, and interpretation of rocks formed during or affected by the event that produced the Manicouagan Impact Structure.

FIELD WORK

The area was mapped during four field seasons (1964-1967), by parties ranging in size from seven to thirteen men. Traverses were plotted on aerial photographs and location of outcrops and geologic data were transferred to topographic base maps with a scale of 1:40,000. Float-planes and canoes were the most commonly used vehicles. A helicopter was used extensively during the 1966 season, and briefly during the 1965 and 1967 seasons.

Outcrops within the Manicouagan Impact Structure are generally abundant, although sparse in some critical areas near the center of the structure. Outcrops outside the structure are generally small, expect above treeline at about 2500 feet.

PREVIOUS WORK

A. P. Low (1897), was the first to give a geologic description of the area. Hammond (1945) briefly described the geology along the shores of Lake Mouchalagane and suggested that the apparently flat-lying igneous rocks along the inner shores were Late Precambrian or Early Paleozoic in age. E. R. Rose (1957), of The Geological Survey of Canada, worked in the area for a month and published a geologic reconnaissance map showing the major geologic features. Jean Bérard (1962), of the Geologic Exploration Service, Department of Natural Resources, Quebec, mapped the perimeter of the Manicouagan Impact Structure and a small part of the interior. His work was confined to that area along the shores of Lakes Manicouagan and Mouchalagane, below an elevation of 1200 feet, that would be flooded upon the completion of the dam at Manicouagan 5.

Leslie Kish (1962, 1963, 1968), also of the Geologic Exploration Service, mapped the northeastern corner of the area bounded by latitudes 51°30' and 51°45', and by longitudes 68°00' and 68°30'. Kish gave only a brief description of the rocks inside the Manicouagan Impact Structure because he was primarily concerned with the rocks east of the structure. The interpretation of the geologic map in the area mapped by Kish is based almost entirely on his data and maps. None of the above workers recognized shock metamorphic effects in the rocks of the Manicouagan Impact Structure.

The Dominion Observatory of Canada made a geophysical survey of the Manicouagan Impact Structure in 1963 as part of a long range study of possible meteorite craters on the Canadian Shield (Beals et al., 1963; Innes, 1964). M. R. Dence of the Observatory discovered the first evidence of shock metamorphism in the structure during this expedition in 1963. He recognized maskelynite (shock-produced plagioclase glass) in the rocks of the central mountains of the structure (Bunch et al., 1967).

K. L. Currie (1964) of the Geologic Survey of Canada was the first geologist to begin detailed mapping in the Manicouagan Impact Structure, and was a strong advocate of a volcanic-tectonic origin. Currie mapped the area in the 1963, 1965, and 1966 seasons. He and I collaborated to produce a preliminary report and map (Murtaugh and Currie, 1969). This preliminary map incorporated all of our data and that of earlier workers. Currie (1972) has since completed a final report with a revised map.

I reported earlier on portions of the geology of the area (Murtaugh 1965, 1969a, 1969b, 1972, 1975). Several individuals who worked as my field assistants have reported on aspects of the geology of Manicouagan Impact Structure: D. W. Roy, Jr. (1969a), made a computer analysis of joints around the western rim and in the interior of the structure. Ulf Dworak (1969a, 1969b), described shock effects in plagioclase from the central mountains. Burkhardt Dressler (1970) described shock metamorphic phenomena in the structure. Jean-Pierre Bassaget (1968) mapped the area east of Lake Manicouagan as an assistant partychief.

S. R. Wolfe (1971) made a K-Ar isotope study of rocks in the area based on two partial seasons of work with my field parties and J. L. Lager (1969) made a petrographic examination of some of the Precambrian rocks.

Acknowledgements

I am grateful to several professors at the Department of Geology and Mineralogy of the Ohio State University who were helpful during the investigation. Dr. G. E. Moore, Jr., adviser for my doctoral dissertation (Murtaugh, 1975), visited me in the field, helped in the examination of numerous thin sections, and read interim reports and drafts over a period of several years. Drs. Gunter Faure and E. E. Ehlers helped in discussions of specific problems.

M. R. Dence, of the Dominion Observatory of Canada, deserves special thanks for intercepting me on the way to my first field season in the Manicouagan Impact Structure and warning me of the strange and wondrous things I would soon behold. Without this warning my first field season would undoubtedly have been a catastrophe.

K. L. Currie, of the Geological Survey of Canada, collaborated with me in producing a preliminary geologic map and report. Although we disagree on the interpretation of almost everything concerning the geology of this area, the free interchange of information between us helped this report immeasurably.

It is impossible to list all the field assistants who served during the course of four long field seasons. Particular thanks are due D. W. Roy, Jr., and Jean-Pierre Bassaget, who survived two field seasons as

senior assistants, and who undertook independent investigations of part of the geology of the area. S. R. Wolfe worked with the party under the auspices of the U.S. Geological Survey, and in fact contributed the work of a senior assistant for the better part of a field season.

DESCRIPTION OF THE AREA

Location and Access

The area mapped lies between latitudes 51°00' and 51°45' and longitudes 68°00' and 69°30', and comprises most of map 22N, Lac Manicouagan, of the Federal 1:250,000 topographic map series. The geologic map comprises about 6500 km^2 of Saguenay County, Quebec. The center of the Manicouagan Impact Structure is about 70 km southwest of the town of Gagnon, and about 130 km north of the dam at Manicouagan 5.

The southern edge of the area is accessible from the Manicouagan 5 damsite by an unimproved road and by boat or canoe on the Manicouagan reservoir. A road from Manicouagan 5 to Gagnon is under construction in the eastern part of the area. The filling of the reservoir since the completion of the field work has made it possible to circumnavigate the periphery of the structure. Many of the lakes within the mapped are are large enough to accommodate float planes.

Settlement and Resources

The area has no permanent inhabitants. In years past, Montaigne Indians from Betsiamits, on the St. Lawrence River, trapped here in the winter.

Spruce are the most abundant trees. Alder and birch are present, but not abundant. Thick undergrowth in areas of high density of spruce trees is interrupted by patches of caribou moss and swamps. The spruce trees constitute a possible source of pulpwood. Trees from a few square kilometers in the southern part of the area were cut before flooding began. The cut wood was not removed and now clutters the shores of the reservoir.

Animals are not abundant. The only large animals seen frequently in the summer are moose. Indians report the presence of caribou in the winter. Bears were seen only three times in four seasons, although bear sign is abundant. Beaver are fairly common, but the large number of ancient beaver dams suggests that they were much more abundant in the past. They are probably repopulating the area following a decrease in the intensity of winter trapping. Fishing is good, with grey or lake trout, speckled or red trout, and great northern pike being the varieties most commonly caught.

PHYSIOGRAPHY

The most striking topographic feature of the area is the nearly circular polygon bounded by Lakes Manicouagan and Mouchalagane (geological map, frontispiece). The polygon, 65 km in diameter, is the eroded scar of an ancient crater formed either by the impact of a cosmic body or by volcanic-tectonic processes. The shape of the structure shown on the geological map was modified (frontispiece) as the water rose to a level of 1200 feet[1] behind the dam at Manicouagan 5. Hypsographic maps

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[1] Elevations are given in feet rather than meters for convenience in referring to the geological map.

by the Hydroquebec Division of the Quebec Department of Natural Resources indicate that the bounding lakes extend below sea level, and so were over 700 feet deep before flooding began.

Terrain Outside the Structure

The dominant topographic feature of the northeastern part of the area is a massif called the Manicouagan Uplands by Kish (1968). The massif, underlain primarily by metagabbro, ends abruptly at the east shore of Lake Manicouagan, although metagabbro crops out at low elevations along the west shore of the lake. The massif extends eastward beyond the map area, and has a total length of about 80 km. The high treeless peaks of the massif include the highest point in the map area, which is Mount Loaf (elevation = 3623 feet). Low rolling hills underlain by gneisses border the massif.

The major topographic feature of the southeastern corner of the area is a massif composed of mearly massive charnockitic rocks. Its maximum elevation is 3233 feet. The massif is surrounded by lower hills underlain by well-foliated charnockitic rocks.

The northern part of a large massif made up of anorthosite occupies the southwestern corner of the area, where rounded barren peaks rise to an elevation of 3230 feet. This massif is cut by a steep-walled canyon that contains Lake Tetepisca. Sheer cliffs rise 700 feet above the shores of the lake. The massif is bordered by a broad valley with few outcrops that in turn is surrounded by low rolling hills underlain by gneiss.

Another massif underlain by anorthosite extends from the northwestern part of the area to near the outer shore of Lake Mouchalagane. The massif ends abruptly there, but the central mountain of the structure is formed of the same anorthosite. It is clear that this massif was disrupted by the formation of the impact structure. This northwestern massif was given the name of Mount Brilliant in the field because of the sheer shining cliff of anorthosite along the Seignelay River, which is visible from points on Lake Mouchalagane over 25 km away.

The broad areas between the massifs described above contain low rolling hills that are underlain primarily by gneisses. The hills have a maximum elevation of about 2000 feet. Low cliffs border most of the long narrow lakes that are characteristic of this hill terrain. Most of the lakes are elongated in a northeast or northwest direction, roughly parallel to two of the sides of the Manicouagan Impact Structure.

A drainage divide in the low hills of the western part of the area separates streams draining toward Lake Mouchalagane from those draining toward Lake Tetepisca. This divide is coincident with an abrupt change in the number and variety of joints in bedrock, which distinguishes rocks near the impact structure from those farther away. The divide is, on the average, about 15 km from the outer shore of Lake Mouchalagane, and may mark the maximum extent of structural disturbance attributable to the structure-forming event. A similar divide in the eastern part of the area is much more difficult to delineate because of the great variety of rock types and their different responses to erosion.

The area between the drainage divides and the shores of the bounding lakes are characterized by a large number of small valleys, some of which are concentric and some of which are radial with respect to the impact structure. The valleys are not apparent on topographic maps, but show up well on aerial photographs.

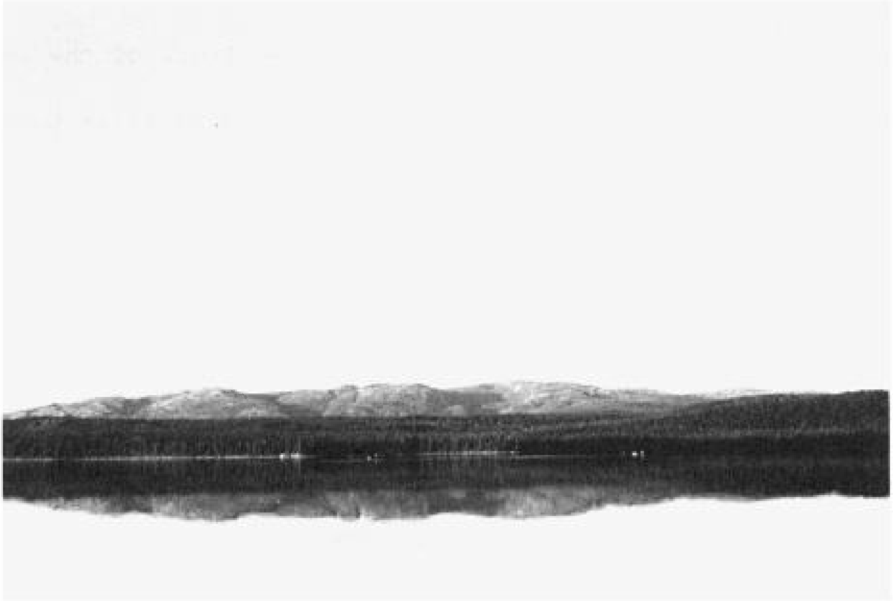
Terrain Inside the Structure

Four physiographic features comprise the interior of the Manicouagan Impact Structure. An outer lowland lies just inside the bounding lakes, Manicouagan and Mouchalagane. An annular plateau formed by nearly flat-lying Triassic igneous rocks is immediately inside, and topographically higher than, the outer highlands. The third feature is an inner lowland that lies between the annular plateau and the fourth feature, the central mountain, Mount de Babel.

The outer lowland is underlain by slightly shock metamorphosed and locally brecciated gneisses that are nearly covered by glacial deposits in the north and south. A few low cliffs of Ordovician limestone crop out along the inner shores of the bounding lakes. The lowland contains the same type of concentric and radial valleys that characterize the area just outside the bounding lakes. Some of these valleys contain highly interesting cross-sections of the rim of the structure. Unfortunately, these valleys have been largely flooded, along with most of the remainder of the outer lowlands.

The annular plateau of Triassic igneous rocks rises above the outer lowlands in steep, locally stepped, cliffs that culminate in bare vertical faces. The elevation of the highest parts of the plateau is about 2350 feet. The annular plateau is cut in places by erosional valleys that are approximately radial with respect to the center of the structure, and approximately parallel to one or another side of the polygon occupied by the bounding lakes. The inner edge of the plateau is formed by low cliffs that descend to the inner lowland.

The inner lowland is underlain mostly by moderately-shocked gneisses, but locally by a few dikes and erosional remnants of the rocks of the annular plateau. The maximum elevation of that part of the inner lowland underlain by gneiss is about 1500 feet, whereas that part underlain by remnants of the rocks of the annular plateau may be as high as 2000 feet. Much of the inner lowland is covered by glacial deposits.



Pl. I

Mount de Babel, the central mountain of the Manicouagan Structure. View from 10 km southwest. Relief is about 470 m.

The term central mountain is something of a misnomer because the apparent geometric center of the structure (ⓧ on the geologic map), is about 3 km southeast of the mountain. The central mountain, Mount de Babel, lies somewhat north and west of the actual center. Mount de Babel rises about 1500 feet above the inner lowland (Pl. I). The highest of the rounded barren peaks is at an elevation of 3124 feet. The central mountain is essentially a massif underlain by anorthosite like that in the massif to the northwest. The rocks of Mount de Babel differ from those comprising the massif outside the structure only in that the anorthosite is shock metamorphosed and that the north slope is underlain by shock metamorphosed biotite gneiss. Mount de Babel is roughly rectangular, and has nearly straight sides that contain many steep cliffs. The mountain is divided by a northeast-trending valley that does not extend to the level of the inner lowland. A few outliers of the anorthosite underlie small hills around the central mountain. These hills have a maximum elevation of 2250 feet.

GLACIAL GEOLOGY

Kish (1968) reported glacial striae trending between 190° and 200° on the metagabbro of the Manicouagan Uplands. Roches moutonnées in the Lake Tetepisca area and tree-lined glacial grooves in the south part of the Manicouagan Impact Structure have the same orientation. Two small nivation cirques are present on the south slope of Mount de Babel.

Unconsolidated glaciofluvial deposits with cross-bedding and cut and fill structures form terraces at an elevation of 975 feet along the shores of Lake Mouchalagane and its tributary streams. Glacial erratics are mostly of local bedrock, but some that are foreign to the area were observed. Pink quartzites are the most common erratic type not derived from local bedrock. Much of the area at low elevation is covered by a blanket of till in the form of hummocky ground moraine. Eskers follow the courses of many of the broad stream valleys.

In one locality near Lake Mouchalagane, that is now underwater, at least 3 m of a pale grey-brown till is overlain by 30 cm of a darker grey-brown till, which is in turn overlain by a meter of bedded sand with a 3 cm yellow-brown weathered zone. These units are overlain in turn by 10 m of cross-bedded sand capped by a meter and a half of organic soil.

GENERAL GEOLOGY

SUMMARY OF AREAL GEOLOGY

Bedrock consists of diverse Precambrian metamorphic and plutonic rocks; Ordovician sedimentary rocks; and the shock metamorphosed rocks, breccias, igneous rocks (impact melt?), and contact metamorphosed rocks of the Triassic Manicouagan Complex. Age relations among some of the Precambrian units and among some of the Triassic units are uncertain.

The relative ages of the Precambrian rocks as indicated in the Table of Formations (Table 1), is at best tentative. Each worker in the area has arrived at very different conclusions (Table 2), as to the relative ages of the rock units. Problems arise from the polymetamorphic and multideformational history of the rocks; the reconnaissance nature of the geological mapping done; the abundant glacial and vegetative cover and consequent scarcity of good outcrops and exposures of contacts; the equivocal nature of contacts that were observed; and the paucity of absolute age dates available and the difficulty of interpreting those few dates.

Metagabbro (Unit 1) (granulitic gabbro of Kish, 1968), is the main rock type underlying the large massif in the northeastern part of the

TABLE 1 - SUMMARY OF FORMATIONS

Age	Unit	Subunits and Lithology
Cenozoic (Pleistocene, recent)	(17) Glacial Deposits, Alluvium	Till, outwash, eskers, glaciofluvial deposits; alluvium
Mesozoic (Triassic)	Manicouagan Complex	
	Contact Metamorphosed Country Rocks	Bedrock of shock stages 0, I, II contact metamorphosed by units 16 and 15. Rocks with decomposed mafic minerals, zeolitized rocks, hornfelsed anorthosite, melted and vesiculated gneisses.
	(16) Monzonite	Medium to coarse-grained brown, grey, or red massive rock with lath-shaped pyroxene phenocrysts. (May be younger than Unit 15)
	(15) Latite	Aphanitic to fine-grained brown, red, or grey massive rocks. (15a) Medium-grained latite. May be in part Unit 16 or transitional between 15 and 16.
	(14) Basalt	Aphanitic black rock, locally glassy, locally vesicular. (14a) Red or greyish-black spherulitic rocks that grade to basalt (14), red breccia (13c), and suevite (13b).
	(13) Breccias	(13a) Autochthonous breccias. Rotated fragments in comminuted matrix. (13b) Suevite. Brown, green, or red polymict breccia with heterogeneous glasses and mixed shocked and unshocked fragments. (13c) Red breccia, nearly monomict breccia with heterogeneous glasses and shocked fragments. May be correlative with suevite (13b). (pt) Pseudotachylite.
Mesozoic (Triassic)	(12) Shock Metamorphosed Country Rocks	Rocks of shock stages 0, I, II of Stöffler (1971). Shock stage 0 not shown on map (see text). (12a) Shock Stage I. Planar features in quartz and feldspar, deformation bands in hornblende. (12b) Shock Stage II. Diaplectic glass (formed by shock in the solid state).
Paleozoic (Ordovician)	(11) Sedimentary Rocks	Limestone; minor shale, siltstone.
Precambrian?	(10) Mica-Amphibole Peridotites	Unmetamorphosed mica-amphibole peridotites.

Age	Unit	Subunits and Lithology
Precambrian	(9) Basic Dikes	Basalt, diabase: partly recrystallized and locally metamorphosed to amphibolite facies.
	(8) Anorthosites	Metamorphosed garnetiferous anorthosites, minor gabbroic anorthosite including minor peridotites, pegmatites, and a breccia pipe. (8a) Lake Tetepisca anorthosite. (8b) Mount de Babel anorthosite.
	(7) Basic and Ultrabasic Rocks	Raudot Lake layered intrusive pluton; Brien anorthositic gabbro. (7a) Ultrabasic rocks. (7b) Coronitic gabbro.
	(6) Gagnon Group (Grenville Supergroup?)	Brecciated metaquartzite (6?), white metaquartzite, ferruginous metaquartzite, iron formation, marble, well-banded graphitic paragneiss, muscovite-bearing quartzofeldspathic gneiss.
	(5) Granitic Gneiss	Undifferentiated granitic gneiss, minor granite, probably of several ages. (5a) Mixed granitic gneiss and grey gneiss.
Precambrian	(4) Grey Gneiss Complex	Hornblende-biotite-quartz-feldspar gneisses, commonly garnetiferous, locally with sillimanite or kyanite. (4a) Metamorphosed mafic and ultramafic rocks.
	(3) Amphibolite-Granulite Transitional Facies Rocks	Mixed grey gneisses (4), charnockitic gneisses (2), and granitic gneisses (5), tan gneisses (tan pyroxene-bearing rocks transitional between granulite and amphibolite facies), melanocratic gneisses (mafic gneisses associated with the hybrid gneisses).
	(2) Charnockitic Rocks	Green hypersthene-bearing rocks of diverse composition. (2a) Weakly foliated or nearly massive rocks. (2b) Gneissic rocks with abundant biotite and/or hornblende. (2c) Charnockitic syenite. (2d) Charnockitic diorite.
	(1) Manicouagan Uplands Metagabbro	Homogeneous hypersthene-clinopyroxene-labradorite rock, commonly lineated. (1a) Biotite-hornblende metagabbro, retrograde facies of (1). (1b) Granulite facies rocks intercalated with metagabbro.

TABLE 2

CHART SHOWING RELATIVE AGES OF PRECAMBRIAN ROCKS
AS GIVEN IN DIFFERENT PAPERS*

This paper Unit no.	Murtaugh	Currie (1972)	Murtaugh & Currie (1962)	Bassaget (1968)	Kish (1968)	Berard (1962)
10	Peridotite	Basic Dikes	Basic Dikes	Basic Dikes	Basic Dikes	Basic Dikes
9	Basic Dikes	Peridotite, Raudot Lake Massif	Peridotite, Raudot Lake Massif Anorthosite		Basic and Ultrabasic Rocks	
8	Anorthosite	Gagnon Group	Anorthosite		Granitic Gneiss	
7	Basic and Ultrabasic Rocks Raudot Lake Massif	Grey Gneiss	Melanocratic Gneiss		Anorthositic Rocks (differs from Anorthosite)	Granitic Gneiss
6	Gagnon Group	Mixed Gneisses, Transitional Rocks	Gagnon Group		Raudot Lake Massif	Anorthosite
5	Granitic Gneiss	Granitic Gneisses, (includes granitic charnockites)	Granitic Gneiss		Mixed Gneiss	Metagabbro
4	Grey Gneiss	Charnockitic Rocks	Grey Gneiss	Charnockitic Rocks	Grey Gneiss	Charnockitic R
3	Transitional Rocks, Mixed Gneisses (includes melanocratic gneiss)	Anorthosite	Mixed Gneiss, Transitional Rocks	Granitic Gneiss	Gagnon Group	Mixed Gneiss
2	Charnockitic Rocks	Melanocratic Gneiss	Charnockitic Rocks	Metagabbro, Granulite Facies Rocks in Metagabbro	Charnockitic Rocks	Gagnon Group
1	Metagabbro, Granulite Facies Rocks in Metagabbro	Metagabbro, Granulite Facies Rocks in Metagabbro	Metagabbro, Granulite Facies Rocks in Metagabbro	Grey Gneiss	Metagabbro, Granulite Facies Rocks in Metagabbro	Grey Gneiss

* This is not a correlation chart. Names of units used in other papers are changed to correspond to descriptions of units used in this paper (first column). All authors did not work in areas containing all units. Not all units of each author are used.

area. The borders of the metagabbro were retrogressively metamorphosed to biotite-hornblende metagabbro (Unit 1a). Orthogneiss, paragneiss and other metasedimentary rocks of the granulite facies (Unit 1b) are intercalated with the metagabbro.

Charnockitic rocks (Unit 2) are a suite of hypersthene-bearing igneous rocks of diverse composition that have been metamorphosed to the granulite facies. Nearly massive or weakly foliated charnockitic rocks (Unit 2a) grade into gneissic charnockitic rocks (Unit 2b). Charnockitic rocks intrude metagabbro (Unit 1). The charnockitic rocks are locally intercalated with, and may grade into, the amphibolite-granulite transitional facies rocks (Unit 3), the grey gneisses (Unit 4), and the granitic gneisses (Unit 5).

A broad transition zone (Unit 3) from the amphibolite facies to the granulite facies extends north-south through the central part of the area. The rocks of the transition zone include intercalated charnockitic rocks, grey gneisses, granitic gneisses, tan gneisses, and melanocratic gneisses. The tan gneisses contain clinopyroxene and are the characteristic rock of the transition zone. A scapolite-bearing melanocratic gneiss is a minor unit on the western side of the transition zone.

The grey gneiss complex (Unit 4) consists of amphibolite facies gneisses and associated metamorphosed mafic and ultramafic rocks (Unit 4a). The gneisses are predominantly quartz-plagioclase-biotite-hornblende rocks.

Granitic gneisses of different composition and textures, and probably of different ages, are mapped here as a single unit (Unit 5). Most of the different types were described by Kish (1968), and he did not map them separately.

Complexly folded rocks of the Gagnon Group (Unit 6) appear to overlie the grey gneisses in the western part of the area. The sequence consists of white quartzite, marble, ferruginous quartzite, iron formation, well-banded graphitic paragneiss, and muscovite-bearing quartzofeldspathic gneiss.

The basic and ultrabasic rocks comprising Unit 7 were mapped and described by Kish (1968). The Lake Raudot intrusive pluton contains layers of dunite, magnetite-bearing gabbro, anorthosite, anorthositic gabbro, troctolitic anorthosite, and troctolite. The western and northern parts of the pluton that are in the map area of this report are metamorphosed and metasomatized. Plugs and dikes of metamorphosed ultrabasic rocks (Unit 7a) cut gneisses in the northeast part of the area. Coronitic gabbro (Unit 7b) locally cuts the ultrabasic rocks.

Two anorthosite plutons constitute Unit 8. The Lake Tetepisca anorthosite (Unit 8a), in the southwest corner of the area, is made up predominantly of labradorite megacrysts set in a matrix of fine labradorite grains. The Mount de Babel anorthosite (Unit 8b) extends from the northwest part of the area to the center of the Manicouagan Impact Structure. The Mount de Babel anorthosite differs from the Lake Tetepisca anorthosite in that it contains only fine to medium-grained plagioclase.

Dikes of basalt and diabase (Unit 9) in the east part of the area are similar in hand specimen to igneous rocks of the Manicouagan Complex, but differ in thin section. The dikes are locally metamorphosed. One dike was dated at 665 ± 75 m.y. by the K-Ar whole rock method (Currie, 1972).

Small peridotite intrusions (Unit 10) crop out inside the Manicouagan

Impact Structure. They are mica-amphibole peridotites that are undeformed and unmetamorphosed, except for shock effects related to the formation of the impact structure. They are interpreted as Late Precambrian in age, but may be as young as Triassic.

Ordovician sedimentary rocks (Unit 11) lie unconformably on, or are in fault contact with Precambrian rocks. With two minor exceptions, they crop out only within the Manicouagan Impact Structure, mostly along the shores of the bounding lakes. They are predominantly limestone, but thin basal units of siltstone and shale are exposed in a few places.

The Manicouagan Complex consists of a diverse group of rocks that have undergone mineralogical, chemical, textural, or structural change during the formation of the Manicouagan Impact Structure. I divide the rocks of the Manicouagan Complex into four groups: shock metamorphosed country rocks; breccias; igneous rocks; contact metamorphosed country rocks.

The classification of shock metamorphism adopted is basically that of Stöffler (1971), and is shown in Table 9. The outermost limit of shock effects in the country rocks appears to be a change in the number of joints and the number of sets of joints about 45 km to 50 km from the center of the structure. The outermost limit of shock effects in minerals is the appearance of kink bands in biotite at about 35 km from the center of the structure. Quartz becomes extensively fractured and locally cleaved at 27 km from the center.

The outer limit of shock stage I (Unit 12a) is marked by the appearance of kink bands in hornblende and planar features in quartz at about 20 km from the center of the structure. Multiple sets of planar features in quartz and feldspar, and kink bands in garnet and pyroxene, appear closer to the center. The outer limit of shock stage II (Unit 12b), at 12 km from the center of the structure, is marked by the appearance of diaplectic glass (glass formed by solid-state vitrification). In a few outcrops, virtually all the quartz and feldspar is converted to diaplectic glass. Shatter cones occur in rocks of shock stages I and II, and appear to be most common in rocks near the transition from stage I to stage II.

Autochthonous breccia (Unit 13a), consisting of rotated fragments in a comminuted matrix, crops out sporadically near the bounding lakes. Suevite (Unit 13b) is an allochthonous polymict breccia containing shocked and unshocked fragments and heterogeneous glassy blebs in a matrix that can be clastic, cryptocrystalline, or glassy. Suevite crops out inside the bounding lakes near the base of the outer edge of the annular plateau of igneous rocks. Dikes of suevite intrude both autochthonous breccia and unbrecciated country rocks, but locally grade into the autochthonous breccia, as well as into basalt (Unit 14). Thin sheets of suevite locally overlie country rocks.

A red, nearly monomict breccia (Unit 13c), consisting of shocked fragments and heterogeneous glassy blebs in a matrix of glass or devitrified material, crops out near the base of the inner edge of the annular plateau. The red breccia appears to be stratigraphically equivalent to suevite. It grades locally into shocked and partly melted country rock, and apparently grades into the overlying latite (Unit 15), as well as into a spherulitic dike rock (Unit 14a).

Pseudotachylite (pt) is a glassy rock, charged with small inclusions, that forms irregular veins, dikelets, and rootless pods in country rocks inside the annular plateau of igneous rocks.

Basalt (Unit 14) overlies Precambrian country rock in a few places near the base of the outer edge of the annular plateau of igneous rocks. Rare basalt dikes locally have suevite selvages. Spherulitic dike rocks (Unit 14a) are border phases of basalt as well as some suevite, and possibly, latite (Unit 15).

The annular ring of igneous rocks consists of a subhorizontal sheet of latite (Unit 15) and monzonite (Unit 16). The monzonite has been dated at 210 ± 4 m.y. by the K-Ar whole rock method (Wolfe, 1971). Similar ages, discussed later, were obtained by different workers using different techniques. The latite is the lower unit. It grades abruptly upward into the monzonite. A medium-grained rock (Unit 15a) was mapped as a phase of the latite, but it may in part be monzonite. No evidence of flow structure or individual flow units was found. Dikes and tabular subhorizontal bodies of latite and monzonite crop out in the interior of the structure. The latite contains inclusions of highly shocked and thermally metamorphosed country rocks.

Contact metamorphic effects in the country rocks are related to the monzonite and latite, and, to a lesser degree, to the pseudotachylite. Contact metamorphic effects are: decomposition of mafic minerals to aggregates of opaque minerals, minute birefringent minerals, and glass or cryptocrystalline material; zeolitization in the form of replacement of plagioclase in anorthosite; recrystallization of anorthosite to small laths of plagioclase; melting and vesiculation of gneiss in inclusions and near dikes of latite.

Contact metamorphic aureoles are abnormally, apparently impossibly, wide. In places the width of the aureoles is from three to seven times the thickness of the igneous body that appears to have caused the metamorphism.

In the interpretation presented here, the Manicouagan Impact Structure was formed by the hypervelocity impact of a cosmic body, possibly a comet. The shock metamorphism was caused by the impact. The structure was a crater excavated by the impact, with its marginal form controlled by excavation and slumping along regional fracture zones. The shape of the floor of the crater was modified by the rebound of the center, which uplifted Mount de Babel and the rocks around it. The breccias are impact breccias. The igneous rocks are impact melt. Emplacement of the impact melt before dissipation of residual shock heat caused the abnormal contact metamorphic effects.

PART I: THE PRECAMBRIAN AND PALEOZOIC ROCKS

MANICOUAGAN UPLANDS METAGABBRO (Unit 1)

Kish (1963) coined the term "granulitic gabbro" for the rock described here as metagabbro. His purpose was to indicate a rock of gabbroic composition that had been metamorphosed to the granulite facies. Kish's term is not used here because "granulitic" refers to a variety of ill-defined textures (see, for example, the AGI Glossary of Geology), and not to metamorphic grade.

Metagabbro is the major rock type in an elongate massif that extends eastward for about 80 km from the shores of Lake Manicouagan. The central part of the massif consists of pyroxene metagabbro intercalated with granulite facies gneisses and metasedimentary rocks. The north and south borders of the massif consist of biotite-hornblende metagabbro.

Pyroxene Metagabbro (Unit 1)

The main rock of the massif is dark grey, medium-grained to coarse-grained, and has a speckled texture formed by grains of pyroxene and plagioclase. The structure of the rock ranges from massive to gneissic or lineated. Gneissosity is formed by alternating pyroxene-rich and plagioclase-rich bands. Lineation results from rod-like aggregates of pyroxene grains as much as one cm in diameter.

Plagioclase (labradorite), hypersthene, and diopside or diopsidic augite are the common essential minerals (Table 3). Garnet and/or hornblende are locally abundant. Accessory minerals include apatite, scapolite, and opaque minerals. The opaque minerals commonly rim pyroxenes. I determined the composition of plagioclase in three widely separated specimens by means of oil immersion and twin lamellae extinction angles to be An_{52} to An_{54}.

TABLE 3

MODAL COMPOSITIONS OF METAGABBRO (UNIT 1)

Minerals	K-4-3[a]	K-4-6[a]	L-52-6[a]	12B1[b]	13 x 4[c]	Average of 5 Modes
Plagioclase	46	38	41	60	28.8 (An_{54})	42.8
Orthopyroxene	28	17	20	16	53.6	26.9
Clinopyroxene	17	16	35	19	17.1	20.8
Garnet	--	11	--	--	--	2.2
Opaques	4	15	2	5	--	6.5
Alteration Prod.	5	3	2	--	--	3.3

[a] Kish, 1965
[b] Bassaget, 1968
[c] Murtaugh, this paper

The texture of the metagabbro is cataclastic. Xenomorphic grains of all minerals are rimmed by granulated fragments that are mostly the same mineral as the grains they surround. All anisotropic grains have extreme undulatory extinction. Twin lamellae in plagioclase and schiller structure in hypersthene are bent.

Biotite-hornblende Metagabbro (Unit 1a)

The edges of the Manicouagan Uplands massif consist of zones of biotite-hornblende metagabbro that are 1 to 5 km wide on the north and as much as 11 km wide on the south. Kish (1968) called the northern zone the amphibolitized margin of the metagabbro, and described a gradual northward change into a biotite-hornblende-plagioclase rock that I call biotite-hornblende metagabbro.

This unit retains the general appearance of the pyroxene metagabbro, including the pronounced lineation. The mineralogy is like that of the metagabbro except for the addition of biotite and/or hornblende (Table 4).

TABLE 4

MODAL COMPOSITIONS OF BIOTITE-HORNBLENDE METAGABBRO (UNIT 1A)

Minerals	13 x 6[b]	17 B7[a]	21 C6[a]	10 R6[a]	Average of 4 Modes
Plagioclase	63(An52)	53	47	54	54.3
Orthopyroxene	15	25	19	21	20.0
Clinopyroxene	7	13	20	17	14.3
Hornblende	8.5	10	10		9.5
Biotite	2	--	2	7	3.7
Garnet	1	--	--	--	--
Opaques	1.5	T	1	tr	--
Alteration Prod.	2	T	1	tr	--

[a] Bassaget, 1968
[b] Murtaugh, this paper

Cataclastic texture is less pronounced than in the pyroxene metagabbro because of partial replacement of the mortar-forming fragments by hornblende. Hornblende also replaces pyroxene. Biotite is usually in distinct, discrete grains that locally have kink-bands. All anisotropic grains have undulatory extinction that is less extreme than that in the pyroxene metagabbro.

Granulite Facies Rocks Intercalated with Metagabbro (Unit 1b)

Rocks intercalated with the metagabbro include sillimanite-graphite gneisses, diverse pyroxene-bearing gneisses, and "quartzites". Rare calcareous inclusions are present in the metagabbro. These rocks have been described by Kish (1968) and Bassaget (1968). Only a summary of the major rock types is presented here, based on their reports.

Sillimanite-graphite gneisses containing 47 percent to 62 percent quartz along with garnet, perthite, and minor plagioclase are interpreted as paragneisses. Pyroxene-bearing gneisses contain either orthopyroxene or clinopyroxene, potassium feldspar, and can contain quartz, plagioclase, and minor graphite. Some of these rocks are interpreted as paragneisses and others as orthogneisses.

The "quartzites" described by Kish (1968) contain from 58 percent to 78 percent quartz along with plagioclase and minor garnet. Bassaget (1968) mapped farther south in the metagabbro than Kish. He noted that quartzofeldspathic layers a few centimeters thick have sharp contacts with the metagabbro, whereas layers several meters thick grade into the metagabbro. In addition, Bassaget described mylonitized quartzofeldspathic bands.

Kish (1968) described the calcareous inclusions in the metagabbro as being fine-grained and having thin reaction rims. The common mineral assemblages of these inclusions are wollastonite-quartz-garnet or plagioclase-scapolite-quartz-garnet-diopside. Kish interpreted these assemblages as the result of high grade contact metamorphism by the gabbroic magma.

Metamorphism and Deformation

The mineral assemblage of orthopyroxene-clinopyroxene-plagioclase-garnet is indicative of granulite facies metamorphism in quartz-bearing rocks, but cannot be construed as proof of such metamorphism in rocks of gabbroic composition. However, the mineral composition of the rocks intercalated with the metagabbro do indicate the granulite facies. The biotite-hornblende metagabbro appears to be a retrograde facies of the pyroxene metagabbro.

The lineation and cataclastic mortar texture in the metagabbro was clearly formed by granulation and intergranular rotation. The lesser degree of cataclasis and the partial recrystallization and replacement of mortar fragments in the biotite-hornblende metagabbro suggest that the retrograde metamorphism followed the main period of deformation. The undulatory extinction in all rocks and the kink-bands in biotite in the biotite-hornblende metagabbro suggest that deformation continued after the retrograde metamorphism or that the rocks were affected by an entirely different, later deformation that had no metamorphic effects.

Contact Relations

Biotite-hornblende metagabbro is in fault contact with the grey gneiss complex (Unit 4), and with Units 5 and 7, on the north margin of the massif (Kish, 1968). On the south margin of the massif the contact between these two units is covered, although apparently abrupt. Currie (1972) shows a fault contact between these two units on the south, but there is no evidence for a fault. Bassaget (1968), who did the actual mapping of the south contact, interpreted it as an intrusive one, with the metagabbro intruding the grey gneisses, although there is no evidence for this either.

The charnockitic rocks that intrude and are intercalated with the metagabbro are tentatively correlated, on the basis of their unique lithology, with the larger bodies of charnockitic rocks elsewhere. Kish (1968) reported that rocks of the Lake Raudot layered intrusive (Unit 7) intrude the metagabbro in the northeast.

Origin and Age

Kish (1968) interpreted the metagabbro as a thick series of shallow intrusions or lava flows, in order to explain the homogeneous nature of the metagabbro and the heterogeneous nature of the rocks intercalated with it. The paragneisses, pyroxene gneisses, calcareous rocks, and "quartzites" are thus interpreted as either older rocks intruded by the gabbro, or penecontemporaneous rocks that might have been deposited between lava flows or intruded into them.

Bassaget (1968) interpreted the metagabbro as a large intrusion. He suggested that the intercalated rocks of sedimentary origin might be tectonic slices of rock units faulted into the metagabbro.

It is also possible that some of the "quartzites" may be late stage differentiates of the gabbroic magma that formed layers or pegmatites in the rocks of the massif. Similar rocks form pegmatites in the less deformed Lake Tetepisca anorthosite (Unit 8b). The complete obliteration of primary features precludes a definitive interpretation.

The rocks intercalated with the metagabbro bear some similarity to the rocks of the grey gneiss complex (Unit 4) and the metasedimentary rocks and paragneisses of the Gagnon Group (Unit 6). However, their lithology is more diverse than that of the grey gneiss complex, and they lack the iron formation and abundant marble of the Gagnon Group.

I conclude, in concurrence with Kish (1968), that the metagabbro and its intercalated rocks are the oldest rocks in the area.

CHARNOCKITIC ROCKS (Unit 2)

The term "charnockitic" is used here for rocks that are very similar to those originally described by Holland (1900) as members of the charnockitic series. Holland described the common minerals of the rocks in the series as hypersthene, predominantly blue quartz, blue to green plagioclase and microperthitic potassium feldspar, augite, hornblende, biotite, graphite, zircon, apatite, iron-ores, and finally garnet in gneissic members of the series.

I use the term "charnockitic" for certain rocks of the Manicouagan area, because, whereas the lithologies are nearly identical to the rocks of the type area, some of the Manicouagan rocks do not contain hypersthene and most of the quartz is grey rather than blue. I follow Holland in the use of common rock names for most members of the series, reserving charnockite for granitic members.

An elongate massif in the southeast is the main outcrop area of charnockitic rocks. Nearly massive charnockitic rocks (Unit 2a) form high rounded hills, and well-foliated charnockitic rocks (Unit 2b) form lower hills.

Lithology

Charnockitic rocks of the Manicouagan area are characteristically green where fresh. Weathered specimens are deep honey-yellow or yellow-brown. Pegmatites in the charnockitic rocks have the same color as the country rocks, and are distinguishable only by their texture. Structure ranges from nearly massive and weakly foliated (Unit 2a) to well-foliated and gneissic with local bands (Unit 2b). The charnockitic rocks are generally leucocratic, although some bands in the gneissic rocks have a high proportion of mafic minerals.

Essential minerals are hypersthene, microperthite, and plagioclase, although hypersthene is locally absent (Tables 5 and 6). Important and locally abundant minerals include quartz, clinopyroxene, hornblende, and red-brown biotite. Hornblende and biotite are particularly abundant in the gneissic rocks (Unit 2b). Accessory minerals include apatite, zircon, monazite, allanite, opaque minerals, and light-pink garnet. Alteration products are chlorite and carbonate minerals.

Band or ribbon microperthite is characteristic and well-developed. The rare, more basic rocks contain antiperthite. Myrmekite commonly forms along contacts between quartz and plagioclase grains.

TABLE 5

MODAL COMPOSITIONS OF NEARLY MASSIVE TO WEAKLY FOLIATED CHARNOCKITIC ROCKS (UNIT 2A)

	6R7[a]	6R9[a]	7R2[a]	11x5[b]	Average of 4 Modes
Quartz	--	15	2	20.8	9.45
Plagioclase	11	10	15	46.6	20.65
Alkali-Feldspar (perthite)	70	70	75	30.2	61.3
Orthopyroxene	7	--	5	2	
Clinopyroxene		2	1	3	
Biotite	--	--	--	--	
Hornblende	--	--	--	0.4	

[a] Bassaget, 1968
[b] Murtaugh, this paper

TABLE 6

MODAL COMPOSITIONS OF GNEISSIC CHARNOCKITIC ROCKS[a] (UNIT 2B)

	6R5	7R10	31C1	33C22	31B1a	31B12b	36B4	Average of 7 Modes
Quartz	1	15.20	--	2	25	25	10	13.3
Plagioclase	20.25	5	20	43	10	35	43	25.1
Alkali-Feldspar (perthite)	60	70-75	75	45	50	10	31	48.7
Orthopyroxene	4	2	--	4	2	12	4	4.7
Clinopyroxene	8	1	2	--		15	--	6.5
Biotite	1	0.5	--	2	2	--	3	1.2
Hornblende	2	0.5	2	--	--	--	8	2.0

[a] All data from Bassaget, 1968

The compositions of plagioclase range from An_{15} to An_{45}. Bassaget (1968) found that leucocratic charnockitic rocks had more sodic plagioclase (An_{38} or less), whereas the darker rocks had more calcic plagioclase (greater than An_{38}).

The proportions of minerals in the charnockitic rocks are highly variable (Tables 5 and 6). Rock types present include granite (charnockite *sensu stricto*), syenite, monzonite, grandodiorite, and diorite (diorite specimen not in tables). The different types were generally not mapped in the field because of the difficulty in distinguishing compositional differences among the dark-green or honey-yellow rocks. Two units, however, form well-defined plutons of distinctly different appearance. Unit 2c, in the north, is a highly weathered charnockitic syenite. It is made up of string microperthite with subordinate plagioclase and minor hypersthene, diopsidic augite, garnet and biotite. Unit 2d is a small plug of charnockitic diorite in the south. In hand specimen the rock looks like a green gabbro, but Bassaget (1968) reports the plagioclase composition as An_{42}.

The texture of the charnockitic rocks is xenoblastic, except for idioblastic garnet. Quartz is xenomorphic, and does not have the lenticular shape characteristic of the quartz in amphibolite-granulite transitional facies rocks (Unit 3). Foliation is visible in thin section, even in nearly massive rocks, because of orientation of mafic minerals and lensoid aggregates of felsic minerals.

Metamorphism and Deformation

The assemblage orthopyroxene-clinopyroxene-microperthite-quartz-garnet-plagioclase is indicative of the granulite facies. The occurrence of biotite and hornblende in Unit 2b indicates either a later retrograde metamorphism or a locally higher partial pressure of water during the metamorphism of the charnockitic rocks.

Contact Relations and Age

Charnockitic rocks intrude the metagabbro (Unit 1) as small plugs and are present as layers intercalated with the metagabbro. I correlate these rocks with other charnockitic rocks in the area on the basis of lithology, and conclude that they are younger than the metagabbro.

Charnockitic rocks are intermingled with grey gneisses (Unit 4) and granitic gneisses (Unit 5) in a manner that defies interpretation. Bassaget (1968) described a passage from charnockitic rocks into grey gneiss and into granitic gneiss through a zone of lit-par-lit mixtures of the respective rocks, or of rocks that are not clearly of one type or the other. For example, nearly massive charnockitic changes to a lit-par-lit mixture of charnockitic rocks with pyroxene-bearing granitic gneiss then to a mixture of grey gneiss with granitic gneiss. Transition from charnockitic rocks to grey gneiss in the south central part of the area is over a broad terrain of mixed gneisses and hybrid gneisses.

Origin

The plugs and bands of charnockitic rocks in the metagabbro (Unit 1) strongly suggest that the rocks are intrusive. Bassaget (1968) described rare inclusions of mafic hornblende-biotite gneiss in the charnockitic rocks. The charnockitic rocks appear to comprise a suite of igneous rocks that were formed initially under conditions of regional metamorphism or were later subjected to high grade regional metamorphism.

AMPHIBOLITE-GRANULITE TRANSITIONAL FACIES ROCKS (Unit 3)

The transition from amphibolite facies to granulite facies is marked both by gneisses that do not clearly belong to one facies or the other, and by the mixing of gneisses of different types on a scale too small to map. I follow Turner (1968) in placing such rocks in an amphibolite-granulite transitional facies. The major transition zone extends north-south through the central part of the area. Two distinct rock types, tan gneisses and melanocratic gneisses, are characteristic of this transition zone.

Tan Gneisses (of Unit 3)

Tan gneisses are medium-grained to coarse-grained leucocratic rocks with a faint foliation formed by alignment of mafic minerals and by lenticles or ribbons of quartz. The felsic minerals are plagioclase, microperthite, and, locally, quartz. Mafic minerals are clinopyroxene, biotite, hornblende, and, rarely, hypersthene. Accessory minerals include garnet, apatite, zircon, allanite, and opaque minerals. Chlorite and carbonate minerals are rare alteration products. The tan gneisses include rocks with the compositions of granite, syenite, monzonite, and granodiorite.

Perthitic texture in the form of bead and string microperthite is less well-developed than in the charnockitic rocks. Plagioclase ranges in composition from An_{25} to An_{35}. Green diopsidic augite is the common clinopyroxene; in some specimens the mineral appears to have an anomalously low birefringence of about 0.015.

The tan gneisses are typically granoblastic, except for ribbons of quartz and lenticles of aggregates of quartz or feldspar grains.

Melanocratic Gneisses (of Unit 3)

Melanocratic gneisses are abundant just southwest of the center of the Manicouagan Impact Structure, and crop out sporadically in the northwest part of the area. They are usually mixed, on a broad scale, with outcrops of granitic gneiss (Unit 5) and tan gneiss of Unit 3. These coarse-grained gneisses are dark grey to black and contain more than 70 percent mafic minerals. Lineation is formed by rod-like aggregates of mafic minerals. A weak foliation is formed by crude layering or alignment of mafic minerals.

The melanocratic gneisses are variable in composition. Hornblende or clinopyroxene usually makes up about 50 percent of the rocks. Other abundant minerals are garnet, scapolite, plagioclase, and, locally, biotite. Accessory minerals include allanite, epidote, sphene, opaque minerals, and rarely, quartz.

Metamorphism and Deformation

The tan gneisses differ from the granulite facies rocks in containing little or no hypersthene, in having less well developed microperthite, and in their color. They differ from the amphibolite facies rocks in their abundant clinopyroxene and microperthite as well as their color. The tan and melanocratic gneisses also differ structurally from the rock of Units 2 and 4 in that they typically have either lineation of mafic minerals or lenticular quartz, features that are rare in Units 2 and 4. The mineralogical differences indicate that these gneisses were metamorphosed at temperatures above those of the amphibolite facies rocks and below those of the granulite facies rocks.

Contact Relations, Origin, and Age

The tan gneisses mark a broad transition zone, 20 to 30 km wide in the south, between amphibolite facies and granulite facies rocks. The melanocratic gneisses crop out near the western edge of the transition zone. On the geologic map Unit 3 indicates areas that are predominantly tan gneisses, but these rocks are invariably mixed with rocks of Units 2, 4, and 5, as well as with the melanocratic gneisses. In places the mixing takes the form of banding a few centimeters thick, giving the outcrops the appearance of a migmatite. In other places, isolated outcrops of the different units are interspersed, suggesting mixing on a larger scale. Nowhere could age relations between the different units be determined.

The tan gneisses may either be charnockitic rocks metamorphosed to a lower grade, and/or grey gneisses (Unit 4) metasomatized and metamorphosed to a higher grade. The melanocratic gneisses might be the equivalent of the metamorphosed mafic and ultramafic rocks (Unit 4a) described in the next section.

The rocks described in this section are placed in the sequence as Unit 3 because they either are physical mixtures of older and younger rocks or metamorphic transitions between younger and older rocks.

GREY GNEISS COMPLEX (Unit 4)

The most abundant Precambrian rocks are medium-grained to coarse-grained grey gneisses. Large isolated lenses of metamorphosed mafic and ultramafic rocks (Unit 4a), and smaller, unmappable zones of compositionally and/or texturally different gneisses are interspersed with the grey gneisses. Outcrops are generally sparse and small, and large cliff-forming outcrops are partially covered with moss and highly stained. The absence of marker horizons makes estimation of thickness impossible.

A well-developed foliation formed by oriented biotite grains is commonly, but not always, parallel or subparallel to banding formed by concentrations of mafic minerals. In places the foliation is inclined at a high angle to the banding. Banding is irregular and rapid changes in thickness of banding along strike are common. Pink pegmatitic material forms rootless lenses, knots, and stringers that are generally conformable with, but locally crosscut, the banding.

Plagioclase, quartz, biotite, and hornblende are the essential minerals (Table 7). Hornblende is absent from some thin sections of leucocratic layers, but is invariably present in mafic-rich layers. Garnet and potassium feldspar are locally abundant. Sillimanite and kyanite are rare. Accessory minerals include apatite, zircon, sphene, clinopyroxene, allanite, epidote, graphite, and opaque minerals. Sericite, chlorite, and calcite are local alteration products.

Compositions of plagioclase show a small but distinct variation by area. Compositions in the north and west range from An_{22} to An_{30}, and average An_{27}. Those in the east and southeast, near areas of granulite facies rocks, range from An_{30} to An_{45}, and average An_{35}.

TABLE 7

MODAL COMPOSITIONS OF GREY GNEISSES (UNIT 4)

	5M3A	4D1	M2	20K2	Average of 4 Modes	38F2B
Quartz	30	57.5	19.7	34	35.5	21.6
Plagioclase	50	39.5	40	50	44.6	18
Alkali feldspar	5	--	11.2	--	8.1	17
Biotite	10	3	13	16	10.5	11.4
Hornblende	3	--	16.5	--	9.8	--
Garnet						20.4
Sillimanite						8.4

Microcline is present in rootless granitic lenses and in poorly defined pink zones in grey gneisses. These pink zones cross the foliation without disturbing it. The zones have diffuse borders, and are unrelated to pegmatites. Where these zones are well-developed, the grey gneisses become pink and granitic, but retain the texture, structure, and general aspect of the grey gneisses and are clearly different from the granitic gneisses mapped as Unit 5.

Two types of quartz are present in most thin sections. One type is unstrained and equidimensional. The other type is slightly biaxial (2V=5°), and forms lenticular grains with strong undulatory extinction and sector twins.

Rare clinopyroxene is commonly relic and resorbed, but in one specimen fresh augite coexists with hornblende and biotite. Sillimanite is present as prisms and as fibrolite in the same thin section. Berard (1962) reported kyanite from several specimens.

The grey gneisses have an average composition equivalent to quartz diorite. Locally, where microcline is abundant, they are granitic. Syenitic grey gneiss crops out in a few places near the Lake Tetepisca anorthosite.

A peculiar, thinly-laminated gneiss crops out on the lower part of the north slope of the Lake Tetepisca anorthosite. The lamination consists of alternating bands of felsic and mafic minerals which are as thin as one millimeter and can be traced for 7 m along strike. Mineralogically the rock is like the grey gneiss, except that biotite is mostly altered to chlorite (penninite). Texturally the rock is fine-grained, and all minerals are elongated and deformed parallel to the lamination.

Metamorphosed Mafic and Ultramafic Rocks (Unit 4a)

Bodies of metamorphosed mafic and ultramafic rocks in the southwestern part of the area range in size from a few meters to nearly a kilometer across. The best exposures are near the shores of Lake Tetepisca. A typical specimen of the most common type weathers reddish-brown and is speckled reddish-black where fresh. Garnets, ranging from 2 mm to 2 cm in diameter are rimmed by plagioclase and set in a matrix of mafic minerals. Less common varieties are black ultramafic rocks devoid of garnet and plagioclase. Poorly defined foliation, or lineation, is formed by an inconspicuous layering or alignment of mafic minerals. Coarse granitic pegmatites cut these rocks in a few places.

A typical specimen of the most common type consists mainly of almandite garnet, clinopyroxene (diopside or diopsidic augite), hornblende, and plagioclase (An_{15}-An_{20}). Accessory minerals are sphene, biotite, epidote, apatite, quartz, microcline, and opaque minerals. One specimen contains 15 percent scapolite.

Garnets are euhedral, and have wide clear borders around inner clouded zones. The borders of the clouded zones are sharp, and parallel to the crystal faces. The clouded zones contain small grains of all minerals present in the rock. Small grains of plagioclase are scattered throughout the rock, but tend to cluster around the garnets. Clinopyroxene poikiloblastically includes plagioclase, quartz, and sphene. Opaque minerals form symplectic intergrowths with quartz, plagioclase, biotite, hornblende, clinopyroxene, and sphene.

A hill about one kilometer in diameter, along the east shore of Lake Tetepisca, is made up primarily of the garnetiferous rock just described, but has a rim of isolated outcrops of black ultramafic rocks. These rocks are variable in composition, but all contain orthopyroxene, clinopyroxene, and phlogopite. Varieties contain olivine partly altered to antigorite, an unknown, slightly pleochroic, clinoamphibole, and a colorless micaceous mineral with low birefringence and bent cleavage (chloritoid?).

Metamorphism and Deformation

The mineral assemblages of quartz-plagioclase, biotite-hornblende-garnet, with local kyanite and sillimanite, is indicative of the almandine-amphibolite facies. Sillimanite and a higher anorthite content of plagioclase (An_{35} average) in the grey gneisses in the east suggest that they attained a higher grade of the amphibolite facies than did those in the west

(An_{27} average). This interpretation is supported by the fact that the grey gneisses in the east crop out between two areas of rocks of the granulite facies.

The rootless pink granitic lenses are probably the result of partial anatexis, a common phenomenon in rocks of the amphibolite facies. The microcline-rich pink nebulous zones in the grey gneiss appear to be areas of potassium metasomatism. The lack of perthite suggests a lower temperature of formation than that of the charnockitic rocks (Unit 2) and the granitic gneisses (Unit 5) in which perthite is abundant and well-developed.

Non-dilation replacement pegmatites were observed at two localities near Lake Tetepisca. These 2 cm thick pegmatites transgress foliation, but relic foliation within the pegmatite is continuous with foliation outside the pegmatite. These pegmatites are younger than the foliation, and are clearly the result of metamorphic differentiation of alkali metasomatism.

In one outcrop of metamorphosed mafic rock two sets of garnet bands intersect at a high angle. One set might represent relic primary layering, or one or both sets might have been formed by metamorphic differentiation, perhaps as the result of the migration of mobile constituents to zones of lower pressure such as joints.

Evidence for multiple deformation and polymetamorphism is present in both the grey gneisses (Unit 4) and the metamorphosed mafic and ultramafic rocks (Unit 4a). Mica in several specimens of both types of rock has two well-defined preferred orientations, indicating two periods of deformation. The strained and unstrained quartz in the grey gneisses, and the garnets with clear rims and clouded interiors suggest two periods of metamorphism. Cross-folds in a few outcrops further indicate multiple deformation.

Contact Relations and Age

The grey gneisses and the metamorphosed mafic and ultramafic rocks were not found in contact, except for one possible inclusion of gneiss in garnetiferous mafic rock. The mafic and ultramafic rocks were apparently igneous rocks, and I consider them to be penecontemporaneous with the surrounding gneisses because they have a similar metamorphic and deformational history.

The ultramafic and ultrabasic rocks mapped as Units 7 and 10 are considered to be younger than the rocks described here because of their lesser degree of deformation and local preservation of primary textures. Kish (1968), mapping in the northeast, described as one unit several types of mafic and ultramafic rocks that could not be related clearly to the rocks described here as Unit 4a. Such rocks are mapped with Unit 7. Biotite-hornblende metagabbro (Unit 1a) is in fault contact with grey gneiss on the north side of the Manicouagan Uplands (Kish, 1968). Elsewhere the contact between these two units is covered. The age relations between the grey gneiss (Unit 4), the metagabbro (Unit 1), and the charnockitic rocks (Unit 2) is a problem whose solution depends on the interpretation of the metamorphic history of these rocks. The metagabbro and the charnockitic rocks have been metamorphosed to the granulite facies at deep crustal levels. The outer margins of areas of granulite facies rocks appear to have undergone retrograde metamorphism. I suggest that this happened at a time of amphibolite facies metamorphism, when the grey gneiss was formed. At this time the margin of the metagabbro was converted to biotite-hornblende metagabbro while the charnockitic rocks were remobilized, developing a foliation and locally intruding the grey gneiss to form migmatitic mixtures. An alternative explanation is that the grey gneiss is the oldest rock and that the metagabbro and charnockitic rocks were intruded at a later time. I find it difficult to reconcile this latter interpretation with the fault contact of the metagabbro and the amphibolite facies rocks on the north slope of the massif, and with the generally broad transition zone between the charnockitic rocks and the grey gneisses.

The Gagnon Group (Unit 6) appears to overlie the grey gneisses, although no contacts were found. Rocks of the Gagnon Group 110 km to the northeast overlie similar basement rocks (Quebec Cartier Mining Co., 1972). The Tetepisca anorthosite (Unit 8b) intrudes both the grey gneisses and the paragneisses of the Gagnon Group. Diabase dikes (Unit 9) intrude the grey gneisses at several localities (Berard, 1962).

Origin

The grey gneisses of the Grenville Province, which constitute about sixty percent of the bedrock of the province, have long defied interpretation (Wynne-Edwards, 1972). The monotonous tracts of homogeneous rocks, unrelieved by marker horizons, have a complex metamorphic and deformational history that precludes determination of definitive answers about their origin. The general composition of quartz diorite is compatible with either igneous or sedimentary parent rocks.

The metamorphosed mafic and ultramafic rocks (Unit 4a) are clearly of igneous origin. I interpret the garnetiferous mafic rocks as basaltic or gabbroic sills, dikes, or flows that were intruded into, or extruded onto the parent rocks of the grey gneisses. The ultramafic rocks are clearly of intrusive origin, and their association with the mafic rocks at one locality is suggestive of an ophiolitic origin, but the poor exposures and degree of metamorphism make such a suggestion extremely tenuous.

GRANITIC GNEISS (Unit 5)

Granitic gneiss is abundant in the northeastern and the southeastern parts of the area. Bassaget (1968) described the granitic gneiss in the southeast, and Kish (1968) described that in the northeast.

The granitic gneiss in the southeast is a medium-grained pink rock made up mostly of quartz, microcline microperthite, and plagioclase (Table 8). Biotite, hornblende, chlorite, garnet, allanite, apatite, zircon, opaque minerals, and rare muscovite are accessory minerals. Pyroxene is an accessory mineral near contacts with charnockitic rocks. Plagioclase ranges in composition from An_0 to An_{41} according to Bassaget (1968). Foliation is formed by lenticles and leaves of quartz.

Kish (1968) distinguished three types of granite in the northeast on the basis of feldspar composition and feldspar ratios. He described two-feldspar granite, albite granite, and microcline granite, but did not map them separately. These rocks contain as much as 11 percent mafic minerals, and are therefore generally more mafic than the granitic gneiss in the southeast. The rocks range from slightly foliated to well-foliated, and, in some, quartz and feldspar form lenticles or have flaser structure. Kish described some pegmatites as very coarse-grained and

TABLE 8

MODAL COMPOSITIONS OF GRANITIC GNEISS (UNIT 5)

	1C18[a]	23C4[a]	41Cf[a]	55D36[a]	55D7[a]	5R1[a]	30B10[a]	Average of 7 Modes	20K3[b]	4X1B[b]
Quartz	27	23	31	32	31	34	32	30.0	37	18.6
Plagioclase	3	12	3	16	15	5	4	8.3	23	40.6
Microcline Microperthite	65	60	62	50	53	67	60	59.4	32	18.0
Biotite	2	1	3	1	tr	1.5	4	1.8	3	4.0
Hornblende	3	--	--	--	--	--	--		2	--
Clinopyroxene										7.2
Garnet									tr	11.0

[a] Bassaget, 1968, southeast part of area
[b] Murtaugh, this paper
20K3 from north shore of Lake Manicouagan
4X1B from mixed gneiss zone south of area

undeformed. Kish also described lit-par-lit mixtures of granitic gneiss and grey gneiss; These rocks are shown on the geologic maps as Unit 5a.

Contact Relations and Age

The granitic gneiss in the southeast is layered lit-par-lit with the grey gneiss (Unit 4) and with the charnockitic gneiss (Unit 2). Bassaget (1968) drew the contacts between the units where one type became predominant. The granitic gneiss is clearly intrusive into the grey gneiss, but the age relations of the granitic gneiss and the charnockitic gneiss are not clear. The occurrence of pyroxene in granitic gneiss near contacts with charnockitic gneiss suggests that the charnockitic gneiss is intrusive. Kish (1968) suggested that the granitic rocks in the northeast were of different ages, but he was unable to determine the relative ages. He described a chlorite granite gneiss that intruded shear zones related to the Hart-Jaune fault that cuts the Lake Raudot layered intrusion (Unit 7). The chlorite granite gneiss therefore may either be younger than the other granitic gneiss, or it may be an older rock that was remobilized and chloritized at the time of faulting.

The granitic gneiss described in this section has a wide range of compositions and textures, and it is likely that all of the gneiss is not the same in age. It is mapped here as a single unit because it was not differentiated in the field and the relative ages of different bodies were not determined.

Origin

The granitic gneisses all appear to be intrusive rocks that either have undergone later metamorphism or have been intruded into a stress field and acquired a primary foliation. Some of them may have been remobilized during later periods of metamorphism and become mixed with younger rocks. Kish (1968) interpreted some of the granitic rocks associated with the grey gneisses as having been formed by "metamorphic segregation."

GAGNON GROUP (GRENVILLE SUPERGROUP ?) (Unit 6)

The Gagnon Group includes metaquartzites, iron formation, marble and paragneiss that have either a relic texture, structure, or bulk composition that indicates a sedimentary origin. The rocks crop out almost exclusively as isolated patches in the western part of the area.

Outcrops are generally poor and exposures of different units are discontinuous, with the exception of some extensive low cliffs of marble. The rocks are structurally complex. Some outcrops show small-scale cross-folds. The only relic structure recognized was bedding, and no structures useful in determining tops and bottoms of beds were seen. I suspect that sedimentary facies changes are present, but I could not map them. The complex structure makes it difficult to determine stratigraphic thickness, or even sequence, with any degree of certainty.

Field parties of the Quebec Cartier Mining Company spent parts of two seasons mapping the areas containing iron formation in considerably more detail than the writer. Reports and maps made by these parties, which are on file with the Quebec Department of Natural Resources, were used as a guide in the field work and in the writing of this section of this report.

Description of Rock Units

Brecciated Metaquartzite (Unit 6?)

The westernmost outcrop of metasedimentary rock, a brecciated metaquartzite, is separated from the other metasedimentary rocks by two long, narrow lakes that might follow a fault. The rock is made up of angular fragments, as much as 10 cm across, of white fine-grained metaquartzite in a matrix of white medium-grained metaquartzite. Boundaries between fragments and matrix are distinct in hand specimen, but gradational in thin section, suggesting recrystallization after brecciation. The surrounding grey gneisses are not sheared or brecciated.

White Banded Metaquartzite

White medium-grained metaquartzite, with textural banding that clearly represents bedding, grades across the strike into the ferruginous quartzite described in the following section. The rock consists mostly of recrystallized quartz, but locally contains as much as 15 percent hypersthene and diopside and 10 percent muscovite, the latter distributed along relic bedding planes. One outcrop on the east shore of Lake Mouchalagane contains 30 percent garnet. The white metaquartzite may occupy more than one stratigraphic position within the Gagnon Group. The probable maximum thickness is between 15 m and 45 m.

Iron Formation and Ferruginous Metaquartzite

The iron formation consists of two distinct facies, an iron-silicate facies and an iron-oxide facies. The iron-silicate facies is a dark brown rock with more than 50 percent iron-silicates and as much as 15 percent iron oxides. The iron-oxide facies consists of steel-grey bands of iron-oxides mixed with bands of white massive quartz. The iron-silicate facies grades to the ferruginous quartzite and is similar to that quartzite in mineralogy, texture, and structure. Bedding is less discernable in the iron formation because of the darker color.

The iron-oxide facies is thin and poorly exposed. Ten cm thick bands of fine grey magnetite and specular hematite alternate with bands of massive quartz. The iron-oxide facies crops out near the iron-silicate facies, but no contacts were found. The total thickness of the two facies may be as much as 80 m in places, but appears to be generally much less, perhaps as little as 30 m.

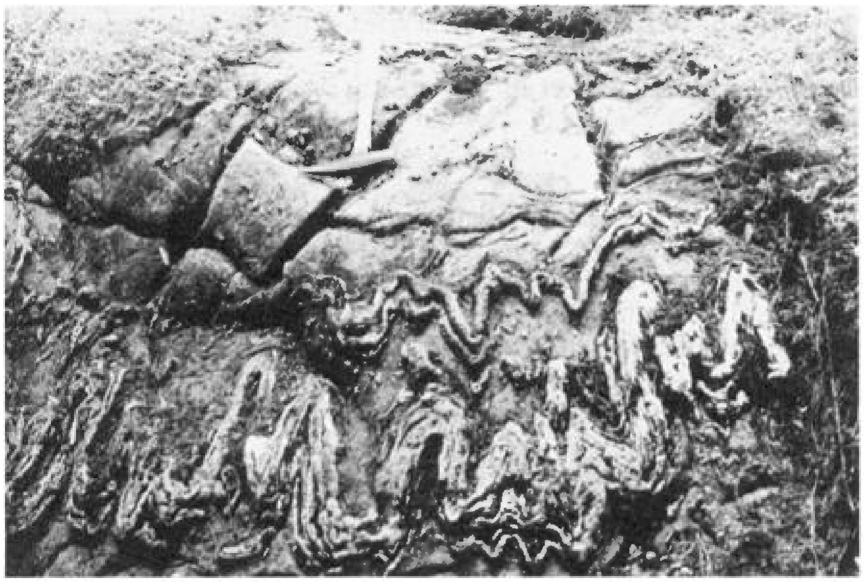
The ferruginous metaquartzite is a muddy-brown medium-grained bedded and foliated rock that contains less than 50 percent iron-silicate minerals. Relic bedding is shown by differences in grain size in quartz layers and by concentrations of iron-silicates along bedding planes. Foliation is a result of the preferred orientation of iron silicates parallel and subparallel to the bedding. Layers of dark green mafic minerals, 5 cm to 10 cm thick, are intercalated with the metaquartzites.

Quartz, orthopyroxene, clinopyroxene, iron-rich amphibole, and magnetite are the essential minerals. Accessory minerals are muscovite, tremolite, talc, and graphite. The dark green bands are composed of actinolite, diopside, and iron-rich amphibole. Calcite is in local microscopic layers.

Some of the orthopyroxene is positive, some is negative. Estimated optic angles indicate that ferrohypersthene is the most abundant orthopyroxene, but that enstatite, hypersthene, and bronzite are also present. Clinopyroxenes are in the diopside-hedenbergite series, and iron-rich diopside is the most common member of the series. Iron-rich amphibole characteristically shows polysynthetic twins, is optically negative, and has a maximum extinction angle of 15°. These data suggest that the mineral is grunerite, though the birefringence and optic angle ($2V=70°-80°$) are too low for most grunerite.

Marble

Marble is white to buff on a fresh surface and weathers dark grey. Relic bedding is indicated by alternating layers of medium-grained and coarse-grained marble and by white quartzite interbeds. Muscovite locally produces a foliation along the relict bedding planes. Layers of massive quartz in the marble may be as thick as 10 cm, and are complexly folded in some outcrops (Pl. II). The origin of the massive quartz layers is unknown, but they may have been beds of chert.



Pl. II

Tightly folded quartz layers in marble.

Calcite is the essential mineral. Colorless diopside, tremolite, and muscovite are minor constituents. Layers containing concentrations of diopside and tremolite stand out because of differential weathering.

Well-banded Graphitic Paragneiss

A well-banded gneiss that weathers rusty-brown is associated with the marble and quartzite in a few places, and crops out sporadically elsewhere. This gneiss is distinguished from the grey gneisses by its weathered color, its well-defined persistent felsic-rich and mafic-rich bands, and its abundant graphite and accessory muscovite. Augen structure is well-developed in outcrops of the rock near the Lake Tetepisca anorthosite.

The essential minerals are quartz, antiperthitic plagioclase, potassium feldspar, biotite, garnet and graphite. Accessory minerals are apatite, zircon, and opaque minerals. The texture is xenoblastic. Some quartz and feldspar grains that are overgrown by other minerals have partly rounded cores that suggest a relic sedimentary texture. Minerals in the augen gneiss are all elongated and sheared, and the augen are formed by aggregates of quartz and plagioclase.

Muscovite-bearing Quartzofeldspathic Gneiss

A whitish-pink poorly foliated gneiss of granitic composition crops out in a few places west of the Mouchalagane River. In hand specimen the rock has the sugary texture of a metaquartzite. The gneiss is composed of about 30 percent quartz, 40 percent fresh non-perthitic microcline, 25 percent plagioclase, and minor muscovite and garnet. Foliation results from alignment of muscovite grains. The texture is xenoblastic. Some of the grains of quartz and feldspar are distinctly rounded, like similar grains in the graphitic gneiss.

Metamorphism and Deformation

An amphibolite facies is indicated by the assemblages of calcite-tremolite-diopside in the marble and quartz-plagioclase-biotite-garnet in the gneiss. The orthopyroxenes in the iron formation and ferruginous quartzites do not indicate granulite facies metamorphism, but rather the abundance of iron in the rocks. Kranck (1961) discussed metamorphic equilibria in the metamorphosed iron formation of the Mount Reed area, 170 km to the northeast, where the rocks are similar to those described here. He listed many possible reactions that could form iron-rich pyroxenes and amphiboles from iron-rich silicates of lower metamorphic grade (minnesotaite, greenalite), or from siderite and quartz.

Foliation and bedding dip uniformly in most outcrops, but are complexly folded in some outcrops. Details that cannot be shown on the scale of the geologic map indicate a complex deformational history that is undecipherable with the data at hand.

The local augen structure in the graphitic gneiss is cataclastic in origin and clearly related to the intrusion of the Lake Tetepisca anorthosite. The border facies of the anorthosite, and the grey gneisses nearby, also have augen structure.

Contact Relations and Age

The marble, quartzite, and iron formation were not found in contact with any other units. The graphitic paragneiss is in contact with the Lake Tetepisca anorthosite (Unit 8a) south of the mapped area, where the gneiss has been deformed so that its layering (bedding?) is parallel to the border of the anorthosite pluton. The iron formation and associated rocks are generally considered to be younger than the grey gneisses (my Unit 4) of the Grenville Province (Wynne-Edwards, 1972). I have no direct evidence to substantiate this. The presence of relic sedimentary textures in the Gagnon Group and the absence of any such features in the grey gneiss suggests that the Gagnon Group rocks are less metamorphosed and may be younger.

The metasedimentary rocks of the Manicouagan area are correlated with the Gagnon Group of the Mount Reed-Mount Wright and Lake Jeanine areas, 170 km to the northeast, on the basis of similar lithology and metamorphic grade (Quebec Cartier Mining Co. Staff, 1972). Rb/Sr and K-Ar mineral dates from gneisses associated with the Gagnon Group in the Mount Reed and Lake Jeanine areas are in the typical Grenville "orogeny" range of 950-970 m.y. (Lepp et al., 1963). The Sokoman iron formation of the central Labrador geosyncline and its associated rocks are generally considered to be less metamorphosed equivalents of the more highly metamorphosed rocks in the Grenville province including the Gagnon Group (Gastil et al., 1960; Wynne-Edwards, 1972). Fryer (1972) dated the Sokoman iron formation at 1879 ± 43 m.y. by composite Rb/Sr whole rock isochrons of overlying slates. This suggests that the Gagnon Group rocks were recrystallized and isotopically homogenized during the Grenville "orogeny".

Wynne-Edwards (1972) summarized the stratigraphic sequences and correlations in the Grenville province. His correlations are made essentially on the basis of lithology with some control exercised by style and orientation of structure, and by a few isotopic ages. He considered the

Gagnon group to be older than the Grenville supergroup, primarily because the latter is intruded by rocks dated between 1250 - 1400 m.y., whereas the possible equivalents of the Gagnon group are dated at between 1787 - 1879 m.y. (Fryer, 1972). The Grenville supergroup and the Gagnon group are similar in that they both contain quartzites, marbles, and graphitic aluminous paragneisses. They are different in that the Grenville supergroup is much thicker and lacks iron formation. Wynne-Edwards also correlates the Wakeham Bay group, a thick, predominantly quartzite sequence in eastern Quebec, with the Grenville supergroup. Recently, however, Sharma and Jacoby (1973) discovered thin beds of iron formation in the Wakeham Bay group, and suggested that this group was correlative with the rocks of the Labrador geosyncline, and therefore, the iron-formation sequences. This in turn suggests that the Grenville supergroup might correlate with the Gagnon group. It is beyond the scope of this report to attempt to unravel the complexities of the Grenville supracrustal rocks. I suggest that the metasedimentary rocks and paragneisses of the Manicouagan area are correlative with the Gagnon group, which in turn may be correlative with the Grenville supergroup.

Origin

The composition and bedding of the marble, quartzite, and iron formation indicates that they are of sedimentary origin. Gastil and Knowles (1960) compared the metamorphosed iron formation sequence in Grenville rocks of the Wabush Lake area with nearby less metamorphosed iron formation sequences that crop out north of the Grenville Front. They suggested that the iron formation sequence originated as chemical precipitates in a near shore environment, and that the associated gneisses originated as argillaceous sediments. The rocks that are called paragneisses here have some rounded grains that suggest a sedimentary origin. The well-banded gneiss with its abundant graphite is clearly sedimentary in origin. The origin of the quartzofeldspathic gneiss is less obvious. It has what appears to be a relic sedimentary texture (rounded grains), and in one locality it appears to form a lens in a garnetiferous quartzite.

BASIC AND ULTRABASIC ROCKS (Unit 7)

The rocks described in this section crop out in the northeast part of the area. They have been mapped only by Kish (1968) and the summary descriptions below are abstracted from his report. The rocks may be of different ages, but on the basis of their general similarity and proximity to each other, and in the absence of detailed knowledge about their ages, I have placed them in a single unit.

Raudot Lake Layered Intrusive Pluton, Brien Anorthositic Gabbro (Unit 7)

The Raudot Lake pluton is a layered intrusive comprised of layers of dunite, magnetite, magnetite-bearing gabbro, anorthosite, anorthositic gabbro, troctolitic anorthosite, and troctolite. Plagioclase compositions range from An_{60} to An_{66}. Plagioclase laths locally are oriented to form a primary foliation. The northern and western parts of the massif, which are in this map area, are deformed, metamorphosed, and metasomatized. Plagioclase is recrystallized, and amphibole, biotite, and chlorite replace pyroxene and olivine. Coronas of amphibole and garnet have formed around olivine. An unusual metasomatic effect in these rocks is the formation of staurolite in altered anorthositic gabbro. Kish attributes the metasomatism to hydrothermal fluids associated with granite that intrude the massif along its northern and western edges.

The Brien anorthositic gabbro crops out southwest of the Raudot Lake massif, along the north side of the Hart-Jaune fault. The anorthositic gabbro is an olivine-pyroxene-labradorite rock that Kish suggested was related to, and perhaps connected with, the Raudot Lake massif. The southeastern part of the anorthositic gabbro is altered to a hornblende-plagioclase gneiss.

Ultrabasic Rocks (Unit 7a)

Several small bodies of ultrabasic rock crop out in the northeast part of the area. One is basically a dunite consisting of 85 percent olivine and minor orthopyroxene, amphibole, and chlorite. Another body consists of foliated garnet-hornblende peridotite. The peridotite is cut by a veinlet of the coronitic gabbro described below. Two ultrabasic dikes consist essentially of primary olivine and orthopyroxene, secondary garnet and green amphibole, and local biotite and chlorite.

Coronitic Gabbro (Unit 7b)

Coronitic gabbros form lenses nearly a kilometer in diameter in older rocks in the northern part of the area. They are medium-grained to coarse-grained bluish-grey rocks that weather rusty-brown. Relic ophitic structure is present. Primary minerals are plagioclase, olivine, and clinopyroxene. Secondary minerals are another clinopyroxene, garnet, hornblende and biotite. Plagioclase is commonly recrystallized to granular aggregates, with a composition of An_{35}, or altered to garnet. Pyroxene and garnet form coronas around olivine, and hornblende and biotite form rims around opaque minerals.

ANORTHOSITES (Unit 8a, 8b)

Two anorthosite plutons crop out in the area. They are similar in mineralogy, but differ in texture and structure and associated minor rocks.

Lake Tetepisca Anorthosite (Unit 8a)

The southwest corner of the area is underlain by the northern part of a pluton of anorthosite that is about 65 km long, 30 km wide, and is elongated northwest-southeast. The following description is based in part on data collected south of the map area during the 1968 Grenville Project.

Lithology

The interior of the pluton is mostly anorthosite made up of blue labradorite grains as much as 10 cm long, commonly set in a matrix of fine-grained grey labradorite. The ratio of matrix to megacrysts increases toward the margin of the pluton, and locally all the plagioclase is fine-grained. Mafic minerals are generally more abundant toward the margins of the pluton, where the rock becomes gabbroic anorthosite, or anorthositic gabbro.

Twin lamellae in plagioclase megacrysts are broad, and commonly bent and sheared. The small plagioclase grains forming the matrix are anhedral, and have narrow, undeformed twin lamellae. Both types of plagioclase have a narrow compositional range of An_{50} to An_{55}.

Clinopyroxene (augite and diopsidic augite), hornblende, biotite, and garnet are the important mafic minerals. Orthopyroxene is abundant south of the map area. Apatite, scapolite, allanite, epidote, and opaque minerals, common rimmed with sphene, are the accessory minerals. Chlorite is an alteration product, particularly near the edge of the massif. Hornblende and biotite are most abundant near the northern border of the massif.

Coronas consist of pyroxene mantled by hornblende, which is in turn surrounded by garnet. Coronas in the map area typically have clinopyroxene cores, but south of the map area they have orthopyroxene cores. Hornblende has clearly altered from pyroxene.

Foliation and lineation are formed by oriented coronitic lenticles 1 cm to 2 cm in length. Trachytoidal texture is locally formed by subparallel orientation of tabular plagioclase megacrysts in a matrix of fine-grained plagioclase. Local rhythmic layering is shown by alternating brown bands of gabbro and bluish bands of anorthosite. The bands range in thickness from 5 cm to 10 cm.

Hornblendite Dikes, Pegmatites, and Breccia Pipe

Dikes of brown weathering hornblendite, as much as two meters thick, cut the anorthosite at several localities. The rock consists of about 90 percent hornblende, along with pyroxene, biotite, and carbonates. The dike rocks have a well-developed lineation parallel or subparallel to the walls of the dikes. The lineation is caused by alignment of euhedral crystals of hornblende that are less than 1 mm long.

Two distinct generations of pegmatites cut the anorthosite. The younger pegmatite is a very coarse-grained undeformed rock composed of pink microcline and grey quartz with minor plagioclase, muscovite, biotite, hornblende, garnet, and rarely, green mica (roscoelite?). These pegmatites are as much as one meter thick, and they cut all other rock units with sharp contacts.

The second, more common, type of pegmatite has a similar mineralogy, but is sheared and well lineated. These pegmatites are thin, rarely attaining a thickness of 30 cm. Quartz and feldspars are sheared into linear aggregates of grains that are as much as 10 cm long and 1 cm thick. The lineation is subhorizontal and parallel to the walls of the pegmatites. Where these pegmatites cut the anorthosite foliation that is formed by an alignment of coronas, that foliation is diverted near the pegmatite, so that it turns and is parallel to the walls of the pegmatite.

A unique breccia pipe cuts the anorthosite on the west shore of Lake Tetepisca. The pipe is cylindrical and about 5 m in diameter. Fragments, that are as much as 10 cm in diameter, weather black and are white on fresh surfaces. The matrix is red.

In thin section the rock is a hash of highly fractured grains of poorly-twinned plagioclase, bent, frayed and kink-banded biotite, minor muscovite, and a few scattered grains of garnet and scapolite, all set in a matrix that is in part finely comminuted particles, and in part cryptocrystalline material that appears to be devitrified glass.

Staining of thin sections indicate that the matrix is potassium-rich, and therefore is probably not comminuted plagioclase or plagioclase glass. This breccia is totally unlike any other rock in the area, including the various breccias of the Manicouagan Complex.

Metamorphism, Deformation, and Origin

The biotite-hornblende-garnet coronas indicate that the present metamorphic grade of the anorthosite is in the amphibolite facies. The local presence of clinopyroxene and orthopyroxene suggests either that the anorthosite was once metamorphosed to the granulite facies, or that it initially formed under granulite-facies conditions. The abundance of orthopyroxene at the south edge of the pluton, proves that this part of the pluton preserves the higher grade facies.

The most common type of foliation and lineation is that formed by discrete lenses, thin discontinuous rods, or layers of mafic minerals. The rods and lenses commonly show corona structure, and are best developed in outcrops in which the plagioclase is all fine-grained. The foliation and lineation would seem to be metamorphic, but detailed field relations suggest that they originated as primary protoclastic structures. This indicates an igneous origin for the anorthosite. The detailed field relations are:

1) Autointrusive apophyses of anorthosite intrude anorthosite in several places. The autointrusive apophyses are foliated, whereas the host anorthosite in those outcrops is not. This indicates that the foliation is a primary, but late stage, protoclastic phenomenon.

2) Where the sheared pegmatites cut the foliation of the anorthosite,

the foliation is diverted so that it follows the pegmatites. I interpret the pegmatites as residual solutions crystallizing along zones of weakness that became shear planes. The residual solutions were emplaced as the anorthosite was nearly consolidated but was still capable of being deformed plastically.

3) Foliation formed by coronitic lenses in one outcrop strikes and dips parallel to rhythmic layering in another outcrop 50 m away. The rhythmic layering is clearly a primary igneous texture. The parallelism of the foliation suggests that it also is primary.

Mount de Babel Anorthosite (Unit 8b)

A pluton of anorthosite 50 km long and 15 km wide extends from just southeast of Mount de Babel, in the center of the Manicouagan Impact Structure, to Mount Brilliant, which lies outside the structure to the northwest. The pluton is disrupted by the impact structure, but scattered outcrops of anorthosite under rocks of the Manicouagan complex indicate that the pluton was once continuous. That part of the pluton that lies within the impact structure has been shock-metamorphosed and hornfelsed but the original features of the rock are preserved in most outcrops. This section describes Precambrian geology, not the shock features.

Lithology

This anorthosite is a fine-grained to medium-grained white rock composed mostly of plagioclase, with minor coronas and bands of pyroxene, hornblende, garnet, and, locally, biotite. Scattered garnets give the rock a speckled appearance.

The plagioclase in the anorthosite ranges in composition from An_{50} to An_{60} and averages An_{53}. Xenoblastic plagioclase grains have a maximum size of 2 mm. All grains show undulatory extinction, but twin lamellae are not bent or sheared.

Mafic minerals include orthopyroxene (enstatite and hypersthene), clinopyroxene (augite and diopside augite), hornblende, garnet, and locally, biotite. Scapolite is a common accessory mineral and locally makes up 10 percent of the rock. Sphene and apatite are minor accessory minerals. Corona structure is formed by garnet and/or hornblende rims around pyroxene. Hornblende is a minor alteration product replacing pyroxene in garnet-pyroxene bands, and elsewhere is abundant as discrete grains.

Zeolites are local alteration products, and where the anorthosite is zeolitized it is pink. I believe that zeolitization is related to solutions from rocks of the Manicouagan Complex, and discuss this phenomenon in Part II.

Both foliation and lineation are formed by elongated and flattened clusters of mafic minerals that locally show corona structure. Garnet-pyroxene bands and schlieren range in thickness from 5 cm to 1 m. The bands are parallel and subparallel to foliation.

Autointrusive Breccias

Breccias of anorthosite, and also peridotite, at one locality on Mount Brilliant, appear to have formed as the result of the intrusion of an early-crystallized phase by a late-crystallized phase of the same magma. The most striking example of this phenomenon is a plug of peridotite that is exposed for about 20 m. The peridotite is composed of serpentine, clinopyroxene, clinoamphibole, and opaque minerals. Coarse-grained dark peridotite is intruded by, and included in, a medium-grained phase of the same rock (Pl. III) that weathers yellow-brown. The two phases are virtually indistinguishable on a fresh surface or in thin section, except for the difference in grain size. The angularity of the included fragments indicates that the coarse phase was consolidated before intrusion of the medium-grained phase.

Pl. III

Autointrusive peridotite in the Mount Brilliant pluton. Dark fragments of coarse-grained peridotite are included in medium-grained peridotite that weathers yellow brown.

Autointrusive anorthosite breccia crops out near the peridotite. The brecciation of the anorthosite is apparent in this outcrop only because the white medium-grained fragments are included in a fine-grained phase that was zeolitized and colored pink. Such brecciation may be more widespread in the anorthosite, but in the absence of selective zeolitization it would not be noticed. Foliation appears to be continuous through the included fragments and the matrix, indicating metamorphism and deformation after formation of the breccia.

Metamorphism, Deformation, and Origin

The Mount de Babel anorthosite is mineralogically similar to the Lake Tetepisca anorthosite, but differs in texture, in structure, in the presence of garnet-pyroxene bands, and in the absence of pegmatites and dikes. The textural difference causes a difference in color, because of the absence of large bluish labradorite grains in the Mount de Babel anorthosite. The aggregate of mafic minerals that are aligned and flattened to form the foliation and lineation are similar, but those in the Mount de Babel anorthosite tend to be more flattened and less elongated. The foliation in the Mount de Babel anorthosite is metamorphic rather than protoclastic because it is penetrative, cutting across the autointrusive breccia. The orientation of the foliation is roughly parallel to the regional foliation outside the pluton, and it is not diverted at the borders of the pluton. The absence of large crystals and the lack of bending and shearing of the plagioclase indicates thorough recrystallization.

The assemblage of orthopyroxene-clinopyroxene-garnet indicates metamorphism to the granulite facies. The presence of hornblende and biotite suggests retrograde metamorphism to the amphibolite facies. I interpret the Mount de Babel anorthosite to be an igneous rock that has undergone one or more periods of metamorphism.

Contact Relations and Age

Wolfe (1971) dated an unshocked biotite-hornblende anorthosite from Mount Brilliant as 932 ± 7 m.y. old by the K-Ar whole rock method. This number probably indicates the recrystallization of the Mount de Babel massif during the Grenville orogeny. The Mount de Babel anorthosite is surrounded by, and I presume intrusive into, the tan gneiss of the amphibolite-granulite transitional facies rocks (Unit 3).

The well-exposed contact between the Lake Tetepisca anorthosite and the grey gneiss (Unit 4) along the shores of Lake Tetepisca is a melange of gneissic biotite-hornblende gabbroic anorthosite and grey gneisses that are intermingled and deformed together. The cataclastic and/or protoclastic nature of the deformation is indicated by the prominent augen structure developed in both rock types. In places the anorthosite appears to include large blocks of the grey gneisses, but deformation makes it difficult to be certain of this.

Rusty-weathering well-layered paragneiss (Unit 6) with augen structure crops out on the southeast side of Lake Tetepisca. The few outcrops here are the tip of a wedge of paragneiss that thickens to the southeast and wraps around the eastern border of the pluton. The paragneiss south of the map area strikes essentially parallel to the border of the anorthosite pluton and dips about 90°. Although no minor intrusions were observed, the distinct impression is that the paragneiss has been upturned and deformed around the intruding anorthosite.

To the southwest, beyond the map area, the anorthosite pluton is bordered by tan gneisses with lenticular quartz that are similar in hand specimen to the tan gneisses of Unit 3 that surround the Mount de Babel massif.

The two anorthosite plutons are included here in a single unit, although it is possible that they are of different ages. Determination of the relative ages of the two anorthosites on the basis of textural, structural, and regional field criteria is equivocal.

On textural and structural criteria, the Mount de Babel anorthosite would appear to be the older of the two. The complete recrystallization and regional foliation in this massif indicates a pre-tectonic or early syntectonic age with respect to some single period of deformation and metamorphism.

Regional field criteria suggest another interpretation. Both plutons are elongate in a northwest-southeast direction, suggesting that they may form a set or part of a set of large-scale contemporaneous intrusions. If this is true, the differences in texture and structure might be explained by differences in depth of emplacement. Wynne-Edwards (1972) suggested that many of the anorthosites were emplaced along an unconformity between the basement rocks and the supracrustal rocks of the Grenville supergroup. The thick sheath of upturned paragneisses on the northeast side of the Lake Tetepisca pluton suggests that such is the case at that locality. The higher grade metamorphic rocks within and without the pluton lie to the south. The dip of primary layering to the interior in the south, beyond the map area, of the pluton suggests that the anorthosite sheet was intruded along the contact of the paragneisses (Unit 6) and the grey gneiss (Unit 4), and above the tan gneiss (Unit 3).

On the other hand, the Mount de Babel pluton was intruded into the higher grade transitional rocks (Unit 3), and therefore presumably at a deeper crustal level. Thus the two plutons may have been intruded at about the same time, but undergone different deformational and metamorphic processes, with primary igneous structures preserved in the Lake Tetepisca pluton, but completely obliterated in the Mount de Babel massif.

BASALT-DIABASE DIKES (Unit 9)

Bérard (1962) described six diabase dikes along the east shore of Lake Manicouagan, and Kish (1968) described diabase dikes as much as 13 m thick in the Manicouagan Uplands. I have since discovered several others. All the dikes crop out east of Lake Manicouagan except for a single dike discovered by Bérard on the Mouchalagane River, just west of the map area.

The dikes are massive brownish-black aphanitic to fine-grained basalt or diabase. Bérard cautioned against confusing the diabase dikes with Triassic igneous rocks (Unit 15). Some dikes are strikingly similar in hand specimen to the Triassic rocks, but they are completely different in thin section.

Plagioclase, pyroxene and/or hornblende, opaque minerals, and, locally, garnet are the essential minerals. Plagioclase is zoned and clouded with small flecks of unidentifiable material. The plagioclase laths have scalloped, resorbed borders. Colorless augite has been partly or completely recrystallized to a mosaic of smaller grains. The augite is locally partly to completely replaced by hornblende. Garnet has grown idioblastically in one specimen. Kish (1968) reported garnet in other altered diabases. Ophitic and intergranular textures are clearly preserved even in the most altered rocks.

Two parallel metabasalt dikes, each less than one meter thick, intrude the biotite-hornblende metagabbro (Unit 1a) on the south slope of the Manicouagan Uplands. The dike rocks contain small laths of plagioclase, and microphenocrysts of plagioclase, in a cryptocrystalline matrix. The primary mafic minerals are altered to pale brown anthophyllite. The plagioclase microphenocrysts are altered to a mosaic of smaller grains of plagioclase.

Metamorphism, Deformation, and Age

The diabase dikes have undergone varying degrees of metamorphism. One dike on Lake Manicouagan has clouded plagioclase and the pyroxene is recrystallized to a mosaic of fine grains. Another dike, 10 km away, is similar except that it contains garnet and in one part of the outcrop pyroxene is partly altered to hornblende. None of the rocks has any foliation, and none is near any younger intrusive body. The dikes may have been affected by the very late stages of the Grenville orogeny or by a post-Grenville metamorphism. Currie (1968) gives a whole rock K-Ar age of 665 ± 75 m.y. on one of the dikes along the shores of Lake Manicouagan.

MICA-AMPHIBOLE PERIDOTITES (Unit 10)

Small plugs of unmetamorphosed peridotite crop out in the central and western parts of the Manicouagan Impact Structure. Similar rocks also occur as inclusions as much as two meters across in the Triassic basalt and suevite units.

The peridotites are massive black rocks with golden flecks, composed essentially of olivine, orthopyroxene, clinoamphibole, mica, opaque minerals, and locally, clinopyroxene. They are locally brecciated.

Olivine is partly altered to iddingsite or antigorite. Hypersthene is locally altered in part to clinoamphibole. Mica is commonly phlogopite or rarely, biotite. Mineral proportions are variable. For example, olivine content ranges from 30 percent to 70 percent.

In rocks with more than fifty percent olivine, the olivine is in interlocking euhedral, subhedral, or subrounded grains with interstitial pyroxene and amphibole. Where olivine comprises less than half of the rock, large poikilitic clinoamphibole grains include euhedral and subhedral olivine. Mica is always interstitial. The rocks appear to result from different stages of cumulus precipitation, where olivine is the cumulus mineral and clinoamphibole, clinopyroxene and mica are the intercumulus minerals.

Origin and Age

The lack of metamorphism suggests that the mica-amphibole peridotites are younger than any of the other Precambrian rocks, and they may be younger than Precambrian. Currie (1972) places these peridotites in a unit called "Heterogeneous basic and ultrabasic fragmental rocks in basaltic matrix." Currie includes in this remarkable unit rocks ranging in composition from basalt to peridotite and in texture from glassy to phaneritic. He interprets all of these rocks to be members of the

Triassic Manicouagan Complex. This unit was originally described in our cooperative preliminary report (Murtaugh and Currie, 1969). The fact that the peridotites are exposed only beneath or near the Triassic rocks initially suggested that the two might be related. Further work indicates that at least two different sets of rocks are involved. The younger rocks are basalts or breccias that contain no shock features, and which contain inclusions of the older peridotites. The mica in both plugs of peridotite and inclusions of peridotite have kink bands, indicating that the peridotite was in place before the shock-producing event that formed the Manicouagan Impact Structure. The peridotites are therefore older than the Triassic igneous rocks of the Manicouagan Complex.

The hornblende-mica peridotites are interpreted here as Late Precambrian in age, although it is recognized that they might be as young as Triassic.

ORDOVICIAN SEDIMENTARY ROCKS (Unit 11)

Outcrops of Ordovician rocks, mostly limestone, are restricted to the inner shores of Lake Manicouagan and Mouchalagane, except for two outcrops in a stream valley between the south slope of the Mount Brilliant anorthosite pluton and the north shore of Lake Mouchalagane. Currie (1968) describes as an outcrop some limestone debris on the south shore of Lake Manicouagan that Bérard (1962) clearly indicates was only boulders. Inclusions of the Ordovician rocks are also present in the overlying Triassic breccias and igneous rocks. The outcrops are generally small, but one area of limestone on Lake Mouchalagane is over one kilometer in diameter. Unfortunately, most of the outcrops were near the shorelines of the lakes and probably have been covered by water since the completion of the Manicouagan 5 dam.

The Ordovician rocks lie unconformably on Precambrian basement. The rarely exposed basal unit of the Ordovician rocks is red siltstone about 20 cm thick. Locally it is overlain by a fissile green shale about one to two meters thick. Most of the Ordovician outcrops consist of fossiliferous grey limestone with grey shaly partings. Currie (1968) described a tan dolomitic limestone overlying the grey limestone in a few localities. Maximum thickness of the Ordovician rocks is about 25 m.

Kish (1968) described the following fossil assemblage: *Receptaculites*, *Streptelasma*, *Diplogratus*, H*ormotoma*, L*ophospira*, *Trochonema*, *Maclurites*, *Vaginoceras*, *Ephipiorthoceras*, *Westonoceras*, *Isotelus*, *Cryptophragmus*, crinoid fragments, and bryozoa. Currie (1968) and Kish both conclude that the rocks are of Middle Ordovician age, probably the Wilderness stage. This assemblage is a typical shallow water assemblage. It is clear that the Middle Ordovician seas covered a much greater part of the Canadian shield than is shown on standard paleogeographic maps.

PRE-TRIASSIC STRUCTURAL GEOLOGY

The Precambrian rocks of the area show a variety of structural features that formed at different times. In this section I describe only those features that appear to have formed before Triassic time and that were not produced during the event that created the Manicouagan Impact Structure.

Folds, Foliation, and Lineation

Kish (1968) and Bassaget (1968) mapped north-trending folds in the granulite facies gneisses (Unit 1b) intercalated with the metagabbro (Unit 1) of the Manicouagan Uplands. Foliation in the metagabbro generally trends northeast and dips moderately southeast. Kish did not describe mineral lineation in the metagabbro, and Bassaget made only a brief reference to it. I found a well-developed mineral lineation in all of those few outcrops that I visited in both Kish's and Bassaget's areas. The lineation is formed by rod-like aggregates of mafic minerals that are as much as one centimeter in diameter. My few measurements all trended about 200° and plunged at gentle to moderate angles. My measurements are too few and widely scattered to permit interpretation.

Foliation in the area has two distinct trends: one strikes northwest and dips northeast; and the other strikes northeast and dips southeast. Two notable exceptions are: 1) directly south of the Manicouagan Impact Structure a strong north-trending foliation is present instead of the northwest trend; 2) along the border of the Lake Tetepisca anorthosite pluton, all foliation, in both the anorthosite (Unit 8a) and the gneisses (Units 4 and 6), strikes northwest, parallel to the border of the pluton. Rarely, foliation produced by biotite grains is oriented at high angles to banding in the grey gneiss.

Details of the structure of the Gagnon Group (Unit 6) are not shown on the geologic map for two reasons: 1) most of the detail is too small to show at the scale of the map; 2) much of the detailed information is based upon confidential reports and maps of the Quebec Cartier Mining Company that are on file with the Quebec Department of Natural Resources.

The details indicate that tight northeast-trending folds have been refolded about north-trending axes. The north-trending axes are apparent in the outcrop pattern of the Gagnon Group on the geologic map.

Small drag folds that could be measured in outcrop typically had curving axial surfaces. The number of such folds that could be measured is too small to be of any value in interpretation. The overall pattern of folds and foliation suggests that the rocks of the area have been folded at least twice, but the existence of cross folds and their orientation cannot be proved except in case of the rocks of the Gagnon Group.

Faults

Kish (1968) carefully mapped three faults in the northeastern part of the area. His evidence for the faults includes abrupt termination of units, sudden changes in direction of foliation, and cataclasis and shear of rocks in the fault zone. The most important of the faults is the Hart-Jaune fault, which extends for 45 km northeast from the mouth of the Hart-Jaune River. Fracturing and brecciation along the fault was accompanied by hydrothermal alteration of the rocks in and near the fault zone.

Bassaget (1968) described and mapped faults in the southeastern part of the map area on the basis of cataclasis, mylonization, and abrupt changes in rock type. I mapped several faults in the southern part of the area using the same criteria.

Currie (1972) and Rose (1955) show many faults on their geologic maps that are apparently drawn on the basis of "linears" in the topography. Such "linears" are common in the map area, but most of those that I have seen in the field show no evidence of being faults and most appear to be eroded joint valleys.

Joints

Joints are not abundant in outcrops remote from the Manicouagan Impact Structure. Commonly, only one or two sets of joints can be measured in any outcrop. The pattern of the joints on a regional basis is best shown by "linears" formed by elongate lakes or straight stretches of stream valleys that have been eroded along the strike of the different joint sets. The two most prominent trends are north-northeast and north-northwest. A less prominent trend is north and a subordinate trend is just north of east.

ECONOMIC GEOLOGY

The major potential resource of the area is the iron formation of the Gagnon Group (Unit 6). All large areas of outcrop of the iron formation that I am aware of have been claimed by the Quebec Cartier Mining Company. Two smaller areas that they did not claim were along the shores of Lake Mouchalagane. They are now underwater.

Details of the tenor of the iron and the thickness of the ore beds are contained in reports of the Quebec Cartier Mining Company that are on file with the Quebec Department of Natural Resources. These reports indicate that the iron formation is as thick as 65 m in places, although it is mostly much thinner. The potential ore contains up to 35 percent magnetite and specular hematite in bands mixed with massive quartz layers.

Some layers of ferruginous metaquartzite contain high percentages of magnetite. Geologic maps and cross-sections by the different company geologists indicate considerable disagreement about the nature of the folds in the Gagnon Group. Exploitation of the iron formation will require unraveling of the structure to determine if a sufficient quantity of iron is present.

Iron formation could be associated with any of the rocks of the Gagnon Group. Aeromagnetic maps of the western part of the map area (Que. Dept. Nat. Resources Aeromegnetic Series maps 4946 G - Lac Mouchalagane, and 4947 G - Lac Landriaux) show a few strong anomalies. Some of the anomalies are associated with outcrops of rocks of the Gagnon Group where I did not find any iron formation. Other anomalies are in areas of little or no outcrop. Such areas deserve further investigation. One area of iron formation outcrop associated with a very strong magnetic anomaly is along the Mouchalagane River just northwest of the area of my original map. This area may be shown in the northwest corner of the final geologic map.

Graphite is abundant in some outcrops of gneiss of the Gagnon Group, but it does not seem to be sufficiently abundant to be economically significant in this remote area.

Kish (1968) described sulfide mineralization in metagabbro (Unit 1) and granulite facies rocks (Unit 1b) in the Manicouagan Uplands. The mineralized outcrops are indicated by Ⓜ on the geologic map. The sulfide minerals are pyrite, pyrrhotite, and chalcopyrite. Details of the mineralization are given by Kish, along with other outcrops that lie beyond the area of my map.

Zeolites are abundant in parts of Mount de Babel, the central mountain of the Manicouagan Impact Structure. The origin and distribution of the zeolites are related to the formation of the structure; therefore they are discussed in the section on economic geology in Part II.

PART II: THE MANICOUAGAN COMPLEX AND THE MANICOUAGAN IMPACT STRUCTURE

Manicouagan is a member of that family of structures that has variously been called cryptovolcanic structures (Bucher, 1936), cryptoexplosion structures (Dietz, 1963; Bucher, 1963), astroblemes (Dietz, 1960), or impact structures. Currie (1972) refers to Manicouagan as a resurgent caldera.

Three modes of origin have been advocated for large circular structures that, like Manicouagan, have floors that are covered, or partly covered, by igneous rocks: 1)endogenetic igneous and tectonic activity; 2) hypervelocity impact of a cosmic body, with the igneous rocks interpreted as impact melt; 3) hypervelocity impact of a cosmic body followed by impact-triggered igneous activity. The rocks of the Manicouagan Complex contain evidence pertinent to determining which of these modes of origin is correct for the Manicouagan Impact Structure.

The Manicouagan Complex (Tables 1, 9) consists of a diverse suite of rocks that originated or underwent mineralogical, chemical, and/or structural changes during the development of the Manicouagan Impact Structure. I divide the rocks of the complex into four categories: shock metamorphosed rocks, breccias, igneous rocks, and contact metamorphosed country rocks. Currie (1972) used the term Manicouagan Complex for only the breccias and igneous rocks. Rocks that clearly belong to the Manicouagan Complex occur,

TABLE 9

STRATIGRAPHIC SECTIONS OF UNITS OF THE MANICOUAGAN COMPLEX[a]

Section at outer edge of annular plateau of igneous rock	Thickness (meters)	Section at inner edge of annular plateau of igneous rock	Thickness (meters)
Monzonite (Unit 16)	0-20	Monzonite	0-150
contact abruptly gradational		contact abruptly gradational	
Latite (Unit 15)	0-170	Latite	0-100
contact not observed		contact gradational(?)	
Basalt (Unit 14)	0-15	Red breccia (Unit 13c)	0-5
contact intrusive in some places and gradational in other places		(Pseudotachylite (pt), everywhere intrusive, is similar to, and may be a variety of, red breccia)	
Suevite (Unit 13b)	0-14		
contact intrusive in some places and gradational in other places		contact intrusive in some places and gradational in other places	
Autochthonous breccia (Unit 13a) and country rock of shock stage 0	unknown	Country rock of shock stages I and II	unknown

[a] Sections are composites of several localities, and thicknesses are estimates. A complete section is not exposed anywhere.

with minor exceptions, inside the structure outlined by Lakes Manicouagan and Mouchalagane.

French (1968a) defined shock metamorphism as ". . . all changes in rocks and minerals resulting from the passage of transient, high-pressure shock waves." Phenomena resulting from the passage of such shock waves range from the simple fracturing of rocks to melting or even volatilization. The classification of shock metamorphic phenomena I adopt (Table 10) is basically that of Stöffler (1971). Evidence presented in this report suggests that the Manicouagan Complex is made up of rocks affected or produced over the entire range of shock phenomena.

TABLE 10

CLASSIFICATION OF SHOCK METAMORPHOSED CRYSTALLINE ROCKS (AFTER STÖFFLER, 1971[a])

Shock Stages	Shock Effects	Peak Pressure (approx., in kb)	Residual Shock Temperature (approx., in °C)
0	Fractured quartz and feldspar, kink bands in biotite		
		100	100
I	Diaplectic quartz and feldspar, kink bands in hornblende		
		350	300
II	Diaplectic quartz and feldspar glasses		
		450	900
III	Fused feldspar (vesiculated glass)		
		550-600	1300-1500
IV	Heterogeneous rock glasses		
		800+	3000+
V	Silicate Vapor		

[a] Stöffler described petrographic criteria for quartz and feldspar, I have added criteria for biotite and hornblende.

An abundant and conflicting terminology for shock metamorphic features has developed in recent years (French and Short, 1968). I define here shock metamorphic features used in this section of the report. The definitions are based on those of French (French and Lowman, 1970; AGI Glossary, second edition):

Diaplectic is a term introduced by Englehardt (Englehardt and Stöffler, 1968) for any feature produced in the solid state by a shock wave.

Diaplectic minerals are those minerals deformed in the solid state by a shock wave.

Kink bands in a mineral grain are straight or curved zones in the mineral that have a different crystallographic orientation than the remainder of the grain.

Planar features are multiple, closely spaced parallel lamellae, no more than a few microns wide, that are characteristic of diaplectic minerals.

Diaplectic glasses are amorphous phases produced in the solid state by a shock wave. Such glasses show no evidence of melting or flow.

Maskelynite is diaplectic plagioclase glass.

SHOCK METAMORPHOSED COUNTRY ROCKS (Unit 12)

This section of the report describes *in situ* country rock shocked to pressures of as much as 450 kb, that is, shock stages 0, I, and II. Approximate boundaries of the different shock stages as shown in Figure 1 are determined by the outer limit of occurrence of characteristic features. Rocks of shock stages I and II are indicated on the geologic map by the numbers 12a and 12b, respectively, as well as by closely spaced horizontal lines. Where the nature of the original rock type was not obliterated by shock metamorphism, the number indicating the Precambrian rock unit is also shown. Rocks of shock stage 0 are not shown on the geologic map for reasons discussed in the following section.

Distances to the outer limit of occurrence of shock metamorphic features is given in kilometers from the approximate geometric center of the Manicouagan Impact Structure. The center is shown by Ⓧ on the geologic map. In order to facilitate location of specific outcrops I have adopted the convention of placing distance and direction from the center of the structure in parentheses, so that (12 km, 210) refers to an outcrop 12 km from the center along an azimuth of 210°

Rocks of Shock Stage 0

The approximate outer limit of rocks affected by shock stage 0, 45-50 km from the center of the structure, is marked in the west by a drainage divide that separates streams that flow toward the Manicouagan Impact Structure from those that flow toward the west (Fig. 1). The number of joints and shears increases radially inward from the divide to the shores of Lake Mouchalagane. Roy (1969) documented this distribution of joint development.

Kink bands in biotite 33 km from the center of the structure mark the outer limit of shock metamorphic effects in minerals. At this distance the kink bands are weakly developed, forming single subparallel sets that do not extend across entire grains. Nearer the center, but still in rocks of shock stage 0, kink bands are well developed and commonly in conjugate sets. Plate IV shows kink bands in a rock from shock stage II that are like the well-developed kink bands in shock stage 0.[1] Feldspars in rocks

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[1] I have reduced the total number of photographs necessary for this report by using photographs of features from higher stages of shock metamorphism to illustrate features of identical appearance that occur in rocks of lower stages of shock metamorphism.

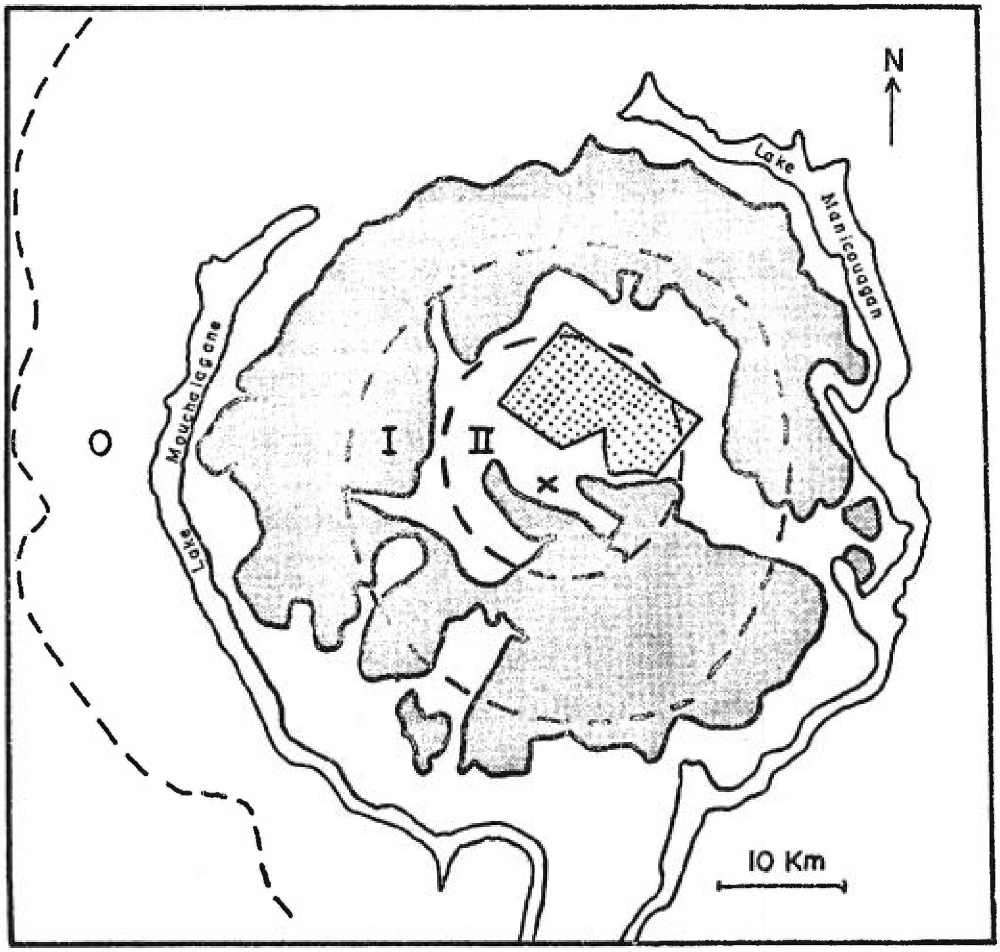
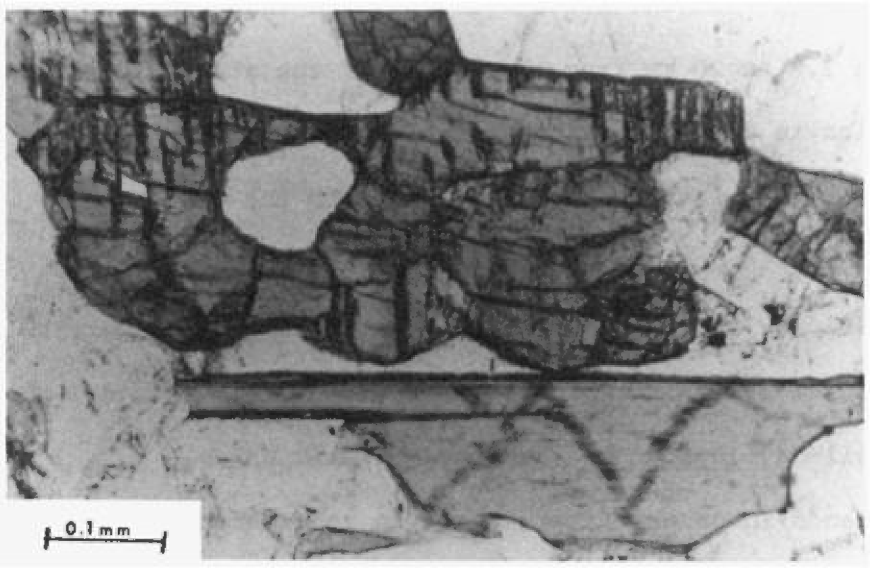


Figure 1. Sketch map of shock zones of the Manicouagan Impact Structure. Numerals = shock stages in the country rocks (see Table 10). Dashed lines = approximate boundaries of shock stages (outer limit of shock stage 0 is not well defined except in the west where it is roughly coincident with a drainage divide as discussed in text). Shaded area = annular plateau of igneous rocks of the Manicouagan Complex. X = approximate geometric center of structure. Dotted area = central massif, Mount de Babel.

of shock stage 0 are extensively fractured and show prominent cleavage; quartz is fractured and shows rectangular fractures that may be cleavage.

Rocks of shock stage 0 are not distinguished on the geologic map because the features described above cannot unequivocally be attributed to shock metamorphism. They are, however, considered to be shocked because of their clear relation in space to rocks of shock stages I and II.



Pl. IV

Conjugate sets of kink bands in biotite (lower dark grain) in gneiss of shock stage I (18 km, 031) cut the cleavage (horizontal) at high angles. Kink bands in hornblende (upper dark grains) bisect the acute angle between the bands in the biotite. Subhorizontal lines in the hornblende are cleavage (plane light).

Rocks of Shock Stage I (Unit 12a)

The outer limit of shock stage I (Fig. 1, Table 10) is marked by the appearance of single sets of planar features in felsic minerals and by kink bands in hornblende.

Planar features are well developed in quartz, but weakly developed in plagioclase and potassium feldspar. Plate V shows planar features in quartz in a rock from shock stage II that are like those in quartz of shock stage I. At 20 km from the center of the structure not all of the felsic grains in a thin section show planar features. Multiple sets of planar features are common in rocks closer to the center.

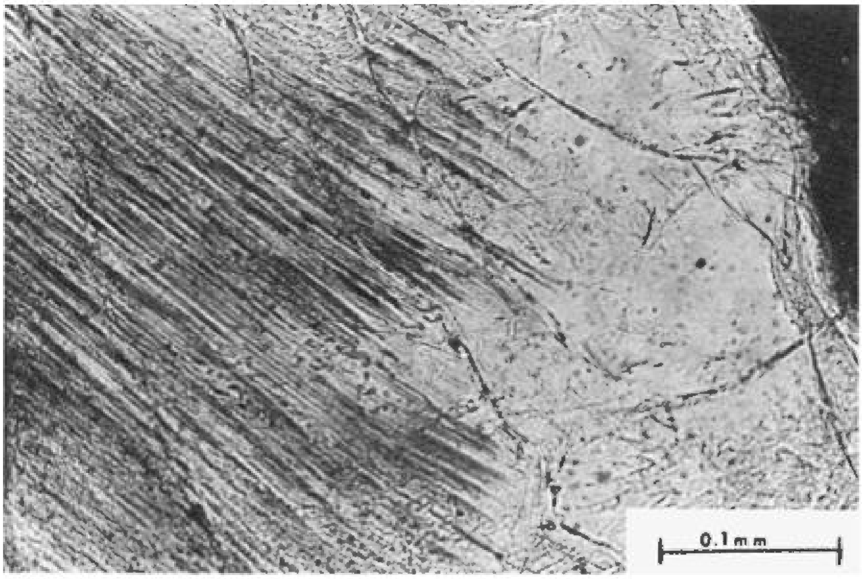
Kink bands in hornblende appear at 20 km from the center of the structure (Pl. IV). The bands contain material that appears to be planar features (Pl. VI). Biotite in rocks of shock stage I typically contains well-developed conjugate sets of kink bands.

Kink bands in garnet first appear in rocks about 12 km from the center of the structure. The kink bands are slightly birefringent and contain planar features. Garnets more than 12 km from the center have features that may be kink bands, but do not show planar features or birefringence.

Shatter cones are most abundant at about 9 km from the center of the structure, near the boundary between shock stages I and II.

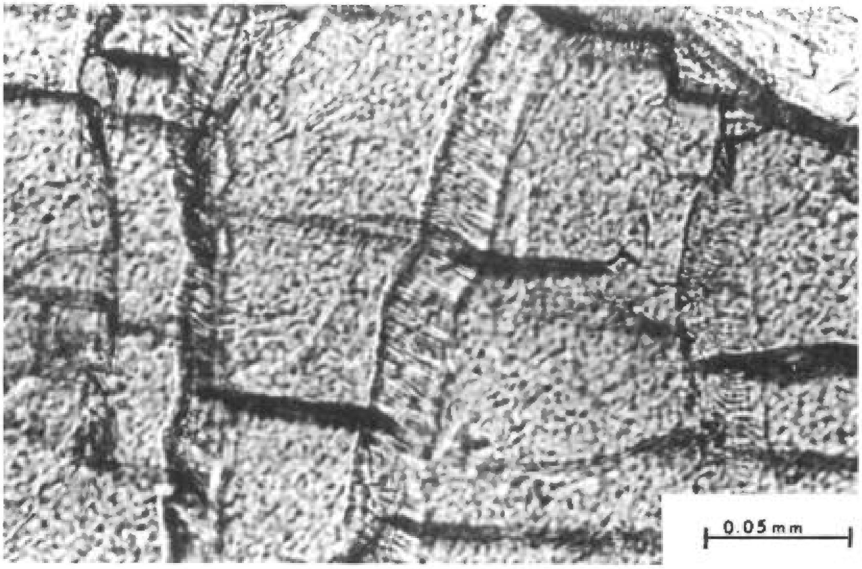
Rocks of Shock Stage II (Unit 12b)

The outer limit of shock stage II, about 12 km from the center of the structure, is marked by the appearance of diaplectic glass in felsic minerals (Fig. 1, Table 10). This limit, as well as the distribution of



Pl. V

Single set of planar features in quartz in gneiss of shock stage II (8.7 km, 250)(crossed ploarizers). Such planar features also appear in quartz of shock stage I.



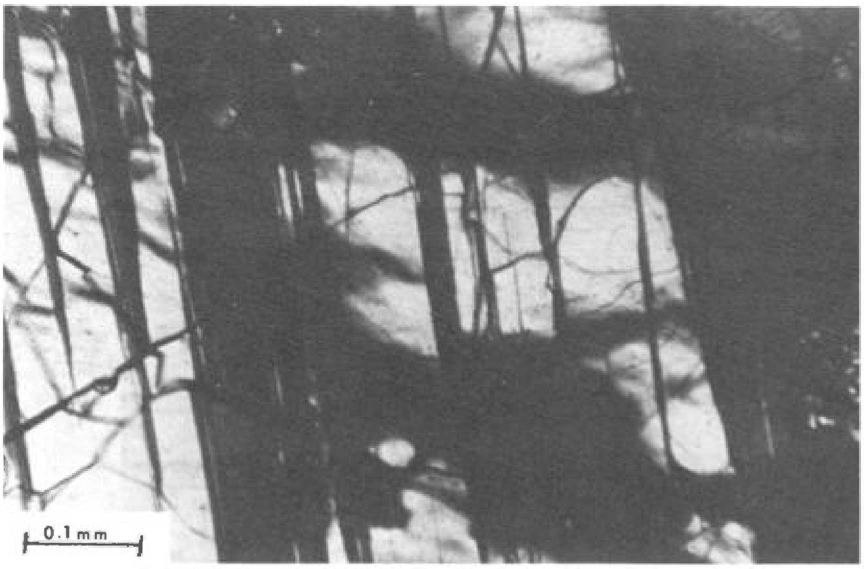
Pl. VI

Kink bands (nearly vertical)containing planar features in hornblende in gneiss of shock stage II (6.5 km, 225). Such kink bands are developed in rocks of shock stages I and II. Bending of the cleavage (horizontal) into parallelism with the planar features within the kink bands is particularly evident in the central band (plane light).

shock intensity within the area affected by shock stage II, is difficult to determine because of cover by glacial material, vegetation, and igneous rocks of the Manicouagan Complex. For example, there are no outcrops within 3 km of the geometric center of the structure. It is clear that the outer limit of shock stage II is not symmetrical about the center. It is also clear that there is not a radial inward increase of shock intensity within the area of shock stage II.

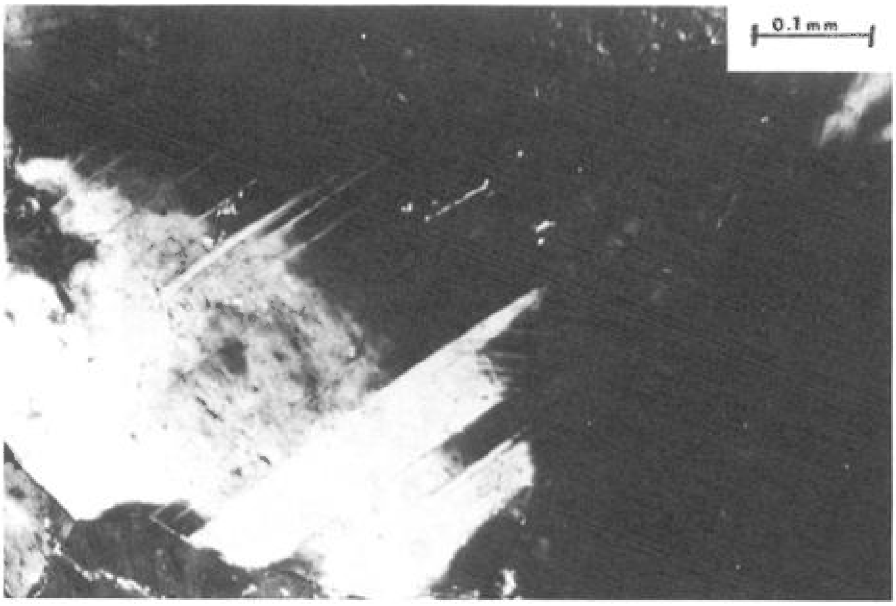
Diaplectic glass occurs sporadically in rocks of shock stage II. This glass differs from normal glass in that morphological features of the original grains are preserved, flow structures and vesicles are absent, and refractive index and density are higher than those of normal glass of the same composition (Englehardt and Stöffler, 1968). Maskelynite (diaplectic plagioclase glass) was discovered at Manicouagan by Michael Dence and described in detail by Bunch et al. (1967) and Dworak (1969a, 1969b). Maskelynite in some samples is developed without any apparent crystallographic control (Pl. VIIA). In other samples, crystallographic control is evident, as some twin lamellae show a greater development of maskelynite than other lamellae (Pl. VIIB). In some samples, patches of minerals completely converted to diaplectic glass are interspersed with patches that show only multiple sets of planar features.

A few striking outcrops of anorthosite on Mount de Babel, particularly on Maskelynite Peak, show nearly complete conversion of plagioclase to diaplectic glass. Microscopic comparison of these shocked rocks with unshocked rocks from the same unit outside the structure clearly shows that the conversion to glass has taken place without disrupting the original grain boundaries (Pl. VIII).



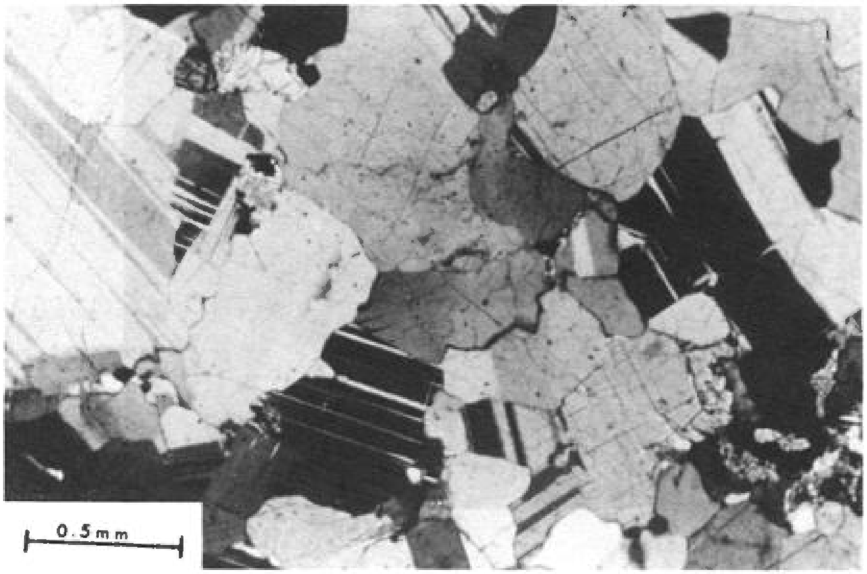
Pl. VIIA

Wavy black areas (sub-horizontal) of maskelynite in anorthosite from Maskelynite Peak (7.5 km, 050). Nearly vertical dark bands are twin lamellae (crossed polarizers).



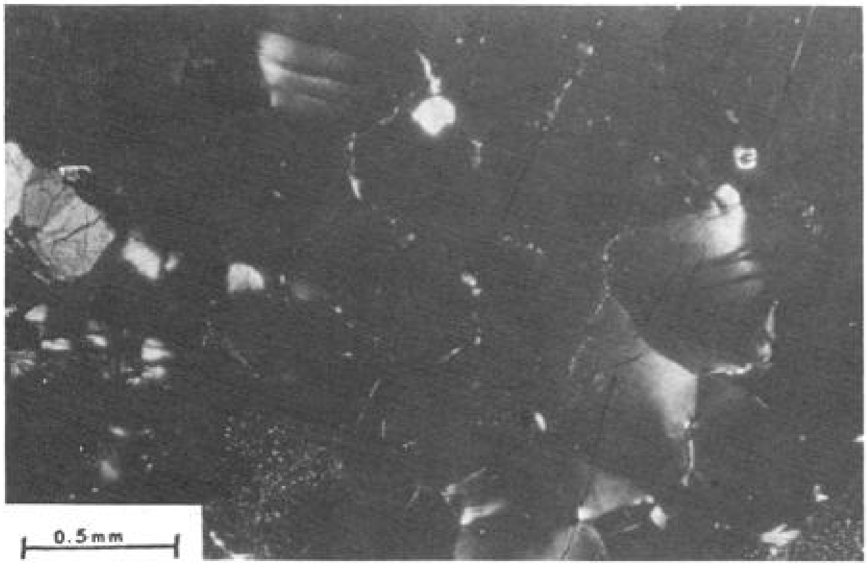
Pl. VIIB

Maskelynite developed in part of a plagioclase grain from Maskelynite Peak (7.5 km, 050). The upper right (black) part of the grain is all maskelynite. Crystallographic control is evident in the way the maskelynite grades into birefringent areas differentially in alternate twin lamellae (crossed polarizers).



Pl. VIIIA

Unshocked anorthosite from Mount Brilliant (41 km, 320) (crossed polarizers). Compare with Pl. VIIIB.



Pl. VIIIB

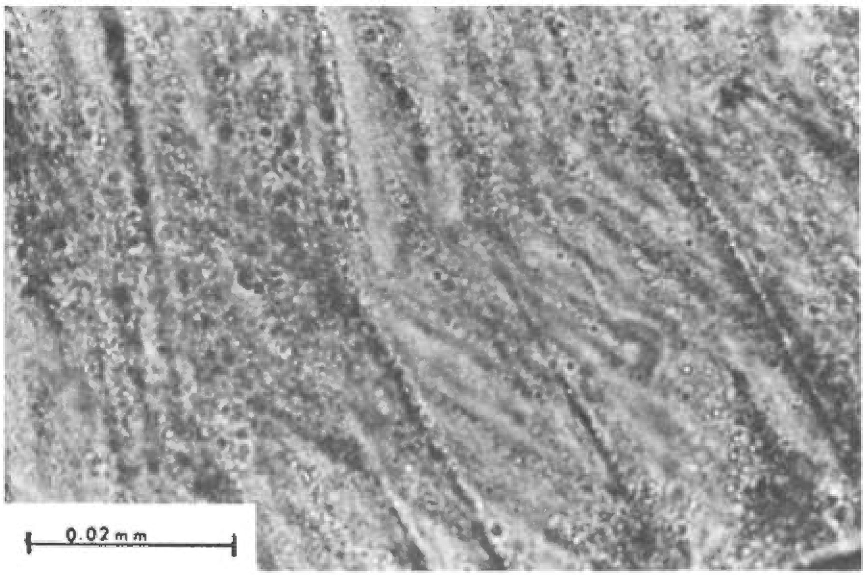
Extensive development of maskelynite in anorthosite from Maskelynite Peak (7.5 km, 050)(crossed polarizers). Plagioclase is almost totally converted to maskelynite, but grain boundaries (partly recrystallized) are preserved. Compare the texture with Pl. VIIIA. Bright grains are pyroxene or scapolite.

Birefringent feldspar in rocks containing diaplectic glass has anomalous optical properties, making determination of plagioclase composition uncertain. Optical angles of plagioclase from Mount de Babel are as low as 20°

Multiple sets of planar features are abundant in quartz (Pl. IX), plagioclase (Pl. X), and microcline in rocks of shock stage II. Planar features are not abundant in anorthosite containing maskelynite. Locally, quartz has a brown "toasted" appearance and rectangular or curved fractures in addition to planar features. Granitic rocks that contain diaplectic minerals and diaplectic glass have a blue-tinged opalescence in hand specimen.

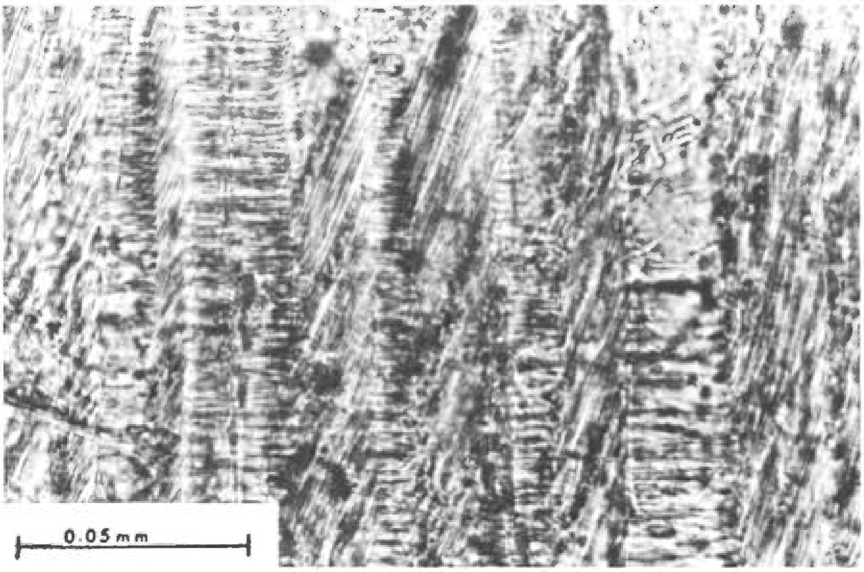
Single sets of planar features appear in scapolite at 6.5 km from the center of the structure. Multiple sets of planar features appear in scapolite in the anorthosite from Mount de Babel. Wolfe and Horz (1971) described in detail the planar features in scapolite from the Manicouagan Impact Structure. Weakly developed planar features occur in some apatite in rocks of shock stage II.

Conjugate sets of kink bands in mica are very well-developed, and there are commonly more sets in micas in shock stage II than in micas in shock stage I (Pl. XI). Subparallel sets of kink bands in adjacent grains are shown by garnet, hornblende, and pyroxene. Subparallel sets of fractures are formed in adjacent garnet and hornblende grains.



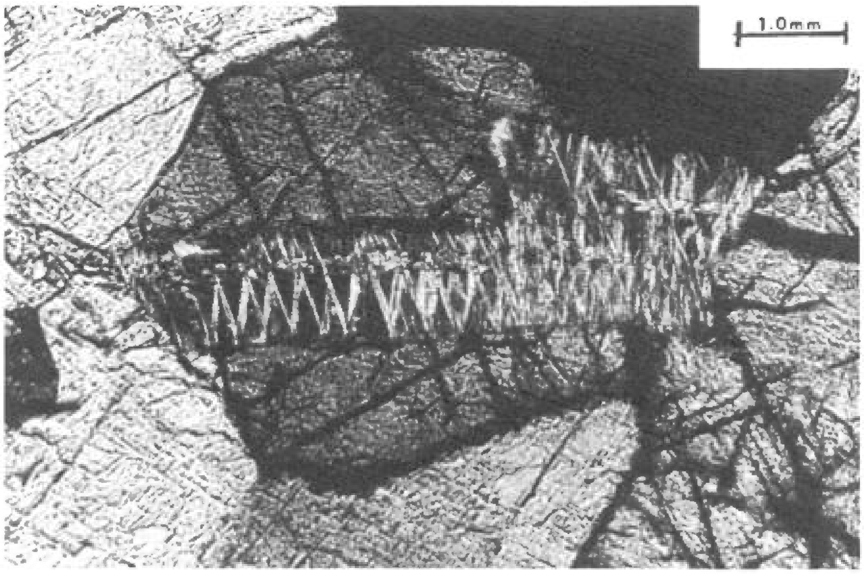
Pl. IX

Multiple sets of planar features in quartz in a gneiss inclusion in latite of the Manicouagan Complex (27 km, 290). The inclusion shows well-developed shatter cones. Such planar features are present in country rocks only within about 12 km of the center of the structure.



Pl. X

Multiple sets of planar features in a plagioclase grain in gneiss from shock stage II (8.7 km, 250) (plane light). Crystallographic control of the development of the planar features is shown by their different orientations in the different twin lamellae.



Pl. XI
Very well-developed conjugate sets of kink bands in two tabular grains of phlogopite (sub-horizontal) surrounded by pyroxene (8.7 km, 266)(crossed polarizers). The rock is peridotite (Unit 10).

Origin of the Shock Metamorphosed Country Rocks

Milton and De Carli (1963) reported complete conversion of plagioclase to maskelynite in a gabbro shocked to 250-350 hb, but later work indicated that partial transformation to maskelynite takes place at 180 kb (Ahrens, 1969). Quartz is transformed to diaplectic glass at a shock pressure of 360 kb (De Carli and Jamieson, 1959). Horz (1968) determined that planar features first appeared in quartz at about 100 kb, but were more abundant at higher shock pressures. P. B. Robertson (1972) produced planar features in microcline at experimental shock pressures greater than 150 kb. Kink bands in biotite have been produced at shock pressures as low as 9 kb (Horz and Ahrens, 1969). Data from rocks shocked in nuclear explosions suggest that 9 kb is a lower limit for the formation of kink bands (Cummings, 1968).

Chao (1968) used the decomposition of mafic minerals into oxides and glass as an indicator of postshock temperatures and consequently, peak shock pressure. I have deliberately omitted a description of the decomposition of mafic minerals from this section on shock metamorphism, because it is obvious from the field relations that such decomposition is in most places a result of contact metamorphism by igneous rocks of the Manicouagan Complex.

The shock effects in the country rocks of the Manicouagan Impact Structure clearly show an outward decrease in intensity from the boundary of shock stage II. This concentric distribution of shock effects ranging from 350 kb or more in rocks of shock stage II down to 9 kb or less in rocks of shock stage 0 is difficult to account for by any other process than hypervelocity impact of a cosmic body. The locally sporadic distribution of shock effects is to be expected in polycrystalline rocks of diverse composition. Additionally, the area including shock zone II has been disrupted by uplift and overturning of rocks following the formation of the central massif.

BRECCIAS (Units 13, pt)

A variety of breccias overlie, intrude, or grade into the shock metamorphosed country rocks of the Manicouagan Impact Structure (Table 9). Each variety has distinctive lithologic characteristics and modes of occurrence, but it is possible that all types except pseudotachylite are facies of a single breccia unit.

Autochthonous Breccia (Unit 13a)

Dence (1964) proposed the term autochthonous breccia for rocks from Canadian craters that are made up of rotated local fragments in a comminuted matrix. Autochthonous breccia in the Manicouagan Impact Structure occurs sporadically in rocks of shock stage 0. The breccia is in local patches, as small as 4 m, and rocks surrounding the breccia are unbrecciated. The best exposures are, or were, in valleys near the edge of the structure that are approximately radial or concentric with respect to the center of the structure. These valleys are now partly or completely flooded.

The fragments in the autochthonous breccia range from angular to sub-rounded and vary considerably in size within one outcrop (Pl. XII). The amount of matrix ranges from practically none to twenty percent or more. Some breccia that appears to grade to suevite (Unit 13b), contains as much as fifty percent matrix.

In thin section the matrix is composed of comminuted rock fragments, mineral grains, and parts of grains. The only microscopic features in minerals that might be attributed to shock metamorphism are weakly developed kink bands in biotite.

Suevite (Unit 13b)

Suevite in the Manicouagan Impact Structure is an allochthonous polymict breccia containing shocked fragments, unshocked fragments, and glassy blebs in a clastic, cryptocrystalline, or glassy matrix. The term suevite comes from the Reis Crater in Germany where it is applied

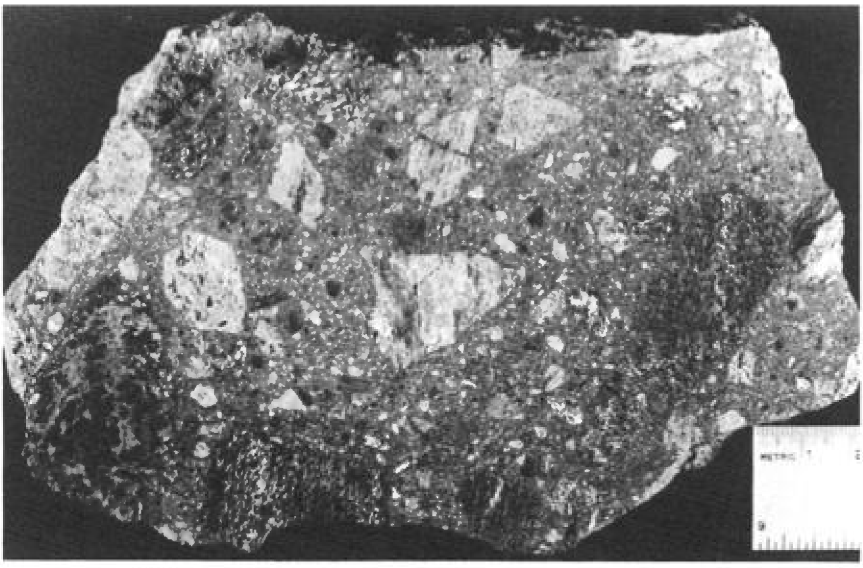
Pl. XII - Autochtonous breccia in grey gneiss (29 km, 290).

to impact breccias that contain a mixture of unshocked, shocked, and fused material (Englehardt, 1971).

Suevite is the lowermost allochthonous unit of the Manicouagan Complex (Table 9). It crops out at or near the base of the outer edge of the annular plateau of igneous rocks in the form of sheets as much as 14 m thick, dikes as much as half a meter thick (Pl. XIII), and small irregular intrusive bodies. The sheets of suevite overlie country rocks of shock stage 0, and the dikes intrude those rocks. Some dikes branch and anastomose, and in places intrude and mix intimately with autochthonous breccia.

Suevite is commonly green, but some is red or black. It contains angular and sub-rounded inclusions of a wide variety of rock types (Pl. XIV). Some inclusions show evidence of shock but most do not. Granitic inclusions in places have rims of brown glass that are as thick as 3 cm. Flattened blebs and streaks of brown glass as much as 10 cm long do not have the aerodynamic form characteristic of the fladen in the suevite of the Reis.

Pl. XIII
Vertical dike of suevite (29 km, 290). Curved joints to the left of the dike are in gneiss, and do not bound another dike.



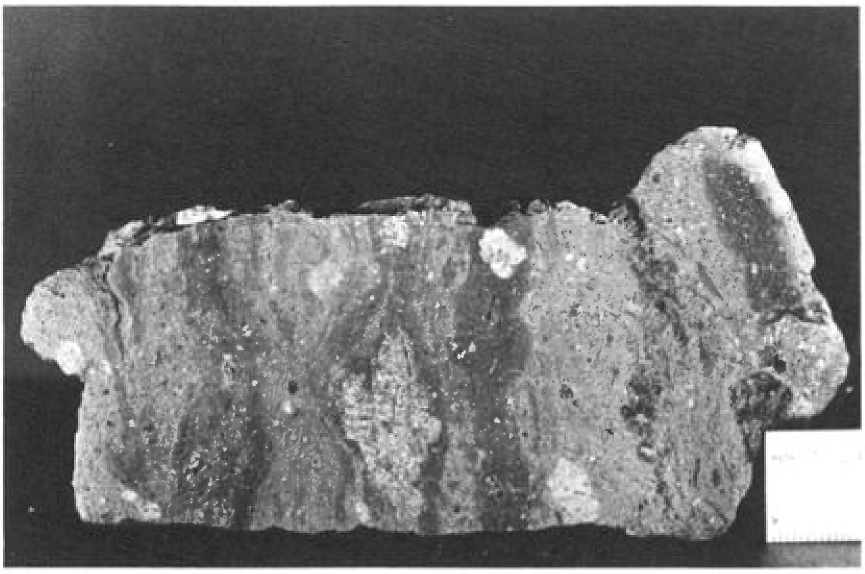
Pl. XIV
Suevite containing granitic and other rock fragments (19.5 km, 100). The granitic fragments show evidence of partial melting.

Thick sheets have well-developed flow structure (Pl. XVA). Some suevite dikes are vesicular.

In thin section, suevite consists of rock and mineral fragments set in a matrix that can be finely clastic, cryptocrystalline, or devitrified glass charged with flecks of opaque material. Less than one-third of the fragments show evidence of shock in the form of planar features, and, rarely, diaplectic glass.

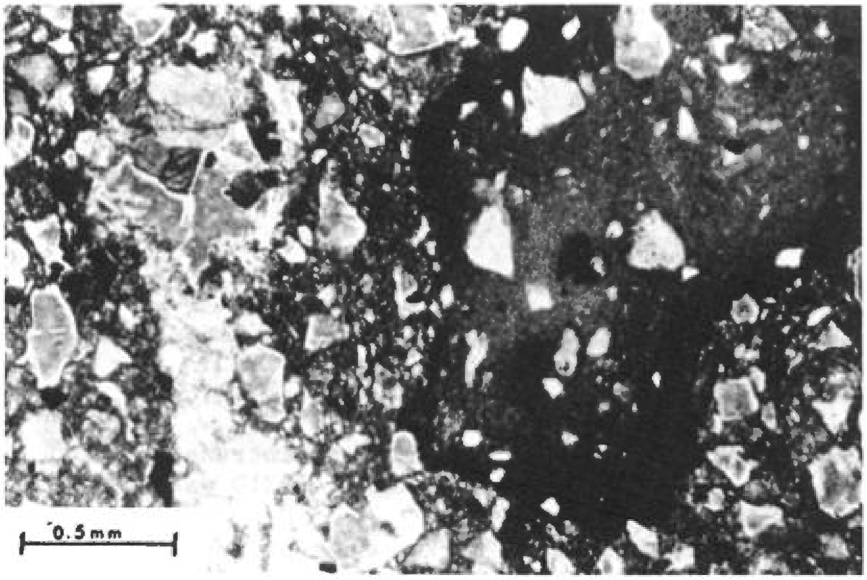
The bands in the suevite with flow structure (Pl. XVA) are distinctly different from each other in thin section. The black bands have a matrix of glass or devitrified glass and contain only glass blebs and a few fragments, all of which show evidence of shock stages I and II. The green bands have a clastic or cryptocrystalline matrix, and contain many fragments that show no evidence of shock or are of shock stage 0. The green bands also contain streaks and blebs of glasses of diverse color and composition (Pl. XVB). Fragments in the glass blebs commonly show evidence of shock stage II. Mafic minerals in the glass blebs are decomposed to a fine mixture of opaque minerals and glass. In some places the shapes of the mafic minerals are preserved; in other places the former mafic minerals are stretched and have diffused borders with the surrounding glass.

The chemical composition of suevite differs even within the same locality. Table 11 shows the different chemical compositions of the matrix of two suevite samples that were collected within 200 m of each other.



Pl. XVA

Suevite with flow structure shown by green and black bands (28 km, 290). Chemical composition of the matrix is given in Table 11 (sample 16X1D).



Pl. XVB

Streaks of different glasses in suevite sample shown in Plate XVA (plane light). The streak on the right is brown with a black rim. The streak on the left is grey and black glass, and cryptocrystalline material.

TABLE 11

CHEMICAL COMPOSITIONS OF SUEVITE MATRIX[a] AND HOST ROCKS

	16X1D Suevite	29D2A Suevite	29D2B Gneiss host to 29D2A
SiO_2	56.91	48.72	54.62
TiO_2	0.65	0.91	0.67
Al_2O_3	14.90	17.27	19.79
Fe_2O_3	3.72	4.11	2.18
FeO	2.74	5.34	3.59
MgO	5.72	6.04	2.13
CaO	5.44	7.36	5.40
Na_2O	3.64	3.88	5.52
K_2O	2.92	1.92	1.98
H_2O (+)	1.44	2.38	1.98
H_2O (-)	1.24	0.29	0.25

16X1D - Suevite with flow structure (28 km, 290)

29D2A & 29D2B - Suevite (29D2A) that intrudes gneiss in same valley as that from which sample 16X1D was collected.

[a] Samples of suevite were picked free of megascopic inclusions so that the analyses would not be affected by large inclusions.

Agglutinated Sand Balls

One of the most peculiar rocks in the area is associated with suevite in a radial valley near the edge of the structure (28 km, 290). Agglutinated sand balls (Pl. XVI) line the walls of several 15 cm thick veins in gneiss. The balls are made up of well-rounded quartz sand cemented by a matrix of clay and very fine comminuted fragments of quartz.

The veins all crop out within 100 m of outcrops of Ordovician rocks. The basal unit of the Ordovician rocks is a fine-grained sandstone that is the only likely source for the rounded grains in the sand balls.

The basal sandstone is locally intruded by suevite. Suevite borders one of the veins of agglutinated sand balls for a short distance. It appears that the sandstone was in some way mobilized by the suevite and injected into fractures in the gneiss where the agglutinated sand balls then formed.

Pl. XVI
Agglutinated sand balls from vein in gneiss.

Red Breccia (Unit 13c)

Red breccia is a nearly monomict breccia that contains shocked fragments and glass blebs in a glassy or cryptocrystalline matrix. It crops out near the base of the inner edge of the annular plateau of igneous rocks, and in gneisses of shock stage II inside the edge of the plateau. The red breccia is in the same stratigraphic position as the suevite (Table 9), and the two rock types may be facies of a single unit.

Outcrops of red breccia are small, no more than a few meters across, and of two types. One type is in stream valleys where the red breccia is stratigraphically between the latite (Unit 15) and the shocked country rocks. The other type is on cliff faces where irregular patches of red breccia intrude and/or grade into the surrounding gneisses.

The matrix of the red breccia ranges from bright red to dark red, and is commonly vesicular. The fragments are mostly of a single rock type in any single outcrop. Where country rock is exposed nearby, the fragments are of that type of rock. Most fragments are rimmed with a dark red glass that grades into the lighter red glass of the matrix. The composition of the matrix is different in different outcrops, and in one outcrop is similar to the composition of the country rock (Table 12).

In thin section, most fragments show either the effect of high shock pressure or high temperature, or both. Quartz grains typically have multiple sets of planar features, or they have the toasted brown appearance and sets of curved or rectangular cracks that is common in some rocks of shock stage II. Mafic minerals are partly or completely broken down to fine mixtures of opaque material and glass. The matrix is shot through with blebs of heterogeneous black, red, brown, and white glasses, much like the suevite.

TABLE 12

CHEMICAL COMPOSITIONS OF RED BRECCIA MATRIX[a] AND ASSOCIATED ROCKS

	7H5A Red breccia matrix	2K1LA Red breccia matrix	21D3G Gneiss, host to 2K1LA	21D3A Gneiss, near 21D3G	21D3C Vesicular Gneiss, near 21D3G
SiO_2	56.78	68.02	72.16	47.59	59.72
TiO_2	0.76	0.30	0.07	1.19	0.31
Al_2O_3	14.66	14.58	13.01	19.18	17.96
Fe_2O_3	6.82	3.93	2.88	5.99	4.89
FeO	0.68	0.16	0.12	4.36	0.25
MgO	4.95	0.98	0.53	4.59	0.67
CaO	5.19	2.08	0.98	8.97	2.01
Na_2O	4.16	4.56	3.40	3.40	4.44
K_2O	2.96	5.24	5.32	0.79	6.44
H_2O (+)	0.88	0.22	0.42	1.86	0.63
H_2O (-)	1.44	0.14	0.12	0.29	0.22

7H5A - Red breccia (11.5 km. 285).

2K1LA - Red breccia (7 km. 262).

21D3G - Shocked granitic gneiss that is intruded by and grades into 2K1LA.

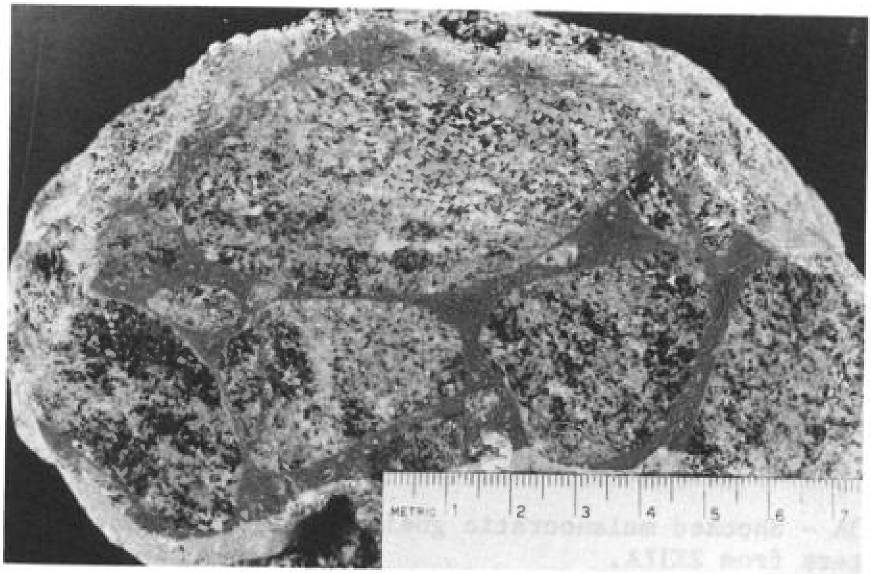
21D3A - Shocked melanocratic gneiss that is in contact with 21D3G a few meters from 2K1LA.

21D3C - Vesicular gneiss, now mostly devitrified glass. Crops out about 20 m from 21D3G.

[a] Samples of red breccia were picked free of megascopic inclusions so that the analyses would not be affected by large inclusions.

Pseudotachylite (pt)

Pseudotachylite is an allochthonous breccia made up of shocked and apparently unshocked fragments in a glassy or cryptocrystalline matrix. The matrix is pink, red, or black. Pseudotachylite occurs in dikes and rootless pods in rocks of shock stages I and II. It is most abundant in the anorthosite of the central mountains, particularly in the southern part of that mountain. Dikes are as much as 20 cm thick, and some show flow structure. Dikelets either follow preexisting fractures, or form anastomosing networks (Pl. XVII). Pseudotachylite forms selvages along some garnet-pyroxene bands in the anorthosite and in one outcrop the pseudotachylite appears to have formed within a garnet pyroxene-band.



Pl. XVII

Anastomosing veins of pseudotachylite in melanocratic gneiss (6.5 km, 225).

In thin section, some pseudotachylite veins contain rock and mineral fragments that either show planar features or diaplectic glass, or have been melted and now consist of devitrified glass. Other pseudotachylite veins contain fragments of felsic minerals that appear unshocked, but inclusions of mafic minerals in these veins have kink bands. Mafic minerals are partly or completely decomposed to very fine aggregates of opaque material and glass. The thermal decomposition of mafic minerals indicates that the pseudotachylite of the Manicouagan Complex was molten when intruded.

Table 13 compares the chemical compositions of two pseudotachylite veins and their different country rocks. The composition of each pseudotachylite and its host rock is similar but not identical. Shand (1916) described the same relationship from the type area in the Vredefort Ring.

Contact Relations

Suevite grades into both autochthonous breccia and dikes of basalt in several outcrops in a radial valley near the edge of the structure (27 km, 290). At one locality a 1 m thick composite dike intrudes autochthonous breccia. The autochthonous breccia country rock grades into suevite (Pl. XVIII), which in turn grades into the basalt core of the dike. In some outcrops suevite grades into a spherulitic rock (Unit 14a) that in turn grades into basalt (Unit 14). In other outcrops layers of basalt overlie suevite. Veins of black suevite cut green suevite with sharp contacts and both suevites intrude autochthonous breccia.

Isolated outcrops of red breccia in stream valleys appear to form a layer between shocked country rocks and latite (Unit 15). Other outcrops

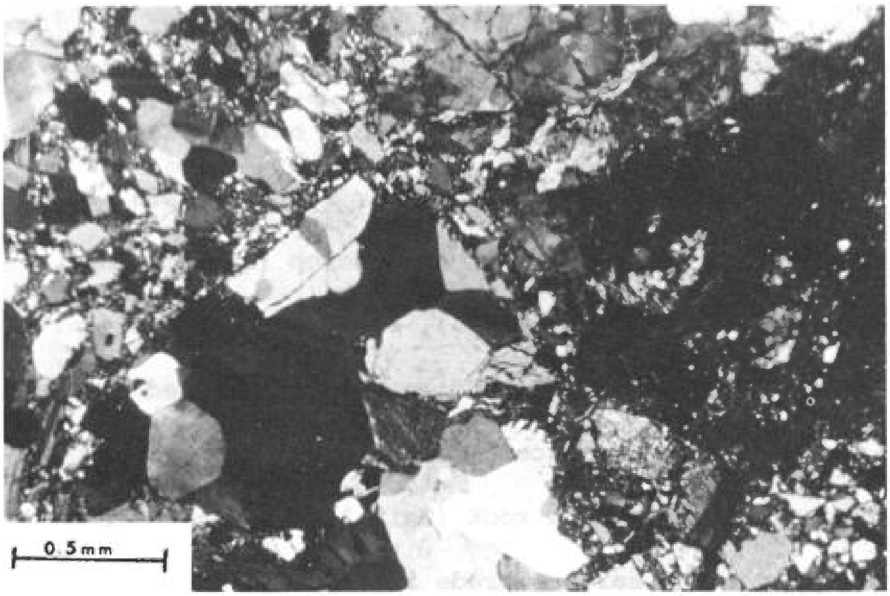
TABLE 13

CHEMICAL COMPOSITIONS OF PSEUDOTACHYLITE AND HOST ROCKS

	32A2C	32A2B	20X2C1	20X2C2
	Pseudotachylite	Anorthosite, host to 32A2C	Pseudotachylite	Melanocratic gneiss, host to 20X2C1
SiO_2	49.97	52.29	50.71	47.37
TiO_2	0.21	0.20	0.71	0.34
Al_2O_3	25.55	26.53	17.61	20.16
Fe_2O_3	2.01	1.50	4.25	1.75
FeO	0.10	0.23	2.34	4.06
MgO	1.48	1.86	7.00	8.75
CaO	9.06	10.50	8.50	12.45
Na_2O	6.12	5.24	3.52	2.92
K_2O	0.76	0.57	2.44	0.62
H_2O (+)	4.25	1.17	1.82	1.29
H_2O (-)	0.50	0.25	0.50	0.13

32A2C & 32A2B - Pseudotachylite (32A2C) vein that intrudes shocked anorthosite (32A2B) on Mount de Babel (4.5 km, 010).

20X2C1 & 20X2C2 - Pseudotachylite vein (20X2C1) that intrudes shocked melanocratic gneiss (6.5 km, 225). Vein and host rock are shown in plate XIXB.



Pl. XVIII - Photomicrograph of the outer part of a composite dike of basalt and suevite in autochthonous breccia (27 km, 290). Autochthonous breccia on the left grades into glassy suevite on the right, which in turn grades into basalt (crossed polarizers).

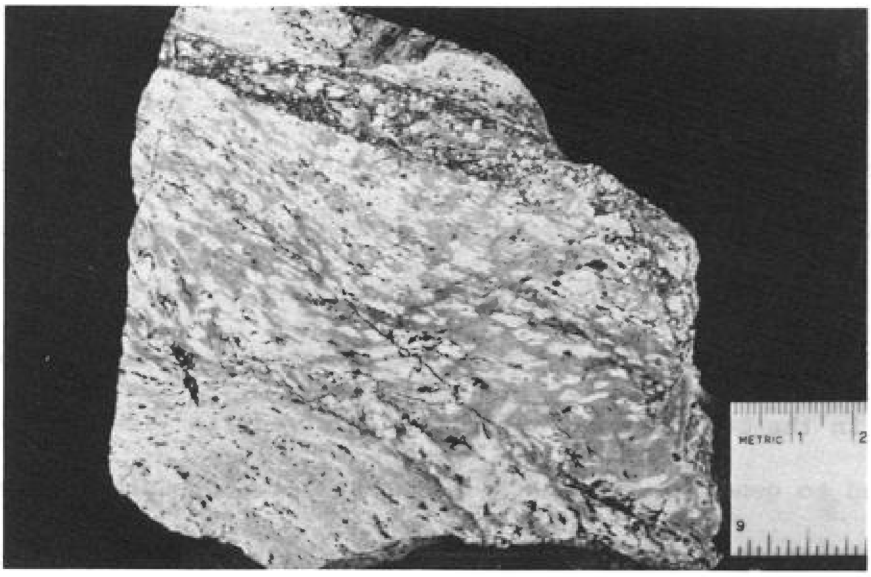
on cliff faces clearly show a local gradation from red breccia into shocked country rocks, and from shocked country rocks through red breccia into spherulitic igneous rocks (Unit 14a), and possibly into latite.

A small cliff (7 km, 272) shows the transition from red breccia to shocked country rock. Shocked granitic gneiss grades into a zone of gneiss that shows flow structure and includes autochthonous fragments of gneiss (Pl. XIXA), The flow stage is apparently a transitional phase into red breccia. The area of presumed transition is covered by talus, but pods of red breccia that contain fragments of the granitic gneiss (Pl. XIXB) are exposed near the top of the talus. The chemical composition of the matrix of red breccia (sample 2K1LA, Table 12) is similar to, but different from, that of the orange gneiss (sample 21D3G). The lower silica and higher iron oxide, magnesia, soda, and lime content of the matrix might be explained by inclusion in the matrix material of a higher proportion of mafic bands than in the analyzed sample of the gneiss. The composition of the matrix of the red breccia in this outcrop is clearly different from other country rocks near by (Table 12, samples 21D3A, 21D3C), as well as from red breccia matrix in another outcrop (sample 7H5A).

Another cliff (17.5 km, 215), made up of latite (Unit 15), has at its base an inclusion, 10 m in diameter, of shocked gneiss with a one-meter-thick rim of red breccia on one side. The rim of red breccia grades into a spherulitic igneous rock (Unit 14a). Elsewhere on the cliff the spherulitic rock appears to grade into latite (Unit 15), although the contact is covered.

Pseudotachylite intrudes shocked country rock with sharp contacts everywhere. In one outcrop (7 km, 262), a dikelet of pseudotachylite intrudes the orange gneiss that shows flow structure (Pl. XIXA). Apophyses of the gneiss can be seen to intrude and mix with the rock of the dikelet in the upper right center of the sample shown in Pl. XIXA. This intrusion of the dikelet suggests that the gneiss was developing flow structure at the time the dikelet was being intruded. This indicates that pseudotachylite and red breccia formed penecontemporaneously.

In summary, the lower allochthonous units of the Manicouagan Complex, suevite and red breccia, overlie, intrude, and grade into country rock. Igneous rocks of the Manicouagan Complex overlie, intrude, and grade into the suevite and red breccia. Suevite crops out near the edge of the Manicouagan Impact Structure and red breccia in the interior of the structure. The two rocks occupy the same stratigraphic position. I interpret these breccias as being rock facies of a structure-wide chronostratigraphic unit.



Pl. XIXA

Flow structure in granitic gneiss, apparently a transition to the red breccia shown in Pl. XIXB. A fragment of unmelted gneiss is in the lower left. A dark vein of pseudotachylite cuts the upper part of the specimen. The gneiss appears to have flowed into the lower part of the vein on the right side of the sample.

Pl. XIXB

Red breccia with fragments of orange gneiss from the same outcrop shown in Pl. XIXA. Chemical compositions of the orange gneiss and the matrix of the red breccia are given in Table 12 (samples 21D3G, 2K1LA).

Origin of the Breccias

The breccias of the Manicouagan Complex may be of volcanic or impact origin. A volcanic origin would involve the intrusion and eruption of a gas-charged magma that was the precursor of the more quiet eruptions that formed the igneous rocks of the Manicouagan Complex. Currie (1972) suggested that such a gas-charged magma was a possible cause of the shock metamorphism in the bedrock, but this seems unlikely in view of the pressures required to generate the shock features. It is possible, however, that the intrusion and eruption of the breccias was a result of endogenetic causes triggered by, or unrelated to, an impact event.

Shock metamorphic features are unknown in breccias from clearly volcanic areas. Such fragments might be included in volcanic material that moved across the floor of a recently formed impact crater. It is difficult, however, to explain the discrete blebs and streaks of heterogeneous glasses in the suevite and red breccias by such a mechanism. Formation of these breccias requires extremely rapid production, dispersal, mixing, and quenching of glasses of diverse composition. I am unaware of volcanic processes that could cause them.

The impact model that I propose can explain the observed phenomena as results of a single event. In experimental and theoretical work on small artificial craters, Gault et al. (1968) describe the movement of particles during the formation of a crater. Mobilized material that initially travels radially away from the crater center is deflected upward and outward as the result of the interference of rarefaction waves with the compressional shock wave. Much of the material excavated is removed from the crater in ballistic trajectories by a process called jetting. At this stage there is flow along the crater wall. Extrapolation from simple crater models to large and complex natural craters must of necessity be tenuous, but I shall attempt to use such a model to explain the Manicouagan breccias.

In the impact model, suevite would form from a complex turbulent cloud of volatilized, fused, and fragmented country rock that swept across the floor of the still forming crater. The turbulent cloud would move outward behind the shock wave as the crater was being excavated. New cloud material would be generated as the shock wave moved outward. The new material would show progressively lower shock effects as the shock wave decayed. That part of the cloud formed near the center of the structure would contain mostly fused material nad highly shocked fragments, whereas that part of the cloud formed nearer the edge of the crater would contain mostly fragmented material. Autochthonous breccia would form locally where the shock wave had decayed to pressures too low to disperse the fragmented material. Some suevite would be injected outward and downward into newly formed openings in the country rocks, and some suevite would intrude and mix with the autochthonous breccia. Parts of the cloud would settle to form the sheets of suevite. The black suevite with abundant glass and the green suevite with the clastic matrix would be formed from different parts of the cloud. In some places they might intrude separately, whereas in other places they might mix and form sheets of suevite.

Suevite, apparently moving along thrust fault planes, heated, disaggregated, and mobilized the basal sandstone of the Ordovician rocks. This mobilized sand was then injected into openings where it formed the agglutinated sand balls.

The red breccia was formed either on the borders of large inclusions near the base of the latite, or in and on shocked country rock near dikes of latite or near the base of the latite. The shocked country rock containing or underlying the red breccia shows extensive evidence of thermal alteration in such places (discussed in the section on contact metamorphism), but shows no such evidence in other places. The red breccia may be country rock that was fused at the time of impact but not dispersed. It may also be, in some places, shocked country rock that was melted by heat from the igneous rocks of the Manicouagan Complex.

Currie (1972) analyzed five pairs of pseudotachylite veins and their host rocks. The composition of two of the pseudotachylite veins were very similar to the host rocks, but the other three veins were lower in silica and higher in magnesia and lime. Currie suggested that a mixture of 40 percent to 70 percent of an alkali olivine basalt fluid with the different host rocks would make them equivalent in composition to the pseudotachylite. (There is no olivine in any of the igneous rocks of the Manicouagan Complex.) He concludes that the pseudotachylite was formed by basaltic fluids forced through rocks that had just been shattered by an explosion of igneous origin.

In the impact model that I propose, pseudotachylite would be formed as a product of the local fusion and mobilization of shocked country rock at the time of impact. I described earlier the tendency for pseudotachylite to occur along or in mafic-rich bands in anorthosite. The differences in chemical composition that Currie found between pseudotachylite and host rock might be accounted for by the incorporation into the pseudotachylite of a greater proportion of mafic minerals than is present in the average host rock. I cannot explain the sporadic occurrence of pseudotachylite.

IGNEOUS ROCKS (Units 14, 15, 16)

The igneous rocks of the Manicouagan Complex have the textural and mineralogical characteristics of normal igneous rocks. They are in places intrusive and in other places probably extrusive. Most of them are contained in the vast sheet of igneous rocks that underlies the annular plateau of the structure. The maximum thickness of the igneous rocks is about 335 m. None of the igneous rocks crops out outside of the structure as delineated by Lakes Manicouagan and Mouchalagane. The latite and monzonite give Lower Triassic paleomagnetic poles (Larochelle and Currie, 1967; W. A. Robertson, 1967), and different workers have obtained K/Ar whole rocks ages on these rocks that range from 190 m.y. to 225 m.y. (Wanless et al., 1966; Currie, 1972; Wolfe, 1971). The latite and monzonite are clearly of Triassic age.

Currie (1972) interprets these igneous rocks as normal igneous rocks formed inside a caldera that shows some peculiar shock effects. Dence (1971) and Murtaugh (1969b) suggest that the igneous rocks may have crystallized from impact-melted country rocks. The evidence pertinent to determining the origin of the igneous rocks includes the following:

1) The nature and composition of the rocks themselves.
2) The nature and location of the inclusions in the igneous rocks.
3) The contact relations among the igneous rocks, and also among the igneous rocks (Units 14, 15, 16), the breccias (Unit 13, and the shocked country rocks (Unit 12).
4) The peculiar intense contact metamorphism associated with some of the igneous rocks.
5) The relationship of the igneous rocks to the structural evolution

of the Manicouagan Impact Structure.

6) The interpretation of the time of shock metamorphism and the time of crystallization of the igneous rocks, based upon isotopic age dates.

In this section of the report I describe and interpret the evidence indicated in points 1-3. The other points are discussed in later sections. I defer discussion of the origin of the igneous rocks to the final section of the report, when all the pertinent evidence has been presented.

Basalt (Unit 14)

Basalt crops out sporadically near the base of the outer edge of the annular plateau of igneous rocks. Small dikes of basalt in country rocks of shock stage 0 are easily confused with black suevite. The two rocks can be differentiated by the presence of plagioclase microlites and the absence of heterogeneous glasses in the basalt. The basalt is exposed mostly in isolated outcrops that appear to form a discontinuous layer at the base of the latite (Unit 15). No features were observed that are exclusively characteristic of basaltic lava flows (Murtaugh, 1962), as opposed to sills. At one locality the basalt shows a chilled margin against an undulatory surface that was probably the primary floor of the structure (the secondary floor would have been the top of the allochthon of the Manicouagan Complex). Vesicles in the chilled margin show no evidence of deformation by flow. The basalt in this outcrop was analyzed by Currie (1972) and his analysis is reproduced in Table 14.

The basalt is a black aphanitic rock that is locally vesicular and

TABLE 14

CHEMICAL COMPOSITIONS OF BASALT AND TACHYLITE

	820	11K1F
	Basalt[a]	Tachylite[b]
SiO_2	49.50	50.80
TiO_2	0.97	0.66
Al_2O_3	18.20	14.17
Fe_2O_3	5.00	2.70
FeO	3.40	4.36
MgO	4.90	8.11
CaO	7.10	7.82
Na_2O	4.00	3.68
K_2O	1.39	1.97
H_2O (+)	4.30	4.38
H_2O (-)		1.08

[a] Analysis from Currie (1972). Sample was collected from outcrop shown in Plate XXVA (27 km, 290).

[b] Tachylite vein in peridotite (25 km, 200).

glassy. In thin section the basalt has a felted texture. Microlites of plagioclase and small equant grains or laths of orthopyroxene and clinopyroxene are set in a cryptocrystalline matrix.

Tachylite (basaltic glass) forms the upper part of a thin basalt layer near the edge of the structure (29 km, 290). The tachylite is nearly colorless in thin section, although black in hand specimen. It contains spherical vesicles and veinlets of cryptocrystalline material.

Two different types of ellipsoidal structures both show the same strong preferred orientation. One type is composed of either light brown glass or devitrified glass and a fine mosaic of recrystallized material. The other type is nearly colorless and could not be differentiated from the surrounding tachylite except for a thin rim of birefringent material around the lenticle.

Some of the abundant inclusions in the basalt show evidence of shock stages I and II, although the country rock under the basalt is mostly of shock stage 0 and rarely of shock stage I. One outcrop of basalt (29 km, 290) contains rounded inclusions of black peridotite that are as much as 2 m in diameter. The inclusions have a similar mineralogy and the same intense development of kink bands in phlogopite as peridotite in shock stage II (8.7 km, 266; Pl. XI).

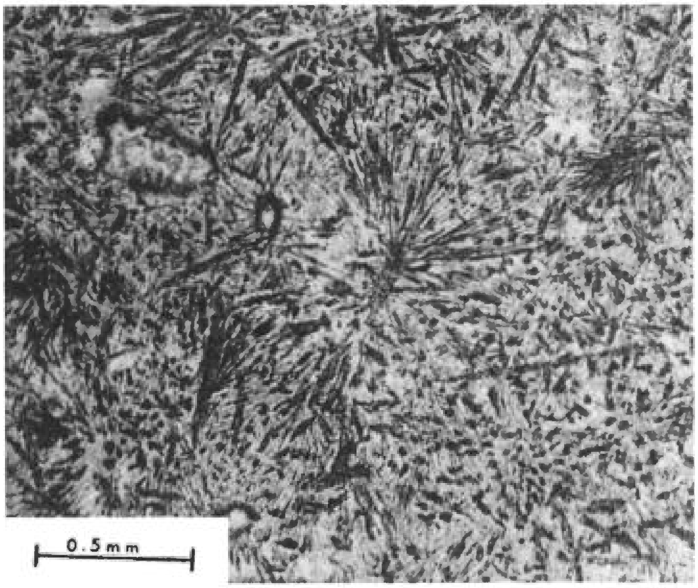
Veins of tachylite as much as 1.5 cm wide cut peridotite (Unit 10) exposed on one cliff (25 km, 200). The chemical composition of this tachylite is given in Table 14. The tachylite is dark brown in thin section and shows perlitic fractures. The glass contains droplets and lenticles of black glass that have rims of light brown glass. The light brown rims merge with the droplets and the brown glass and appear to be a reaction rim. Some of the droplets have a core composed of clear devitrified glass, small recrystallized grains, and what appears to be diaplectic glass. The droplets and lenticles show a strong preferred elongation normal to the vein walls. This outcrop may be a very large inclusion or megablock in the basalt. Only tachylite cuts the peridotite, but isolated outcrops of basalt surround the peridotite. In thin section, the peridotite is fragmented by closely spaced sub-parallel fractures of the type characteristic of shock stage II. Some grains of olivine show planar features.

Spherulitic Rocks (Unit 14a)

Spherulitic rocks are black, grey, or red rocks with distinctive spherulitic structures up to 1 cm in diameter. With one possible exception, discussed later, they form dikes or parts of dikes of basalt or black suevite near the base of the outer edge of the annular plateau. I place the spherulitic rocks here in the stratigraphic sequence because of their association with basalt, but it is possible that they may in places be phases of other units.

In thin section the spherulites are made up of plagioclase, orthopyroxene or clinopyroxene, and opaque material (Pl. XX). The matrix is composed of anhedral grains of the same minerals and cryptocrystalline material.

Inclusions in the spherulitic rocks are rarely more than 5 cm in diameter. Inclusions of felsic material either consist of devitrified glass, or show planar features and rarely, diaplectic glass. Some inclusions are permeated by the spherulitic rock, and the original minerals are recrystallized to aggregates of smaller grains. In such inclusions, mafic minerals are completely decomposed to aggregates of opaque material and cryptocrystalline material and have lenticular or droplet shapes that indicate partial melting and flow.



Pl. XX
Photomicrograph of spherulitic rock (28.5 km, 272) (plane light). Long dark grains are pyroxene bordered by opaque material.

Latite (Unit 15)

Latite is the lower major unit (Table 9) of the thick sheet of igneous rocks. The latite is well exposed on cliffs that mark both the outer and inner edges of the annular plateau. Dikes of latite are present within the inner edge of the plateau. The upper and lower contacts of the latite are only rarely exposed, making it difficult to estimate the thickness of the unit. I estimate the maximum thickness to be 170 m.

The latite is typically reddish-brown, but can be brown, red, or grey. Vesicles are rare. No trace of flow structure was seen. Latite grades upward from aphanitic to medium-grained (Unit 15a) near the monzonite contact (Unit 16).

The latite has an intergranular texture, with small grains of anhedral pyroxene and opaque minerals between stubby grains of anhedral and subhedral plagioclase. Augite and nearly uniaxial pigeonite are the pyroxenes.

Magnetite and hematite are the common opaque minerals. Plagioclase is commonly zoned. Currie (1972) reported that measurements on zoned plagioclase by means of a universal stage gave values ranging from An_{25} at the rim to An_{60} in the core. I determined compositions ranging from An_{45} to An_{50} on unzoned plagioclase. Point counts on stained thin sections (Table 15) indicate that sanidine is present in roughly equal proportion to the plagioclase. This is not obvious in thin section because most of the sanidine is present as broad clear rims on the plagioclase, and it can be mistaken for an outer zone of the plagioclase. Some sanidine and anhedral quartz is interstitial. Needle-like grains of apatite penetrate the quartz and some of the plagioclase. Very small grains of pleochroic brown biotite are present in trace amounts. Chemical analyses of two latite samples are given in Table 16.

Inclusions are large and abundant near the base of the latite, and decrease in size and abundance upwards. Xenocrysts are common in thin section. Large inclusions are more common near the outer edge of the annular plateau. The largest inclusion known to be completely enclosed in latite is about 15 m across. Outcrops of what appear to be even larger inclusions are near the base of the outer edge of the plateau, but such outcrops are either isolated from the latite or show only their upper surfaces in contact with the latite. Such outcrops may be actual inclusions, or megablocks on the original floor of the structure. I interpret such outcrops as inclusions or megablocks because they show evidence of shock stages I and II in areas where the country rocks show only evidence of shock stage 0. Some inclusions are completely recrystallized and others are composed of vesiculated and devitrified country rock that locally shows columnar jointing (Pl. XXI).

TABLE 15 - MODAL COMPOSITIONS OF LATITES AND MONZONITES

	21X1B3A Latite[a]	21X2B3B Monzonite[a]	8F1D Latite[a]	8F4 Monzonite[a]	Aver. of 8 monzonites (after Kish, 1968)
Quartz	0.3	5.3	3	3.8	10.28
Plagioclase	39.3	38.3	31	34	38.91
Sanidine	38.3	40.3	34	42	32.45
Pyroxene	20.7	12.7	32	13.2	11.32
Opaques	1.7	3.3		7	7.04

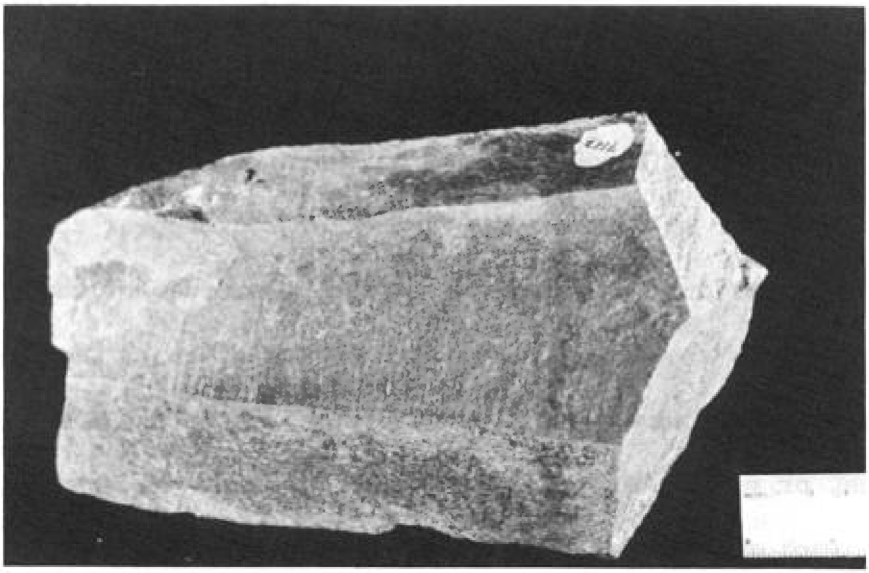
21X2B3A - Latite from cliff (11.4 km, 248).

21X2B3B - Monzonite above 21X2B3A. Point count just above contact in same thin section as 21X2B3A.

8F1D - Latite along stream (20 km, 279).

8F4 - Monzonite farther upstream and stratigraphically above 8F1D (20.5 km. 279).

[a] Approximately 500 points counted on thin sections in which plagioclase and potassium feldspar were stained.



Pl. XXI

Columnar joint developed in small inclusion of gneiss in latite. Foliation in the inclusion is nearly vertical in the photograph. In thin section the gneiss now consists of devitrified glass.

TABLE 16 - CHEMICAL COMPOSITIONS OF LATITES AND MONZONITES

	14X1B	14X1A	K131	K533
	Latite[a]	Monzonite[a]	Latite[b]	Monzonite[b]
SiO_2	57.92	58.05	58.18	58.23
TiO_2	0.66	0.49	0.78	0.80
Al_2O_3	15.82	17.04	16.32	16.38
Fe_2O_3	2.94	4.29	3.27	4.80
FeO	3.77	1.72	3.18	1.72
MgO	3.66	3.26	3.31	3.82
CaO	6.78	5.47	6.36	5.99
Na_2O	4.00	4.04	3.86	3.68
K_2O	3.34	3.92	2.85	3.06
H_2O (+)	0.47	0.51	0.79	0.70
H_2O (-)	0.35	0.52	0.35	0.15

[a] Latite collected 3 m below monzonite from small cliff (11.4 km, 252).

[b] Analysis from Kish (1968). Samples are from the northeastern part of the Manicouagan Cryptoexplosion Structure, but the exact localities are not given.

Monzonite (Unit 16)

Monzonite is the upper unit of the Manicouagan Complex (Table 9). It caps the annular plateau of igneous rocks, and in and near the central mountain forms a dike and several flat-lying tabular bodies.

The monzonite is typically brown, but is locally grey or red. Most specimens contain phenocrysts of black pyroxene as much as one cm long. Brown monzonite commonly shows red grains and patches of hematite.

The dominant texture is ophitic, but sub-ophitic and intergranular textures are also present. Anhedral sanidine rims on euhedral or subhedral plagioclase give the rock a xenomorphic-granular appearance.

Three varieties of pyroxene are present: hypersthene, pigeonite, and augite or diopsidic augite. Pyroxene phenocrysts and microphenocrysts are commonly corroded and embayed. Some pyroxenes show fractures and rims partially altered to hematite, and are bordered by small grains of hematite and large grains of magnetite.

Plagioclase occurs as zoned euhedral or subhedral laths and equant anhedral grains. Slightly-zoned plagioclase has a composition between An_{40} and An_{45}. Currie (1972) reported that universal stage measurements on strongly-zoned plagioclase gave values ranging from An_{25} at the rim to An_{60} in the core. He also stated that X-ray and optical data indicated that the plagioclase is the high temperature form.

Wide clear sanidine rims border most plagioclase grains, and sanidine is also present interstitially. Point counts on stained specimens indicate that sanidine is slightly more abundant than plagioclase (Table 15). Point counts by Kish (1968) show plagioclase to be slightly more abundant, but this may be incorrect because he did not stain the thin sections. Currie (1972) reported point counts that show approximately a 7:1 ratio of plagioclase to sanidine in both the monzonite and latite (his larvikite and trachyandesite). I am sure that this is erroneous, because, while I report point counts on only two stained specimens, I have examined thin sections of this unit from many localities and they are all clearly similar in composition. A roughly equal ratio of sanidine to plagioclase would be expected in both the latite and the monzonite because of the proportion of soda to potash in the chamical analyses (Table 16).

Quartz is present interstitially as anhedral grains and aggregates of blade-shaped grains. Similar blade-shaped grains in the Sudbury micropegmatite have been interpreted as paramorphs of quartz after tridymite (Stevenson, 1963). Apatite needles are present as in the latite, but biotite is absent. Chemical analyses of the monzonite are very similar to those of the latite (Table 16).

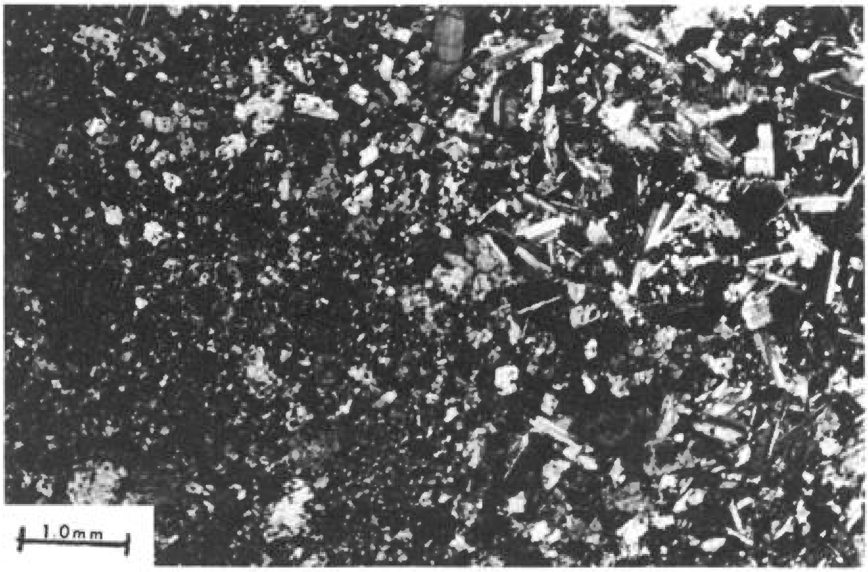
The monzonite contains few inclusions except near its contact with the latite. The upper part of the monzonite contains no inclusions. Inclusions are commonly small and rounded, and typically show evidence of shock stages I and II where recrystallization has not obliterated the original features.

Contact Relations

Basalt overlies gneiss of shock stage 0. Basalt dikes in gneiss of shock stage 0 locally grade into borders of suevite (Pl. XVIII) or spherulitic rocks. Basalt locally overlies suevite. Basalt underlies latite, but the contact between these units was not observed.

Spherulitic rocks occur as dikes or as a transitional phase between suevite and basalt in some dikes. In one outcrop a spherulitic rock grades in one direction into red breccia that borders a megablock of shocked gneiss, and apparently grades in the other direction into latite.

The contact between the monzonite and the latite was elusive when sought and puzzling when found. The contact is best described as an abrupt gradation. Plate XXII is a photomicrograph of the contact. The contact could not be followed for more than a few meters at any one place, but it seemed to be approximately horizontal, although irregular in detail. Small apophyses of latite extend into the monzonite and there are inclusions of latite in monzonite and of monzonite in latite.



Pl. XXII
Photomicrograph (crossed polarizers) of abruptly gradational contact between latite and monzonite (11.4 km, 248).

The rock that both Currie (1972) and I (Murtaugh, 1975 and this paper) show as Unit 15a is a medium-grained rock that in some places may be part of the monzonite, and in other places may be part of the latite. This problem results from the difficulty of mapping small changes in grain size in the field.

Table 15 shows two sets of modal analyses of latite and monzonite from localities where the monzonite is just above the latite. Two of the point counts are from monzonite and latite in different parts of the same thin section. In each set of analyses the monzonite is enriched in potassium feldspar and quartz, and depleted in mafic constituents. Table 16 shows chemical analyses of two latites and two monzonites. Two of the analyses are of latite and monzonite that were collected about 3 m apart, vertically. The analyses show that the monzonite is slightly enriched in silica, soda, and potash, and depleted in lime. The chemistry and mineralogy suggest that the latite and monzonite are part of a single layer of molten material that differentiated slightly while in place. The upper, presumably aphanitic, part has been removed by erosion. Photographs of the contact and an hypothesis for its manner of formation are given in Murtaugh (1975).

The contact of the igneous rocks with the country rock at the inner and outer edges of the annular plateau seems to be at an elevation of 1300 to 1350 feet although in places on the eastern outer edge it may be at 800 feet. The primary floor of the structure is nearly flat, although it may slope down toward the edge of the structure in the east. An estimate of the total thickness of the igneous rocks of the Manicouagan structure was arrived at by assuming a primary structure floor at an elevation of 1300 feet. The highest point on the igneous plateau is about 2350 feet, giving a total thickness of 1050 feet (335 m) for the igneous rocks.

Although the contact between the monzonite and the latite was exposed in only a few places, the approximate location of the contact could be determined in many places. At the outer edge of the plateau the contact is between 1500 feet and 1700 feet virtually everywhere. The elevation near the middle of the plateau (17.5 km, 215) where the contact was seen is 1550 feet. At the inner edge of the annular plateau, the elevation of the contact is at 1350 feet. The contact dips gently inward to the inner edge of the annular plateau. The latite, as much as 170 m thick at the outer edge of the plateau, thins to about 15 m at the inner edge. Near the central mountain the monzonite appears to rest directly on the shocked country rocks, although the contact was not seen.

A single dike and several sills, or flat-lying tabular bodies of monzonite, intrude the anorthosite of the central mountain and its outliers. All of these intrusive bodies crop out at an elevation of about 2100 feet. They are associated with spectacular contact metamorphic effects which are discussed in the next section.

CONTACT METAMORPHOSED COUNTRY ROCKS

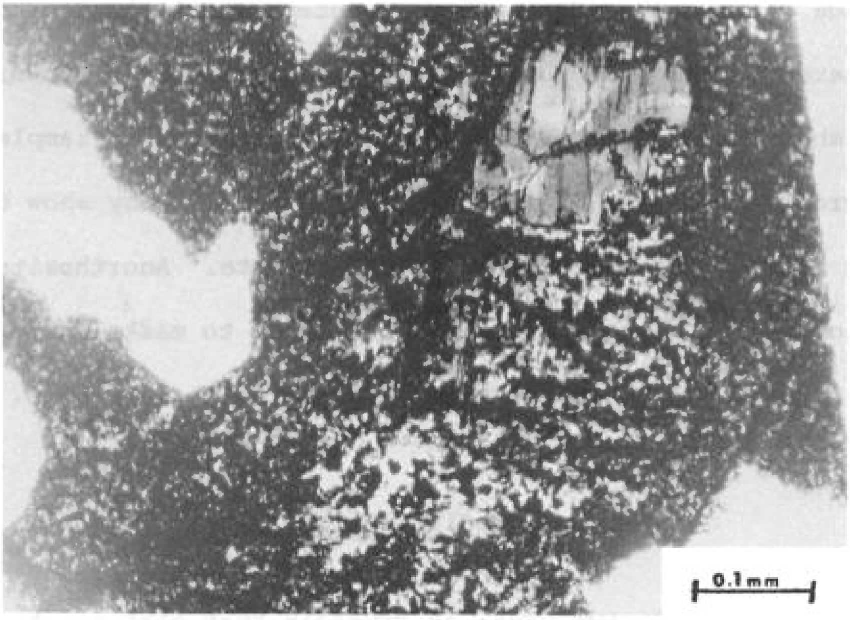
Contact metamorphic effects in the country rocks of the Manicouagan Impact Structure range from nearly imperceptible to spectacular. Large zones of contact metamorphism are shown on the geologic map by inclined cross-hatching.

The contact metamorphic effects are not mutually exclusive, and several effects may be present in a single specimen. Contact metamorphic effects are clearly associated with igneous rocks and pseudotachylite, and in the few places where there is not a close spatial association it is reasonable to assume that the igneous rocks have been removed by erosion. Although contact metamorphism can clearly be related to the igneous rocks, the intensity of the metamorphism and the width of the contact metamorphic zones is such that it does not seem possible for heat from the igneous rocks to be the sole cause of the metamorphism. An hypothesis to explain this problem is presented in the section on the origin of the structure.

Decomposition of Mafic Minerals

A striking characteristic of many of the shocked country rocks is their reddened appearance caused by hematite. Rocks showing such alteration almost invariably crop out near latite and monzonite.

The first stage of decomposition is a reddening and darkening along the borders and cleavages of biotite grains. In a more advanced stage biotite becomes black along borders and cleavages, and the rest of the grain is deep red or red-brown. In the next stage biotite becomes black, or decomposes to an aggregate of small discrete grains of magnetite rimmed by hematite, in a matrix of cryptocrystalline birefringent material (Pl. XXIII). In the vesicular gneiss, described later, relict biotite grains show evidence of plastic deformation, flow, and reaction with the surrounding material.



Pl. XXIII

Photomicrograph of biotite grain in gneiss of shock stage 0 that is decomposed to an aggregate of opaque minerals and cryptocrystalline material (plane light). A relic core of biotite is in the upper right.

Hornblende has decomposed in the same manner as biotite, but at a higher grade of metamorphism. Garnet decomposed in the same way at a slightly higher grade than hornblende, and where garnet and hornblende show advanced decomposition, biotite is completely altered. Not all garnets show reddening, probably because of their lack of iron. Pyroxene decomposed much less readily than other minerals, and is only slightly altered in rocks where garnet and hornblende are highly altered. In zones of intense hornfelsing pyroxene decomposed to an aggregate of opaque minerals and cryptocrystalline material.

There is no correlation between the degree of shock metamorphism and the degree of decomposition of mafic minerals. Chao (1967, 1968) used decomposition of biotite and amphibole as one indicator of shock grade in impact breccias, but noted that unaltered amphibole coexists with diaplectic glass in some specimens. Mafic minerals in rocks of shock stage 0 are highly decomposed in outcrops near latite, but they are unaltered in the same rocks far from the latite. Mafic minerals in rocks of shock stage II show little or no alteration in samples from most outcrops on the top of the central mountain. They show decomposition only near latite, monzonite, and pseudotachylite. Anorthosite in which the plagioclase is almost completely converted to maskelynite shows only slightly altered garnet and hornblende.

Zeolitization

Zeolites occur in two ways: as crystals that coat joint surfaces, and as a replacement of plagioclase.

Zeolites form on joint surfaces as far as 29 km from the center of the structure. In one valley (29 km, 290), trapezohedrons of analcite and rhombohedrons of chabazite are on joint surfaces in autochthonous breccia. The largest crystals are about 5 cm in diameter. Trapezohedrons of analcite and radiating blades of thomsonite as large as 2 cm form on joint surfaces nearer the center of the structure.

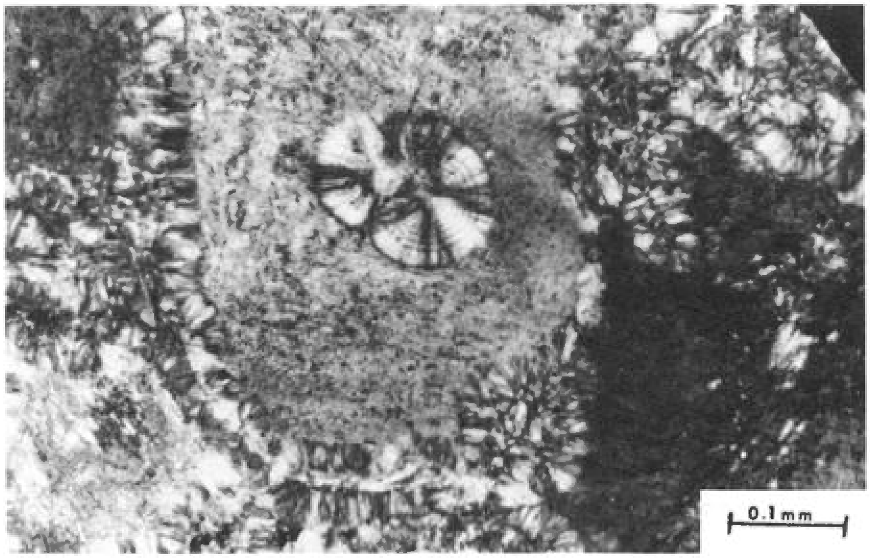
Plagioclase in anorthosite in and near the central mountain is in places extensively replaced by zeolites. In hand specimen such rocks are pink. Locally, zeolitization is so extensive that megascopic analcite crystals are formed *in* the anorthosite.

Extensively zeolitized anorthosite shows evidence of shock stages I or II, where not obliterated by zeolitization. Zeolites replace the rims and interiors of plagioclase grains (Pl. XXIV). Some plagioclase is selectively replaced along cleavages. X-ray analysis of such rocks indicates that the zeolites are analcite and thomsonite (M. R. Dence, pers. comm.; Currie, 1972). Currie also reports traces of potassium feldspar. Plagioclase is commonly a light brown color that may indicate incipient zeolitization.

In Part I of this report I described autointrusive breccia in anorthosite of Mount Brilliant outside the structure, and noted that the breccia could be recognized only because the intrusive phase was pink. The pink color is caused by microscopic zeolites that partially replace plagioclase. Currie (Murtaugh and Currie, 1969) mapped two other occurrences of zeolites on Mount Brilliant.

Hornfelsed Anorthosite

Perhaps the most deceptive and intriguing rock in the area is the

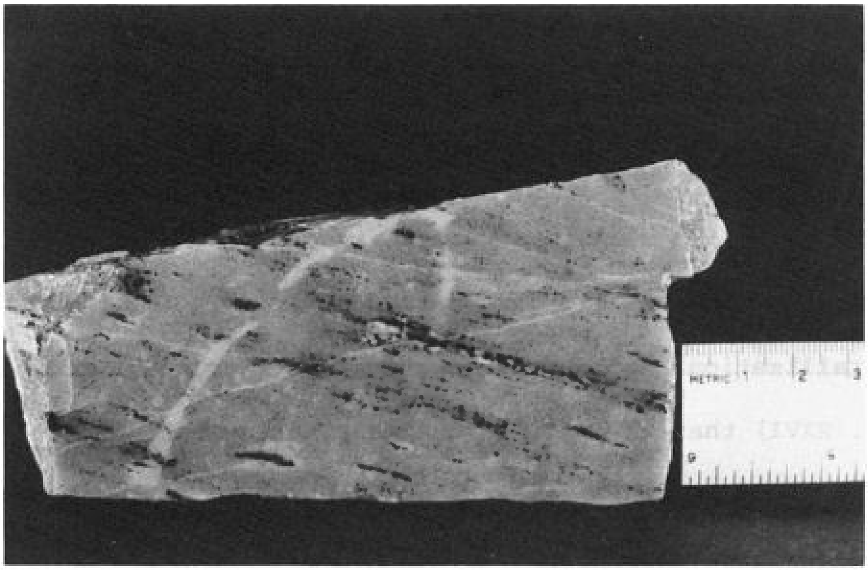


Pl. XXIV - Photomicrograph of spherulitic zeolites replacing the edge and interior of a plagioclase grain in anorthosite (7 km, 060) (Crossed polarizers). The plagioclase is altered and is brown in plane light.

hornfelsed anorthosite that crops out in parts of the central mountain and its outliers. The rock is commonly grey, but some is pink and some is light brown. In hand specimen the hornfelsed anorthosite appears aphanitic, and it may be massive, foliated (Pl. XXV), banded, or brecciated. The massive variety can be easily mistaken for a volcanic rock. Foliation and banding is shown by garnets and mafic minerals that are black in hand specimen..

Hornfelsed anorthosite is made up mostly of microscopic laths and equant grains of plagioclase. Nowhere do these grains show evidence of shock metamorphism. Roy (1969) reported that X-ray analysis of one sample indicated that the plagioclase is the high temperature form. In some specimens, relict primary grians can be recognized, even though they are now a mat of small laths.

Mafic minerals and garnet are completely decomposed to opaque



Pl. XXV - Cut and polished slab of hornfelsed anorthosite showing foliation.

minerals and cryptocrystalline material, and in places are recrystallized to an extremely fine aggregate of unidentified minerals. Some hornfelsed anorthosite contains greenish-black blebs with black borders that are probably recrystallized coronas of pyroxene, hornblende, and garnet.

The origin of the hornfelsed anorthosite and its time of formation are critical to the interpretation of the origin of the igneous rocks of the Manicouagan Complex. Therefore, I describe two localities in detail. Descriptions of other localities are in Murtaugh (1975).

Hornfelsed and Zeolitized Anorthosite in the Median Valley of Mount de Babel (7.5 km, 027)

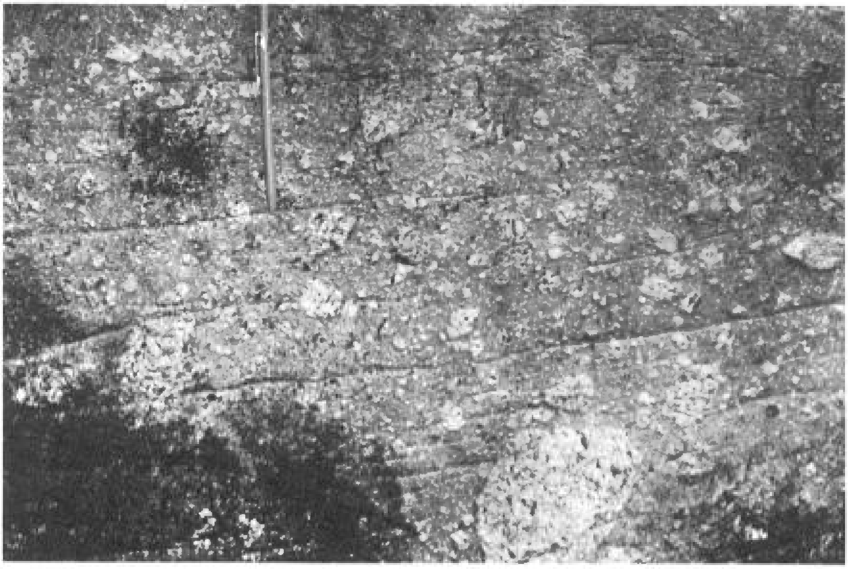
Monzonite underlies most of the floor of the median valley of Mount de Babel. The top of the monzonite is at an elevation of 2150 feet and the lower outcrop is at 2050 feet, but the true thickness could not be determined. Small hills rising above the monzonite show an upward gradation from hornfelsed anorthosite to zeolitized anorthosite to shock metamorphosed anorthosite.

On one hill brecciated and hornfelsed anorthosite above the monzonite is made up of angular white fragments in a dark matrix (Pl. XXVIA). In thin section, the fragments are well defined in plane light (Pl. XXVIB), but difficult to recognize under crossed polarizers (Pl. XXVIC) because of recrystallization. Some fragments contain recrystallized plagioclase laths (Pl. XXVI) that extend into the matrix, indicating that recrystallization took place after brecciation.

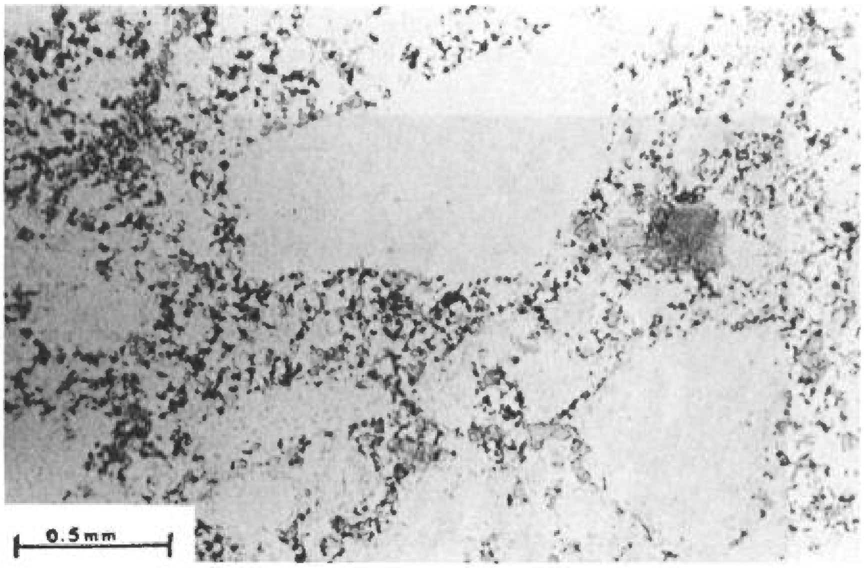
The zeolitized anorthosite above the brecciated and hornfelsed anorthosite is in places what I call a 'ball-fracture breccia,' in which rock is broken into ball-like fragments along smooth curved fractures. The rims of the balls have been extensively zeolitized, and locally these zeolites are well-formed trapezohedrons of analcite (Pl. XXVII). In thin section the balls are a microbreccia made up of fragments of plagioclase in a matrix of smaller plagioclase fragments, zeolites, and cryptocrystalline material. The rims of the balls are mostly a mat of zeolites with minor relic plagioclase.

Hornfelsed Anorthosite in an Outlier Northwest of the Central Mountain (10.5 km, 337)

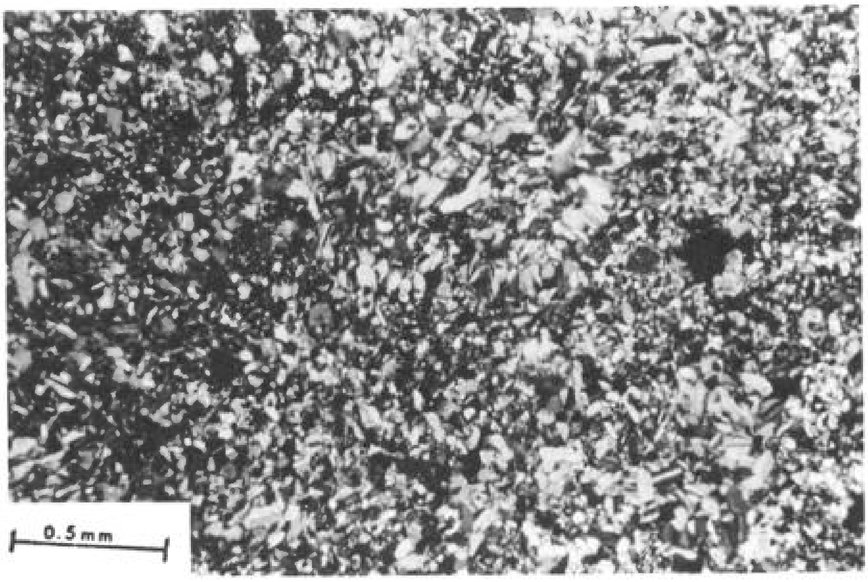
One of the most puzzling outcrops in the entire structure is on the east side of a small hill that is separated from the central mountain by a deep valley. The east side of the hill is underlain by anorthosite and the west part is underlain by gneiss, monzontie, and latite. A dike of monzonite cuts the anorthosite at an elevation of about 2100 feet. The dike is exposed for a distance of about 35 m on the hillside. The



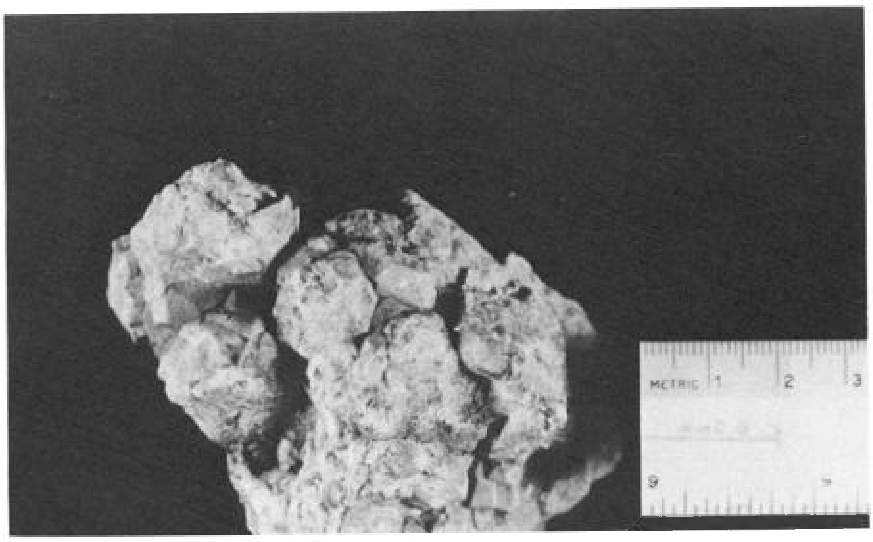
Pl. XXVIA - Brecciated and hornfelsed anorthosite a few meters above monzonite in the median valley of the central mountain (7.5 km, 027). Pen (upper left) gives the scale.



Pl. XXVIB - Photomicograph in plane light of a thin section from the outcrop shown in Pl. XXVIA. White fragments are clearly defined.



Pl. XXVIC - Photomicrograph under crossed polarizers of the same field of view shown in Pl. XXVIB. The anorthosite is completely recrystallized to plagioclase laths and small pyroxene grains. The fragments have slightly larger plagioclase grains that tend to be oriented perpendicular to the edges of the fragments.



Pl. XXVII - Trapezohedrons of analcite that locally form rims on balls in the ball-fracture breccia in parts of the same outcrop as the specimen shown in Pl. XXVI.

dike contains no inclusions and has a sharp contact with the anorthosite. The dike is 7 m thick and is bordered by an impossibly wide contact metamorphic aureole. The aureole can be divided into three zones:

Zone 1 is 10 m to 13 m wide. Plagioclase in the hornfelsed anorthosite is so completely recrystallized that no relic textures can be determined with certainty (Pl. XXVIIIA). Mafic minerals are decomposed to aggregates of opaque minerals and devitrified glass.

Zone 2 is 10 m wide. Plagioclase is recrystallized completely to aggregates of small grains, but the primary texture is preserved (Pl. XXVIIIB). Mafic minerals are decomposed to aggregates of opaque minerals.

Zone 3 is 10 m to 15 m wide. The primary texture is well preserved (Pl. XXVIIIC), but the plagioclase grains show incipient recrystallization in the form of local domains with a felty texture. Some grains show narrow polysynthetic twin lamellae that are unlike those in unshocked anorthosite and are probably shock induced. Some grains show maskelynite or planar features. Patches of zeolites locally replace plagioclase. In places ball fracture breccia shows intense zeolitization of the rims of the ball-like fragments. Trapezohedrons of analcite rim some of the balls.

Photomicrographs of rocks from zones of contact metamorphism around a 7 m thick monzonite dike (10.5 km, 337). All are with crossed polarizers.

Pl. XXVIIIA

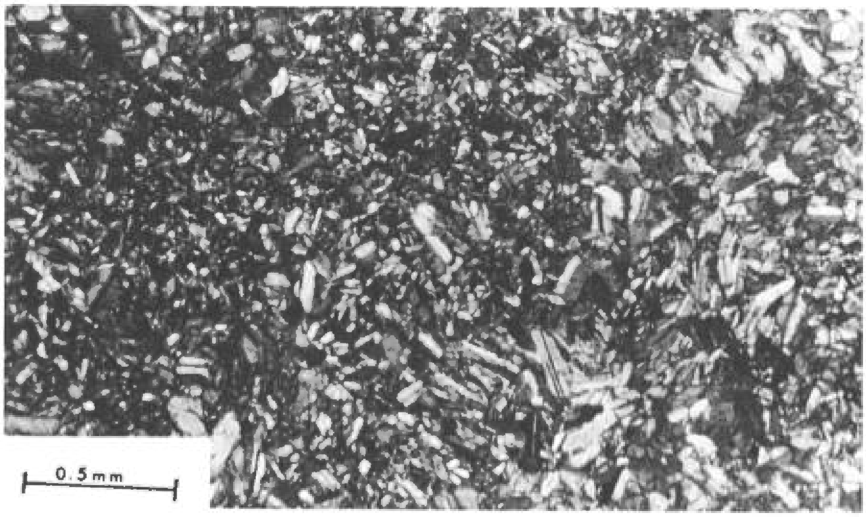
Hornfelsed anorthosite from the 10 m to 13 m wide zone (Zone 1) that borders the dike. The relic primary texture of the anorthosite is not preserved, but breccia fragment boundaries may be indicated by the rows of larger plagioclase grains.

Pl. XXVIIIB

Hornfelsed anorthosite from Zone 2 which extends 10 m beyond Zone 1. Recrystallized plagioclase grains are smaller than those in Zone 1. The primary texture of the anorthosite is preserved. Black euhedral grains are decomposed garnet. Irregular black grains are an unidentified decomposed mafic mineral.

Pl. XXVIIIC

Zeolitized anorthosite from Zone 3, which extends for 10 m to 15 m beyond Zone 2. The plagioclase has a felty texture that in places is incipient hornfelsing, and in places is zeolite. The plagioclase is brown in plane light.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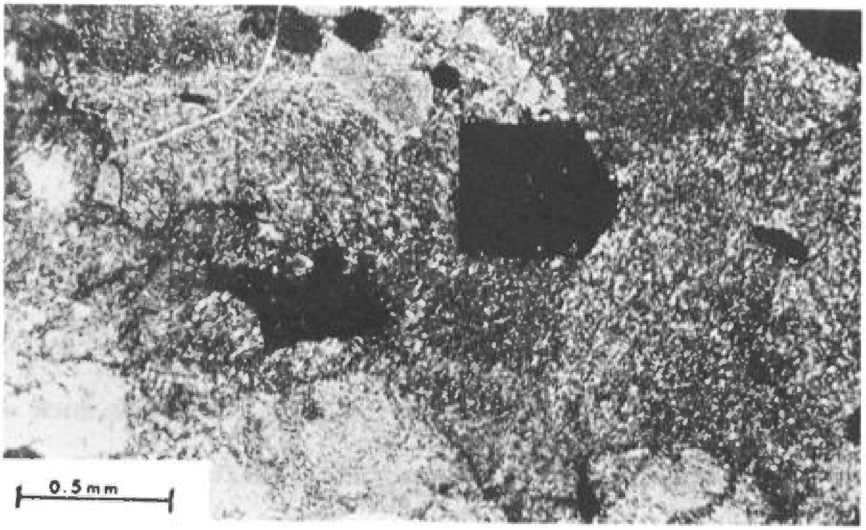
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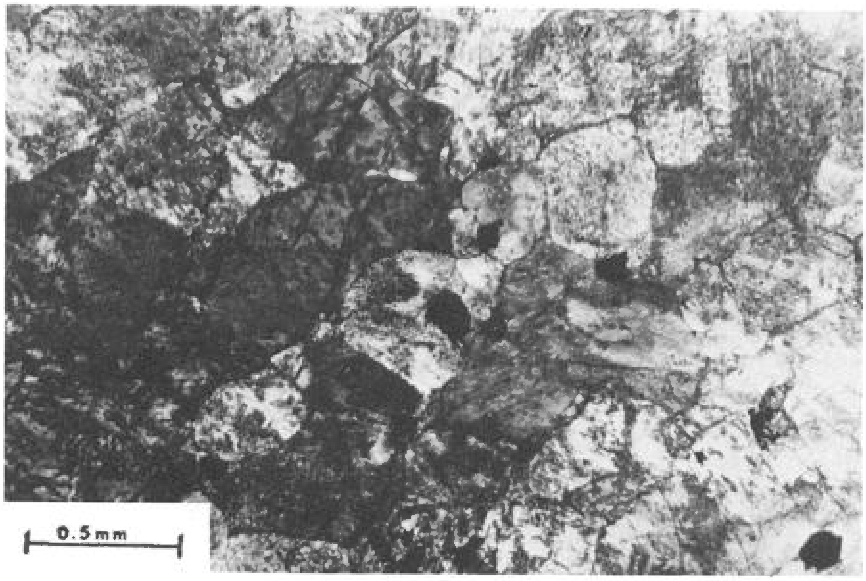
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Melted and Vesiculated Gneisses

Melted and vesiculated gneisses are rocks in which the felsic minerals are almost entirely represented by devitrified glass. Such rocks rarely show evidence of flow. They may show columnar jointing (Pl. XXI). They are found as inclusions in latite near the inner edge of the igneous plateau and form rare outcrops in rocks of shock stage II.

The most startling example of melted and vesiculated gneiss is exposed in an outcrop (7 km, 262) about 50 m north of the outcrop containing the red breccia that grades to granitic gneiss which was discussed in the section on red breccia. The chemical compositions of the granitic gneiss and the vesicular gneiss (Table 12) indicate that they are different rocks.

A 1 m thick dike of grey vesicular aphanitic igneous rock was intruded along the contact between melanocratic gneiss and what is now vesicular gneiss. The melanocratic gneiss above the dike is reddened, and in thin section contains diaplectic glass and highly decomposed mafic minerals.

A 1 m thick layer of gneiss below the dike shows a well-developed linear flow structure (Pl. XXIXA). Vesicles as much as 1 cm in diamater tend to be concentrated in the red-brown mafic streaks. Small grains of an unidentified mineral or minerals are formed on the walls of the vesicles.

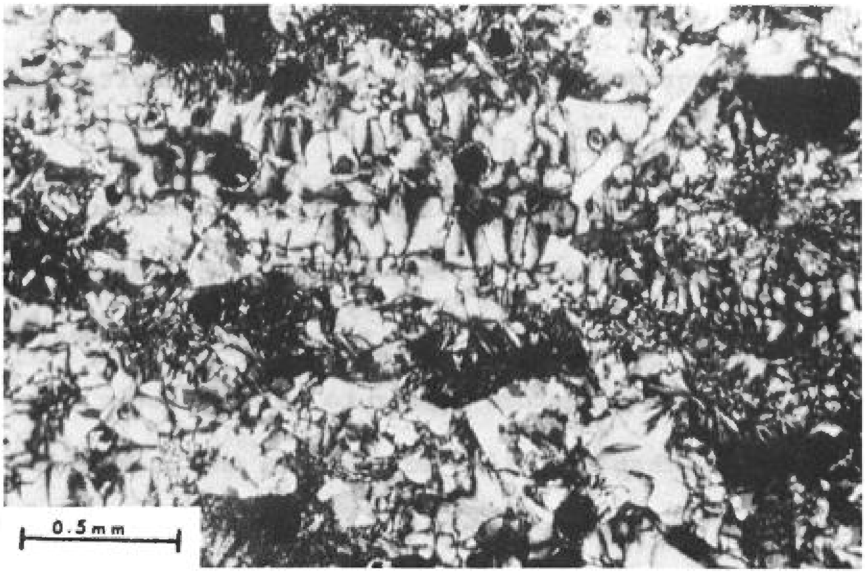
Flow structure is shown by stringers of devitrified glass and elongate aggregates of decomposed mafic minerals (Pl. XXIXB). Some bent and distorted decomposed grains of biotite and hornblende are preserved in the mafic stringers. Pyroxene grains are recrystallized into fine mosaics.

The gneiss has been vesiculated, but does not show flow structure, for a distance of at least 6 m beyond the zone of flow. At a distance of 7 m from the dike the outcrop is covered with overburden. The vesicular gneiss is grey and shows foliation. Vesicles as much as 5 cm long tend to be concentrated along the foliation (Pl. XXXA). Locally the vesicular gneiss shows columnar joints.

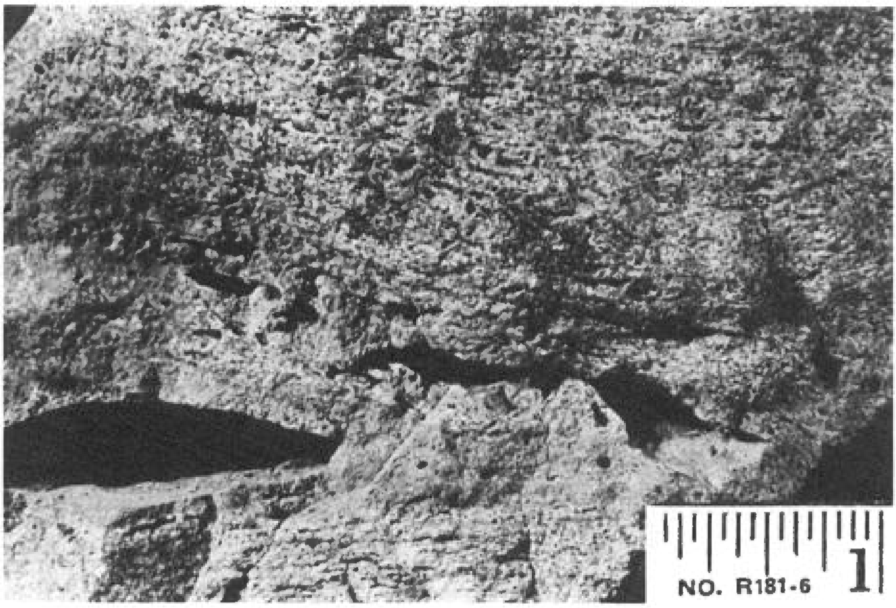
The felsic minerals now consist of devitrified glass which does not show clear evidence of flow (Pl. XXXB). Some elongate blebs consist of recrystallized quartz. Biotite, hematite, and garnet are completely decomposed to aggregates of opaque minerals and devitrified glass. Pyroxene grains are now devitrified glass.

A 1 mm thick veinlet of pseudotachylite in melanocratic gneiss (9.1 km, 272) is bordered by altered hornblende and scapolite that is converted to glass (Pl. XXXI). The scapolite is not vesicular and did not flow. It might therefore appear to be diaplectic scapolite glass, except that only that scapolite adjacent to the pseudotachylite veinlet is vitrified. The affected zone is nearly half as wide as the veinlet. The final section of this report discusses the problem of how such pronounced thermal effect could be produced by this small veinlet and also by the igneous rocks described above.

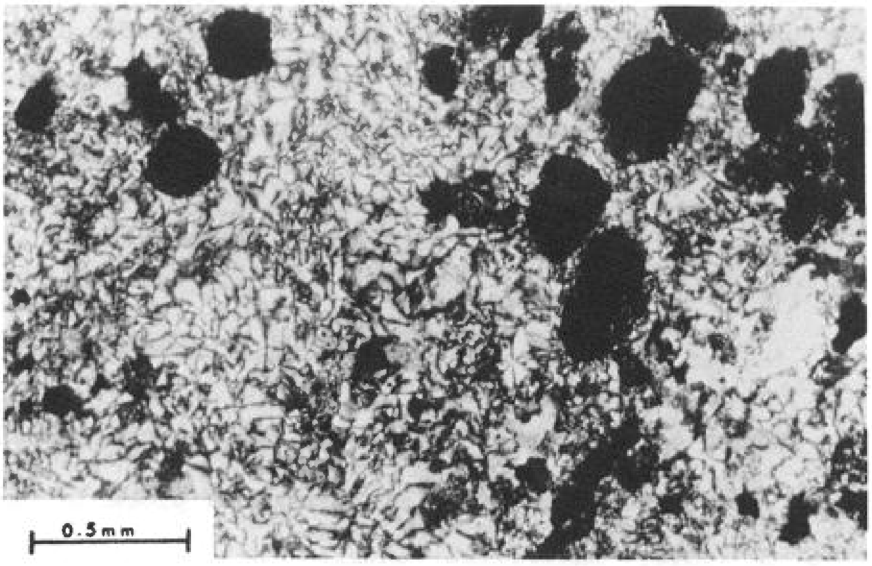
Pl. XXIXA - Melted and vesiculated gneiss showing linear flow structure (7 km, 262) from a 1 m wide zone that borders a 1 m wide dike of aphanitic igneous rock. The scale shows one inch.



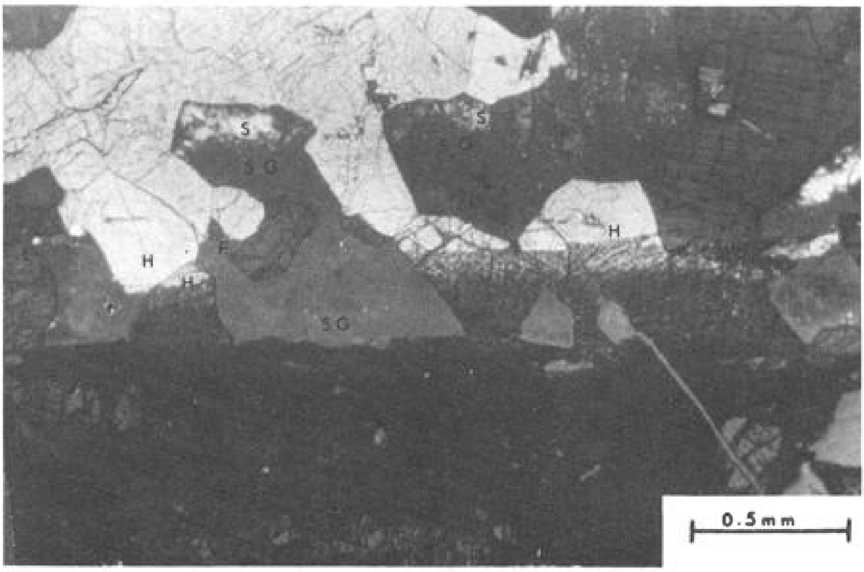
Pl. XXIXB - Photomicrograph of melted and vesiculated gneiss shown in Pl. XXIXA. Felsic minerals have melted and flowed and now form stringers of devitrified glass (crossed polarizers). The devitrified glass shows extinction crosses. Spherical black areas are vesicles with linings of unidentified birefringent material. Other black and dark areas are decomposed mafic material.



Pl. XXXA - Melted and vesiculated gneiss from the same outcrop as the specimen shown in Pl. XXIX, but from a zone that extends 6 m beyond that specimen. Foliation is subhorizontal in the photograph. The scale shows one inch.



Pl. XXXB - Photomicrograph of melted and vesiculated gneiss shown in Pl. XXXA. Felsic minerals are now devitrified glass that shows extinction crosses. Spherical black areas are vesicles. Other black areas are decomposed mafic minerals.



Pl. XXXI - Photomicrograph of the contact of a pseudotachylite veinlet, one mm thick (lower dark material), with melanocratic gneiss (9.1 km, 272). Hypersthene (H) grains with cleavage) is darkened and altered to devitrified glass in a dark band along the border of the veinlet. Scapolite (S) near the veinlet is altered to glass (SG) (medium grey), which intrudes and grades into small white patches of birefringent scapolite away from the veinlet. (The grey color of the glass is apparently due to an accidental rotation of the lower polarizer.)

STRUCTURAL GEOLOGY

Regional Field Relations and Geologic Setting

Linear arrays containing one or more cryptoexplosion structures or impact structures, and other structures of probable igneous origin are known on several continents (Bucher, 1963). Snyder et al. (1965) described an alignment in Illinois, Missouri, and Kansas of eight areas that include cryptoexplosion structures and igneous structures. The Manicouagan Impact Structure does not form part of any alignment of features, but Currie (1965) claimed that most of the Canadian cryptoexplosion structures, including Manicouagan, were within 160 km of a wandering line that he drew to represent the locus of maximum deformation during post-Paleozoic epiorogenic uplift of the Canadian Shield. He considered this to be: ". . . damning evidence against a random external origin . . ." (Currie, 1965, p. 935). It can be argued that many of these structures are present today because they are the latest of the older Canadian structures to be exhumed from their cover of Paleozoic sedimentary rocks. The larger structures, such as Manicouagan and the Clearwater Lakes, are well preserved because of their size and more recent age. Older and smaller craters in the heart of the shield may have been removed by erosion, or reduced to a level such that their characteristic features are not readily observed.

The Manicouagan Impact Structure lies at the intersection of some of the major rock units of the Grenville Province. These units are: a southwest-trending anorthosite pluton (Unit 8b), a west-trending metagabbro pluton (Unit 1), and a north-trending transition (Unit 3) between amphibolite facies rocks (Unit 4) and granulite facies rocks (Unit 2). In addition, the Gagnon Group (Unit 6), a southern extension of the Labrador geosyncline, crops out along the west side of the structure. I do not believe that there is a causal relationship between the location of these Precambrian units and the catastrophic event that formed the Manicouagan Impact Structure, but the possibility must be considered.

Joints and Shear Fractures

The sides of the polygon that coincide with the Manicouagan structure and are marked by Lakes Manicouagan and Mouchalagane are oriented along azimuths of 160°, 200°, 110°, and 250°. The sides of the polygon are interpreted here as faults. Elongate lakes, chains of lakes, and straight segments of streams form prominent topographic linears along these same directions inside and outside of the Manicouagan Impact Structure. Linears aligned in the 160° and 200° directions are better developed, probably because they are subparallel to the direction of ice movement and were more easily eroded by the glaciers. Some of the linears mark faults, but most appear to be joint valleys. Valleys near the bounding lakes commonly show evidence of shearing in the form of displacements of a few centimeters. The shocked anorthosite of Mount de Babel shows a prominent sub-horizontal set that is not developed in other Precambrian rocks.

Earlier I noted that the number of joints in the country rocks in the west increased from the drainage divide to the shores of Lake Mouchalagane. Roy (1969) measured about 6000 joints in 16 outcrop areas in the western part of the area. Among his results:

1) Confirmation of the inward increase in the number of joints from the drainage divide to the shores of Lake Mouchalagane.

2) Lineation, consisting of minor fold axes, mineral lineation, and intersections of cleavages, plotted in two nearly perpendicular planes, one oriented essentially north-south and the other east-west. The east-west plane contained the greatest principal stress axis of conjugate shear fractures that were presumably formed at the same time as the Manicouagan Impact Structure. Roy concluded that, if the cause of the jointing were a shock wave, the wave was locally diverted so that it propagated perpendicular to a regional structural fabric.

3) He could not draw any conclusion about the origin of the structure from the distribution and attitudes of the joints.

In one concentric valley (28.5 km, 259) suevite shows many small slickenside-like striations, indicating some movement after consolidation of the suevite.

Joints are well-developed in the igneous rocks of the Manicouagan Complex, particularly in the monzonite (Pl. XLVI). Steeply-dipping joints in the igneous rocks are sub-parallel to regional joints; in addition, the igneous rocks show sub-horizontal joints that commonly dip between 0° and 15°, but may dip as steeply as 30°. The sub-horizontal joints may be sheeting joints, formed as a result of expansion after glaciation, or they may be joints resulting from contraction upon cooling.

Ball-fracture breccia is a peculiar breccia formed sporadically in rocks of shock stage II. These rocks are locally broken into fragments along curving and anastomosing joints. The fragments show little or no rotation. Weathering causes the fragments to become even more rounded.

Shatter Cones

Shatter cones are fracture surfaces with longitudinal, curving, horsetailing striae (Pl. XXXII). They lack transverse striations and are quite distinct from slickensides or cone-in-cone structures. The striae fan outward from the apex of the cone. Dietz (1947) first suggested that shatter cones were caused by meteorite impact, and he later suggested (Dietz, 1959) that they were diagnostic of meteorite impact. Shatter cones have been found at many cryptoexplosion structures (Dietz, 1968), but not at any unquestionable volcanic structures. Two occurrences of shatter-cone-like fractures have been reported from areas that do not appear to be impact structures (Roy and Hansman, 1971). The structures shown by Roy and Hansman are minute (maximum length of 1 cm), and it is not certain that they are shatter cones. Shatter cones have been produced experimentally in dolomite by impact of a high speed projectile (Shoemaker et al., 1961), and by one nuclear explosion in andesite (Bunch and Quaide, 1968).

Pl. XXXII

Shatter cone segment in gneiss of shock stage I (18 km, 037). Scale is in inches.

Johnson and Talbot (1964) made a theoretical study of the formation of shatter cones. Among their conclusions:

1) Shatter cones form where an elastic precursor shock wave interacts with an inhomogeneity in the medium of transmission.
2) The pressures required for the formation of shatter cones are probably greater than those that could be produced by volcanic explosions.

3) Apices and axes of shatter cones will point towards the origin of the shock wave.

4) Most shatter cones will have apical angles of about 90°.

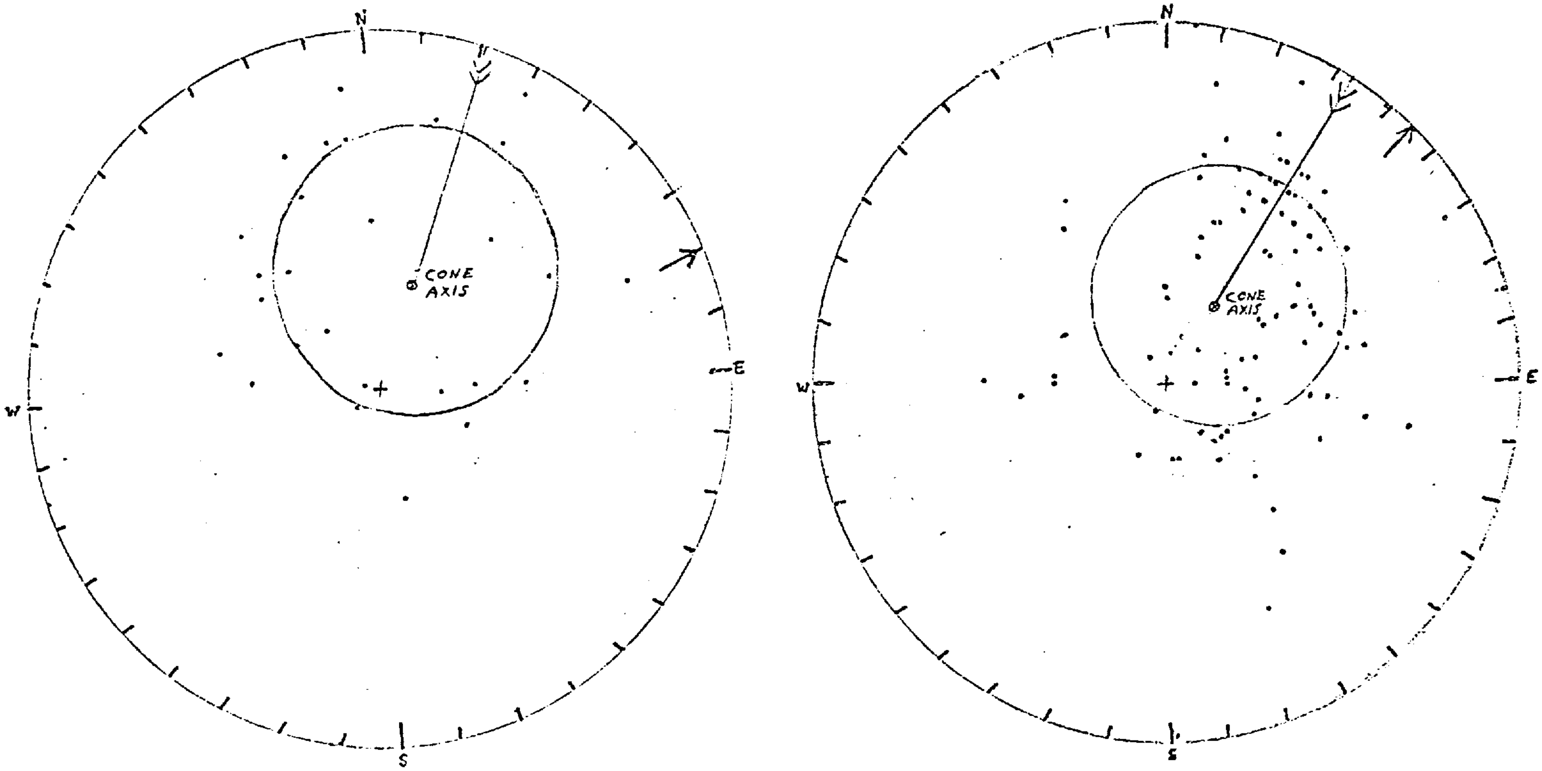
Complete shatter cones are rarely developed, and none were found at Manicouagan. Shatter cone segments in single outcrops at Manicouagan and elsewhere seem to belong to cones that point in widely divergent directions. Manton (1965) plotted shatter cone striae from a single outcrop on an equal angle stereonet, and found that divergent striae defined a single master cone for the outcrop. The plot of the striae showed both the apical angle and the orientation of the master cone. The apparently divergent striae form where different parts of the master cones are generated at neighboring inhomogeneities in the rock.

Manton applied his technique to rocks in the upturned collar of sedimentary rocks that surround the central uplift of the Vredefort Ring. A plot of all the shatter cones in the collar showed that most pointed up and away from the center of the structure, just the opposite of what would be expected if the shatter cones were formed by impact. Manton assumed that the beds had been horizontal everywhere at the time of impact, and had been overturned by the rising of the central uplift subsequent to impact. Using the stereonet, he rotated the upturned beds back to the horizontal, and found that most of the shatter cones pointed inward and slightly upward, as would be expected if the shatter cones were formed by a shock wave generated by impact. Manton's technique has been applied, with similar results, at Sierra Madera (Howard and Offield, 1968), and Gosses Bluff (Milton et al., 1972), two other craters where central uplifts have caused the overturning of sedimentary rocks that are flat-lying outside the craters.

Shatter cones in the Manicouagan Impact Structure are rarely well-developed. They are shown on the geologic map by the letter S, and are the most abundant in rocks of shock stage II, but are formed in rocks as far as 23 km from the center of the structure. Rocks containing shatter cones are almost invariably poorly exposed and it was possible to make statistical studies of striae in only two localities. Even at these localities it was necessary to examine a considerable area of outcrop to get a sufficient number of readings to define a crude cone. Stereonet plots of striae from the two localities are shown in Figure 2. It is apparent that the cones are not well-defined, and cones other than the ones I have shown could be drawn. It is equally apparent that any such cones would point upward and away from the center of the structure. The orientation of the shatter cones suggests that the rocks around the central uplift were deformed to form a collar around the uplift in the manner of the structures just described. Such a deformation cannot be demonstrated at Manicouagan because the deformed rocks are gneisses and their pre-impact attitudes cannot be determined.

Faults

The abundant evidence of shear in the form of slickensides and minor offsets in the radial and concentric valleys near the bounding lakes suggests that they may occupy fault zones, but such fault zones are difficult to prove. In one radial valley (29 km, 290), two different kinds of faults are clearly shown. A normal fault, between gneiss and autochthonous breccia, dips steeply inward toward the interior of the



2A

2B

Figure 2. Equal angle stereonet plot on the lower hemisphere of shatter cone striae. The double barbed arrow shows the trend of the cone axes, which plunge northwest, but because the striae fan out downward the apices point up in the opposite direction. The single barbed arrow points to the center of the Manicouagan Impact Structure. 2A is a 130 m long outcrop (8.7 km, 250) where the chosen fit indicates a cone with an apical angle of 80°. 2B is a 500 m long outcrop (6 km, 225) where the apical angle is chosen at 70°.

structure. A sub-horizontal fault was formed near the base of a block of Ordovician rocks. The sense of movement along the fault, shown by deformation in the basal sandstone of the Ordovician rocks, indicates that the block was thrust outward from the Manicouagan Structure or that the rocks below were thrust inward. A suevite dike terminates against the fault. It is clear that movement on the fault is post-suevite.

Ordovician rocks crop out only along the inner shores of the bounding lakes, except for two outcrops that lie between the south cliff of Mount Brilliant and the north end of Lake Mouchalagane. Along the inner shore of Lake Manicouagan, Ordovician rocks rest on metagabbro (Unit 1) at an elevation of about 708 feet. Metagabbro underlies peaks that rise to an elevation of 3623 feet just beyond the edge of the Manicouagan Impact Structure. Currie (Murtaugh and Currie, 1969; Currie, 1972) interpreted this to mean that the Ordovician rocks are preserved because they have been downfaulted at least 1000 m. The major fault zones are marked by the deep valleys occupied by Lakes Manicouagan and Mouchalagane. Ordovician rocks that overly Precambrian rocks at high elevations outside the structure have been removed by erosion.

What then is the nature of these faults? I interpret them on the basis of an impact model, and by analogy with large lunar craters. I call them slump-block faults, and show them on the geologic map by heavy dark lines with "D" on the downdropped side.

Large lunar craters with central uplifts, such as Tycho and Copernicus, are generally, although not universally, believed to be impact craters. Such lunar craters are nearly circular polygons like Manicouagan. The inner walls of the lunar craters show stepped terraces that I interpret as the tops of slump blocks. In an impact model, the blocks would have soon after the formation of the crater, because of the newly created free face formed by the inner wall of the rim.

By my analogy, the Manicouagan Impact Structure, before erosion, would have looked much like Copernicus and Tycho. The Ordovician rocks would have been removed from the interior of the crater, by vaporization and fusion near the center, and by ejection of fragmented material near the edge. Blocks of Ordovician rocks would have slid outward over the gneisses near the rim. Some would lodge on the rim and some would be ejected from the crater like the allochthonous blocks of sedimentary rocks found on the rim and beyond the rim of the Reis Basin (Bucher, 1963). In places on the rim the Ordovician rocks might be essentially *in situ*, except for having been uplifted slightly when the rim formed. Slump-block faults would develop along regional fracture systems that had been opened or weakened by the decaying shock wave. Downdropping of the slump blocks would carry the Ordovician rocks (and the suevite) to their present elevations. In the conclusion to this report I suggest that the igneous rocks of the Manicouagan Complex are impact melt, and I suggest here that this impact melt covered the innermost downdropped slump-blocks. The Ordovician rocks and the suevite were protected from erosion by overlying igneous rocks, and have been exhumed only recently. Ordovician rocks and suevite on higher slump blocks have been removed by erosion, along with the highly fractured rocks of the rim.

With respect to the development of the present form of the structure along regional fracture zones, Dieta and McHone (1974) suggested that Manicouagan might be a double astrobleme because they observed a tangent ring, of the same size, to the northwest of Manicouagan. Their observation was based on examination of satellite photographs. I have examined thin sections of rocks from outcrops that extend nearly to the center of this ring and found no evidence of shock metamorphism. The tangent ring is clearly an erosional feature developed along the same regional fracture zones that controlled the form of the Manicouagan Impact Structure.

The Central Mountain and its Outliers

The mechanism, and the time, of formation of central mountains, or uplifts, in cryptoexplosion structures has been the subject of much debate. Currie (1972) believes that the Manicouagan structure is a resurgent caldera and suggests that "Mont de Babel rose on the back of an intrusion at depth. . , " sometime after the final eruption or intrusion of the sheet of igneous rocks that now forms the annular plateau. Such a phenomenon has been described from other structures that are clearly resurgent calderas (Smith et al., 1961; Christiansen et al., 1965), although the rocks in the central uplifts of such structures are volcanic rocks and not basement rocks.

Studies of shatter cone orientation and displacement of sedimentary beds in the Sierra Madera Cryptoexplosion Structure (Howard and Offield, 1968; Wilshire and Howard, 1968) indicate that rock units in and around the central uplift moved inwards and upwards at the time of formation of the central uplift. Similar studies of the Gosses Bluff Cryptoexplosion Structure were interpreted in the same way (Milton et al., 1972). These two structures were formed in flat-lying sedimentary rocks.

Roddy (1968, 1970) described experiments performed by the Defense Research Establishment of Canada in which a 500 ton TNT explosion and a 100 ton TNT explosion were set off in alluvium and lake sediments. The

500 ton explosion produced a crater that was 100 m in diameter, 6.5 m deep, and contained a central uplift about 5.5 m high. The 100 ton explosion produced a crater that was 30 m in diameter, 5.5 m deep, and contained a 2 m high central uplift. Roddy noted that, in the larger crater, a plate on the edge of the central uplift later collapsed outward and covered some fallback material. A thin layer of fallback material covered the central uplift of the smaller crater. From a comparison of nuclear and TNT craters Roddy suggested that shallow craters with central uplifts might be produced by low density impacting bodies such as comets.

Milton et al. (1972) made a detailed study of the Gosses Bluff Cryptoexplosion Structure in Australia. This structure is 24 km in diameter and has a central uplift about 4.8 km in diameter. They described overturned plates of the central uplift that now lie on stratigraphically higher units. Some of these plates had simply fallen outward, whereas others, some as large as 100 m across, appeared to have been "propelled outward" as much as 350 m. Some of the plates rest on thin layers of fallback breccia.

Mount de Babel, the central mountain of the Manicouagan Impact Structure, is an eroded rectangular horst split by a median valley. Three sides of the mountain are bounded by steep cliffs of anorthosite. The fourth, northeast, side is a gentle slope underlain by shocked gneiss. Foliation on the northwest block of the mountain trends southeast, and is roughly parallel with foliation in Mount Brilliant, the extension of the anorthosite pluton that lies northwest of the structure. Foliation on the southern part of the southeast block trends northeast, suggesting rotation of this block during uplift. The limited data on the orientation of shatter cones at Manicouagan (Fig. 2) suggests that Mount de Babel is surrounded by gneiss that was uplifted and folded out and away from the central mountain.

I suggest that Mount de Babel was formed by uplift immediately following impact. The shape of the central mountain was determined by the elongate form of the anorthosite pluton and regional trends of structural weakness. Mount de Babel rose higher than the surrounding gneiss, perhaps because the homogeneous body of anorthosite responded differently to the forces causing the uplift.

The small hills around Mount de Babel may be small horsts that formed along with the main uplift. All of the hills show intense contact metamorphism near tabular bodies of monzonite. All of the monzonite bodies are at an elevation of about 2100 feet. The hills may also be megablocks that slid or fell off the central mountain into the accumulating impact melt.

AGE OF THE MANICOUAGAN IMPACT STRUCTURE

The igneous rocks of the Manicouagan Complex have been dated by a number of workers using a variety of techniques, and all agree that the igneous rocks are Triassic. One study of shock metamorphosed rocks suggests that the age of the shock metamorphism and the age of the igneous rocks may be different, a conclusion with which I disagree.

Wanless (1966) reported a whole rock K/Ar age of 225 ± 30 m.y. on a sample of latite. Currie (1972) reported a whole rock K/Ar age of 190 ± 30 m.y. on another sample of latite. Wolfe (1971) determined K/Ar ages on sanidine, plagioclase, and pyroxene separates of monzonite, in addition to whole rock ages. He gave the age of the monzonite as 210 ± 4 m.y. Fleischer et al. (1969) obtained a fission track age of

208 ± 25 m.y. on a sample of a glassy dike that intrudes gneiss near the edge of the structure. Jahn et al. (1976) obtained a 214 ± 5 m.y. date by Rb/Sr internal isochron on mineral separates of a specimen of monzonite.

Robertson (1967) did a paleomagnetic study of samples of latite and monzonite and showed that these rocks had Triassic paleomagnetic poles. Larochelle and Currie (1967) did a paleomagnetic study of samples of basalt, latite, and monzonite that also showed Triassic paleomagnetic poles. They noted that the paleomagnetic data suggested that all three units cooled within a period of 10,000 years.

Wolfe (1971) made a K/Ar isotope study of anorthosite, pseudotachylite, and monzonite from the Manicouagan Impact Structure in an effort to determine the age of the shock metamorphism and the age of the igneous rock. His age of 210 ± 4 m.y. on the monzonite, noted above, would seem to be the most precise age for this rock. He also determined an age of 212 ± 6 m.y. on an inclusion of hornfelsed anorthosite in the monzonite, and concluded that the time of the hornfelsing and the time of the crystallization of the monzonite were the same.

Figure 3 is a reproduction of Wolfe's Figure 3, with my caption added. The dated samples of anorthosite and pseudotachylite are from Mount de Babel with the exception of one unshocked sample from Mount Brilliant. Wolfe plotted the dates against shock pressures estimated by petrographic study of the samples. Samples A, D, B, and C show progressively younger dates from unshocked anorthosite to anorthosite completely converted to maskelynite. Wolfe concluded that the higher peak shock temperatures and residual shock temperatures associated with the higher shock pressure had caused increased outgassing of argon, and consequently lower dates in the more highly shocked rocks. I concur with this conclusion.

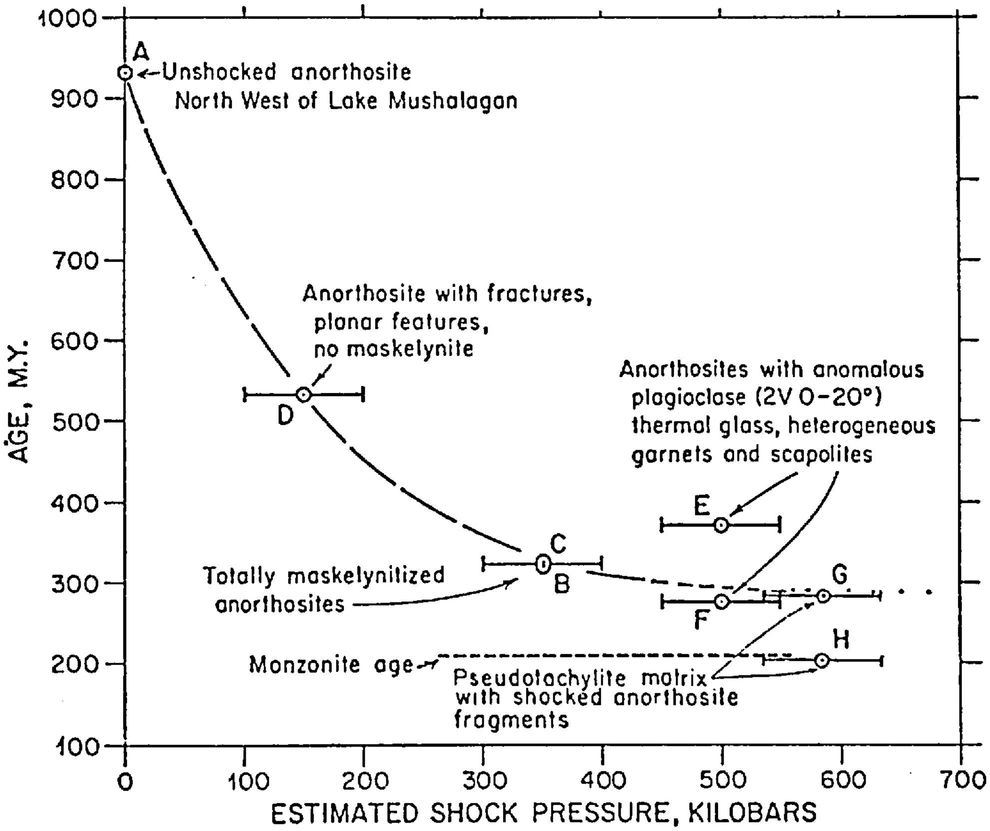


Figure 3. Ages of shocked anorthosites, pseudotachylites, and monzonite (reproduction of Wolfe's (1971) Figure 3). Circled dots are whole rock K/Ar dates. Error bars border the circles. The dashed line is Wolfe's asymptotic curve, which he suggests indicates that the time of shock metamorphism is about 280 m.y. - 300 m.y. (see text for discussion). Sample A is from Mount Brilliant. All other samples of anorthosite and pseudotachylite are from Mount de Babel.

Wolfe then drew a curve through these dates and the younger dates of samples F and G. He suggested that the asymptotic value of this curve, at about 280 m.y. to 300 m.y. was the time of shock metamorphism. I disagree with this suggestion. Samples E and F are similar anorthosites that give discordant ages; Wolfe chose sample F rather than sample E as a control point on which to base his curve. Samples G and H are similar pseudotachylites that give discordant ages; Wolfe chose sample G as a point on his curve. Wolfe recognized the difficulties with his interpretation and also suggested a second possibility. This was that if the date of sample H, 202 ± 3 m.y. is correct, then all older dates are a result of incomplete outgassing at the time of impact, and therefore the age of the shock metamorphism and the formation of the monzonite are the same. I believe that this is the correct interpretation.

In addition, Wolfe made a thermal release study of a sample of maskelynite to determine the amount of argon retention at elevated temperatures. He found that little radiogenic argon was released until 900° C, at which temperature about 30 percent was released. At a temperature of 1300° C about 95 percent of the radiogenic argon had been released, and total release was not obtained until melting. The residual shock temperatures at the pressures at which maskelynite is formed are around 900° C (Table 10). This suggests that plagioclase may be converted to maskelynite without total loss of radiogenic argon and that maskelynite samples may give anomalously high K/Ar dates.

ORIGIN OF THE MANICOUAGAN IMPACT STRUCTURE

Three different models must be considered as possible explanations of the structure and its rocks: 1) volcanic-tectonic; 2) impact; 3) impact-triggered endogenous igneous activity. In this concluding section I describe the models, and then evaluate them in the light of the evidence.

The Hypothetical Models

Volcanic-tectonic Model

Currie (1972) proposed a volcanic-tectonic model as a mode of origin for Manicouagan and interpreted the structure as a resurgent caldera. In his model, updoming of an area somewhat larger than the present structure is followed first by "radial explosions" along marginal radial fractures, and then by explosions in voids in the interior of the structure. The explosions were caused by chemical detonations of a water-poor, hydrogen-rich gas emanating from a magma at depth. Chemical detonations in voids in the fractured center of the dome caused the shatter cones, and detonations everywhere caused the shock metamorphism. Pressures were locally high because of an "opposed anvil" effect in the rocks. Droplets of magma in the gas were mixed with rock powder from the walls of fractures, and the mixture was emplaced as pseudotachylite. Degassing caused collapse of the dome. Collapse was followed by intrusion and eruption of alkali basalt and then by intrusion of monzonite (Currie's larvikite). Latite (Currie's trachyandesite) was intruded along the base of the monzonite. Mount de Babel rose on subterranean igneous rocks. Normal faulting then downdropped parts of the Manicouagan Complex.

Impact Model

There is no satisfactory theoretical model for the formation of an impact crater the size of Manicouagan. I construct here a simple and idealized model based on the following work: Rinehart (1968) discussed the theory of stress wave interaction; Doran and Linde (1966) reviewed the nature of shock waves and shock effects in solids; Bjork (1961) made a theoretical study of the formation of Meteor Crater, Arizona; Shoemaker (1963) made a geological and theoretical study of Meteor Crater; Shoemaker et al. (1963) and Gault et al. (1968) did experimental studies on the effects of hypervelocity impact of small projectiles into different target materials; Roddy (1968) compared nuclear explosion craters, chemical explosion craters, and the Flynn Creek Crater, Tennessee; Milton et al. (1972) made a detailed geological study and a brief theoretical study of the Gosses Bluff Structure, Australia; Dence (1971) made a comparative study of presumed impact melt rocks in cryptoexplosion structures. All of the above studies, except those of Milton et al. (1972) and Roddy (1968), consider only the impact of high-density high-velocity projectiles.

Hypervelocity impact causes the propagation of a shock wave downward into the target and upward into the projectile. Peak pressures and temperatures are attained in the initial stage as both the impacting body and the target are compressed and adiabatically heated. Rarefaction waves that are tensional in nature develop behind the accelerated particles and reflect from free surfaces in the target and projectile. The rarefaction waves reflected from the free surfaces interfere with the shock front, while the rarefaction waves developing behind the shock front overtake it and cause decay of the shock wave. In fact, a whole series of shock waves and rarefaction waves are developed. The shocked materials behave hydrodynamically in this initial compressional stage. Interference of shock waves and rarefaction waves causes the phenomenon of jetting, which is the high-speed ejection of shocked material at relatively low angles.

The compressional hydrodynamic stage is followed by an excavation stage during which a shell of shocked material expands outward around the interior of the forming crater. Rarefaction waves catch up with the expanding shock front, and shocked material is accelerated along complex and changing pressure gradients. Near-surface material moves in a horizontal direction, while that part of the target that is below the projectile moves downward at first, and then outward. Shocked material is sheared upward along the edge of the expanding crater, and most of this material becomes part of a steep-sided aerial cone of debris. Material from the cone that falls outside the crater is called throwout, whereas material that falls inside the crater is called fallback.

The rims of experimental craters and simple, bowl-shaped natural craters are complexly folded and faulted. Material is commonly injected into fractures in experimental targets that were pre-fractured. In addition, targets with two sets of preexisting fractures formed polygonal craters.

The final stage of crater formation is modification by slumping of rim material, fallback of ejecta, and, in TNT explosion craters, formation of a central uplift. The fallback in large natural craters would consist mostly of shocked and volatilized target material.

In the impact model, suevite and some impact melt would be emplaced on and in the floor of the primary crater during the excavation stage. Most of the impact melt would be in the form of a fiery rain of fallback and throwout. The fallback would crystallize in the crater as a layer of igneous rock.

Impact-Triggered Endogenous Igneous Activity Model

French (1970) reviewed some of the possible mechanisms by which impact might initiate endogenous igneous activity. The mechanisms are:

1) Removal of crustal material over a magma chamber.
2) Fusion or partial fusion of crustal or mantle rock that is near the pressure-melting point, because of the sudden removal of overburden and consequent decrease in lithostatic pressure.
3) Formation of a high geothermal gradient under the crater because of the insulation of heat flow by the material that fills the crater.
4) Localization of magmatic activity along fractures opened or enlarged by impact.

Any or all of the mechanisms could conceivably operate to cause later magmatic activity in a large impact crater. It is important to note that there would be a time lapse between the formation of the crater and the initiation of igneous activity.

The Shock Metamorphosed Country Rocks and the Breccias

The origin of the shock metamorphosed country rocks and the breccias of the Manicouagan Complex was discussed in detail in earlier sections, and is only summarized and evaluated here. Diaplectic glass in the rocks of shock stage II indicates that these rocks have been shocked to pressures of about 350 kb. Such pressures are far beyond the range of those generated by any known volcanic explosions. The distribution of shock effects show that shock pressures decreased radially outward from the rocks of shock stage II. Local anomalies in the distribution of shock effects in rocks of shock stage II, and elsewhere, may have been caused by different factors, including: 1) Differing shock impedances of the various minerals that are present in varying concentrations in different rock layers; 2) The complex nature of the advancing shock front as it is reflected and refracted by inhomogeneities in the rocks; 3) Folding, overturning, and faulting of rocks during the formation of the central uplift and the slumping of the rim. The evidence of the shock metamorphism in the country rocks clearly indicates that Manicouagan is an impact structure.

Suevite is a mixture of shocked and unshocked fragments, and blebs and stringers of heterogeneous glasses, in a glassy, cryptocrystalline, or clastic matrix. Earlier I proposed a model in which suevite was deposited from a turbulent cloud of volatilized, fused, and fragmented country rock that swept across the floor of the still-forming crater in the wake of the shock wave. Suevite was locally injected into the country rocks and in places mixed with the still mobile autochthonous breccia. Red breccia, which contains shocked fragments and heterogeneous glasses in a glassy matrix may have formed from shock melted rock that was not dispersed, or it may have formed as the result of local melting of shocked country rocks by heat from the igneous rocks of the Manicouagan Complex. Pseudotachylite was formed by local fusion and mobilization of shocked rocks, perhaps along inhomogeneities in the rocks, and perhaps in part because of frictional heat along shears.

It is possible that a gas-charged magma which erupted and flowed along the floor of an impact crater could incorporate a variety of shocked and unshocked fragments. It is difficult to see how a magma could produce, mix, disperse, and quench a variety of heterogeneous glasses. Conceivably, a superheated gas-charged magma might produce such a phenomenon, but such a process has not taken place in any area of unquestioned igneous activity.

The Igneous Rocks and the Contact Metamorphosed Country Rocks

The origin of igneous rocks in cryptoexplosion structures is a controversial subject, even among geologists who agree that such structures were formed by impact. Dence (1971) reviewed occurrences of igneous rocks in some cryptoexplosion structures and concluded that most of the igneous rocks were impact melt. Currie (1971) reviewed many of the same occurrences and concluded that the igneous rocks, as well as the structures, were of endogenous origin. French (1970) interpreted Sudbury as an impact structure, but concluded that the Sudbury Irruptive was a result of impact-triggered endogenous activity. Dence (1971), Murtaugh (1969b, 1972), and Floran et al. (1976), interpreted the igneous rocks of the Manicouagan Complex as impact melt. Currie (1971) interpreted them as normal igneous rocks.

One approach to the problem is to attempt to calculate the volume of the igneous rocks in the structure, and then attempt to calculate whether impact could have produced such a quantity of melt. Such calculations have been made by several authors (Beals, 1965; Dence, 1971; French, 1970). None of the attempts have been satisfactory because: 1) The amount of melt originally present in the crater is not known and is difficult to estimate; 2) The energy produced by the impact depends upon the mass, density, and velocity of the projectile, all of which are unknown and may range over wide limits; 3) The amount of energy from the impact that is partitioned as heat energy available for melting is unknown.

The basalt of the Manicouagan Complex crops out as layers that may be sills or flows, and as dikes. The basalt dikes intrude country rocks and suevite, but locally, suevite selvages (Pl. XVIII) on basalt suggest that the two rocks may have been formed contemporaneously. The basalt contains inclusions of shocked and recrystallized material, but is otherwise lithologically unremarkable. On the other hand, the tachylite that is in veins in peridotite and that forms selvages on some basalt is a peculiar rock. Earlier I described ellipsoidal and lenticular structures in the tachylite that are made up of recrystallized material, devitrified glass, or glass, and commonly show reaction with the matrix glass. Dence et al. (1974) described spheroids and deformed spheroids in glass from the West Clearwater Lake impact crater in Canada. The spheroids are interpreted as having been droplets of immiscible fluids formed and quenched in impact melt. The ellipsoids and lenticles in the tachylite at Manicouagan are similar to the spheroids from West Clearwater Lake, although they are not spheroidal and they contain recrystallized material.

The basalt might be a basal differentiate of the layer of igneous rocks made up mostly of latite and monzonite, regardless of whether those rocks are impact melt or normal igneous rocks. It might also be a completely separate rock unit of endogenous or impact origin. I interpret the basalt as impact melt from a totally vaporized or fused part of the turbulent cloud that deposited the suevite.

Latite and monzonite make up most of the layer of igneous rocks that underlies the annular plateau. These rocks also form dikes, and tabular bodies that may be sills. In order to decide whether these rocks are impact melt or normal igneous rocks, three basic questions must be considered: 1) Are the latite and monzonite a single rock unit? 2) Is the composition of the latite and monzonite such that it is possible for them to have crystallized from a melt formed by the volatilization and fusion of the country rocks? 3) Is the time of crystallization of the igneous rocks contemporaneous with the shock metamorphism? If the answer to all of these questions is yes, then it is possible to interpret them as having crystallized from an impact melt. If the answer to any question is no, then the igneous rocks must be of endogenous origin.

I have already described the latite and monzonite and the contact between them, and concluded that they form a single rock unit. Currie (1972) suggested that the latite may be intrusive into the monzonite, although his map shows the monzonite as being younger. Currie's interpretation is based, at least in part, on my preliminary work on the contact. Initially I thought the latite was intrusive, and so informed Currie.

Currie (1971, 1972) and Currie and Shaliqullah (1968) made comparisons of the average composition of the igneous rocks of the Manicouagan Complex with the average composition of the country rocks inside the structure. The comparisons are shown in Table 17. They claim that there are statistically significant differences between some of the elements in the averages. I think that their figures show that the average compositions of the two rocks are strikingly similar. It is not possible to realistically estimate the average composition of the rocks that would

TABLE 17

AVERAGES OF CHEMICAL COMPOSITIONS OF IGNEOUS ROCKS OF THE MANICOUAGAN COMPLEX AND COUNTRY ROCKS OF THE MANICOUAGAN IMPACT STRUCTURE (AFTER CURRIE, 1971 AND CURRIE AND SHAFIQULLAH, 1968)

	Average[a] of igneous rocks (monzonite and latite)	Average[a] of country rocks	Average[b] of igneous rocks (basalt, latite, monzonite)	Average[b] of country rocks
SiO_2	57.47	58.03	54.7	54.7
TiO_2	0.74	0.60	0.73	0.63
Al_2O_3	18.33	20.36	19.3	21.6
Fe_2O_3	3.42	2.18	5.47	6.3
FeO	2.63	2.73		
MgO	3.61	2.53	3.92	2.92
CaO	5.71	5.91	5.70	7.0
Na_2O	4.08	4.38	4.02	4.52
K_2O	3.02	2.77	2.95	1.80
H_2O	1.01	0.87		

[a] Currie (1971). Average composition of igneous rocks calculated from 37 analyses of monzonite and latite (Currie's larvikite and trachyandesite). Average composition of country rocks based on 38 analyses, and weighted average of the analyses calculated from Currie's reconstruction of the areal geology inside the Manicouagan Impact Structure.

[b] Currie and Shafiqullah (1968). Average composition of igneous rocks calculated from 22 analyses of basalt, latite, and monzonite. Average of country rocks based on 46 analyses and calculated as in Currie (1971) above.

have been melted by impact because of the wide chemical variability of the rocks of the area, the uncertainty as to the present areal extent of the rocks inside the structure, and the unknown area and depth of melting. The attempts at averaging merely show that it is not inconceivable that the igneous rocks of the Manicouagan Complex could have been formed by impact melting of the country rocks.

I made an X-ray fluorescence study of the Rb/Sr ratios of 27 samples of the igneous rocks of the Manicouagan Complex to try to determine a wholerock isochron age and the initial ratio of Sr^{87}/Sr^{86}. The isochron or the initial ratio might have shown whether the igneous rocks were derived from the Precambrian country rocks or from the mantle. Unfortunately the Rb/Sr ratios were too low to permit such a study. Recently, Jahn et al. (1976) used Wolfe's (1971) 210 m.y. age on monzonite to calculate an initial Sr^{87}/Sr^{86} ratio of 0.70992 for that rock. They state that such a value is high for mantle volcanoes but compatible with formation of the monzonite by melting of the country rocks.

In the section on contact metamorphism I described the peculiar nature of this metamorphism in the country rocks, and pointed out the extraordinary width of the contact metamorphic aureoles around some tabular bodies of igneous rock. I will next consider the contact metamorphism in the light of the different models proposed for the origin of the Manicouagan Impact Structure.

Wones and Eugster (1965) experimentally heated biotites and found no evidence of decomposition below 550° C. Between 600° C and 700° C biotite decomposed to sanidine, magnetite, hematite, and gas. Wittels (1952) experimentally heated amphiboles and found that a pargasite-hastingsite amphibole showed no effects of heating below 600° C, and showed only changes in thermographic curves in the temperature range 750° C to 800° C. Structural disintegration took place in the temperature range 925° C to 1145° C. Yoder (1952) showed that diopside decomposes at about 1391.5° C with a small systematic variance dependent on pressure.

The experimental work gives some idea of the minimum temperatures needed to cause the decomposition of the mafic minerals in the country rocks. It is clear that these temperatures are higher than the temperatures of normal contact metamorphism (Winkler, 1967). The aphanitic and glassy nature of some of the igneous rocks indicates that they must have been heated and cooled quickly. With the exception of the hornfelsed anorthosite and the vesiculated gneisses, none of the country rocks *in situ* show evidence of the recrystallization of felsic minerals that would be expected in normal contact metamorphism.

Jaeger (1967) calculated the temperatures that might be expected in country rocks near tabular intrusions. His calculations showed that the temperature at any distance from the intrusion is essentially a function of the temperature and the thickness of the intrusion, and the initial temperature of the country rock. The water content of each is also a factor. Winkler (1967), using Jaeger's data, calculated that at a distance equal to one-tenth the thickness of the intrusion the temperature of the country rock will be raised to a temperature about one-half the temperature of the intrusion plus the initial temperature of the country rock. At a distance equal to one-half the thickness of the intrusion the country rock will be raised to a temperature about one-third the temperature of the intrusion plus the temperature of the country rock.

The igneous rocks of the Manicouagan Complex are anhydrous. The only hydrous mineral is trace amounts of biotite in some samples of latite. The heat transfer from the igneous rocks to the country rocks must have been essentially by conduction, although water released by the decomposition of the mafic minerals would play some role.

The initial temperature of the melt from which the latite and monzonite crystallized is not known. The presence of sanidine, and quartz paramorphous after tridymite suggests that temperatures were very high.

Granted that the latite and monzonite melt was emplaced at very high temperatures, is it possible that the melt contained sufficient heat to cause all of the observed contact metamorphic effects? I described several outcrops where I measured the thickness of the igneous body and the width of the contact metamorphic aureole. In one outcrop (10.5 km, 337; Pl. XXVIII) an aureole of recrystallized plagioclase and decomposed mafic minerals as much as 23 m wide borders a dike of monzonite that is 7 m thick. In one outcrop (7 km, 262; Pls. XXIX, XXX) a dike of aphanitic igneous rock about 1 m thick is bordered by a zone of melted and vesiculated gneiss that is at least 7 m wide. In both of these cases it is inconceivable that the sole source of heat could have been the melt that crystallized to form the igneous rocks, even if that melt were superheated at the time of emplacement.

I believe that it is necessary for the country rocks to have been preheated to high temperatures in order to account for the observed contact metamorphic effects. Additional evidence for preheating is shown by the vein of pseudotachylite, only 1 mm thick, that is bordered by altered hypersthene and vitrified scapolite (Pl. XXXI). Shaw (1960) reported that Himmelbauer, in 1910, determined the melting points of different scapolites to be around 1100° C. It is inconceivable that the thin vein of pseudotachylite could have contained sufficient heat to have caused vitrification of scapolite, and then cooled to a glass.

If the country rocks were preheated, what then was the cause of the preheating? One possibility is that the rocks were in an area with a high geothermal gradient. For several reasons, I do not believe that this was the case. Some rocks containing decomposed mafic minerals are near outcrops of limestone that show no evidence of heating or deep burial. With the exception of local zeolitization, the country rocks show no evidence of hydrothermal alteration or low grade metamorphism. The abundant glass in the breccias and the glassy and aphanitic texture of many of the igneous rocks suggest that the country rocks were not deeply buried at the time of emplacement of the breccias and igneous rocks. Finally, the nature of the contact metamorphic effects, particularly the decomposition of the mafic minerals, suggests that the rocks were heated and cooled quickly, a circumstance that is unlikely if the country rocks were at depth and heated to high temperatures.

I propose that the source of the preheating was the residual shock heat from the hypervelocity impact of a cosmic body. Stöffler's (1971) estimates of residual shock temperatures for different peak shock pressures are shown in Table 10. These temperatures were derived from experimental studies of shocked quartz and feldspar by De Carli and Jamieson (1959), Wackerle (1962), Milton and De Carli (1963), De Carli and Milton (1965), Horz (1968), and Ahrens et al. (1969). The temperatures are less than 100° C for rocks of shock stage 0, between 100° C and

300° C for rocks of shock stage I, and from 300° C to 900° C for rocks of shock stage II. Chao (1968) gave approximately the same values. Ahrens et al. (1969) estimated somewhat lower temperatures based only on experimental work on feldspars.

In the impact model, rocks near the surface of the primary crater would be intruded and overlain by impact melt before the residual shock heat could dissipate. Rocks of shock stage II near the center of the structure would show greater contact metamorphic effects than rocks of shock stage 0 near the edge of the structure.

Rocks of shock stage 0 at the base of the outer edge of the annular plateau of igneous rocks would have been heated mostly by heat from the thick layer of impact melt. Temperatures would rise quickly and be dissipated into the surrounding, cooler, country rocks. The base of the impact melt would cool rapidly here, hence the aphanitic latite phase would be thick.

Rocks of shock stage II might have had a wide range of residual shock temperatures. Contact metamorphic effects would be greatest where the residual temperatures were the highest and/or where the country rocks were of a composition that melted at low temperatures. Red breccia might be formed where rocks of a low melting composition with high residual shock temperatures were overlain by the impact melt. The impact melt would cool more slowly in the interior of the structure so that the latite phase would be thin and the monzonite phase would be thick. This would account for the way that the contact between the latite and the monzonite slopes downward toward the interior of the structure.

The dikes and sub-horizontal tabular bodies of monzonite that are associated with pronounced contact metamorphic effects present a special problem. The monzonite is a very homogeneous rock. If it is impact melt, it must have formed by the mixing of all of the shock-melted rocks of the structure.

All of the tabular monzonite bodies crop out in hills around the central mountain, or in the median valley of the mountain. I suggest that the hills are blocks that fell, slid, or were propelled off of the central mountain at the time of the uplift, in the manner described by Milton et al. (1972) for similar but smaller blocks at the Gosses Bluff structure. The blocks landed in the accumulating melt and came to rest on the floor of the crater, which was at about the same elevation (currently about 2100 feet) around the mountain and in the median valley. Newly opened fractures in the blocks were filled by impact melt and impact melt underlay parts of the irregular bottoms of the blocks. The contact metamorphic zones exposed today would be related to the impact melt. Presumably, the blocks were completely enclosed in impact melt and the borders of the blocks must have been metamorphosed also, but such areas would be the first to be removed during erosion of the blocks. The contact metamorphic effects are preserved only near the dike and at the base of the blocks.

Zeolitization in the outer part of the aureoles was probably caused by hot fluids that were derived from the decomposition of the mafic minerals and driven outward by heat. Minor zeolitization in the rocks of shock stage 0 and Mount Brilliant was probably caused by hot fluids percolating downward from overlying impact breccia (suevite) or melt.

Rocks on the top of Mount de Babel show significant decomposition of mafic minerals only near veins of pseudotachylite. This suggests that Mount de Babel rose above the main body of impact melt. The zeolitization of much of the anorthosite on the top of the mountain suggests that Mount de Babel was at one time covered by some of the fallback melt.

Conclusion

The Manicouagan Impact Structure is interpreted as having been formed by the hypervelocity impact of a cosmic body. It is likely that the body was a comet. The breccias of the Manicouagan Complex were clearly formed by, or related to, the impact melt. The igneous rocks of the Manicouagan Complex may be of endogenous origin, but the field relations suggest that they were impact melt.

The Montaigne Indians who worked for me in the field as canoemen and cook were trappers in this area many years ago. They say that Mount de Babel was named by a priest who visited the area. He presumably had in mind the biblical tower of Babel. He may have been a prophet.

ECONOMIC GEOLOGY

Zeolites are the only possible mineral resource discovered in the Manicouagan Impact Structure. The zeolites identified so far are analcite, thomsonite, and chabazite. Selected occurrences of zeolites are described in the section of contact metamorphism and more occurrences are described in Murtaugh (1975). I interpret the zeolites as having formed from the action of heat and solutions from the igneous rocks of the Manicouagan Complex on the Precambrian country rocks. Regardless of the origin, areas containing abundant zeolites can be readily identified and mapped.

Zeolites are most abundant in places on the central mountain, Mount de Babel, and some of the nearby hills. They are invariably abundant near outcrops of monzonite in and near the central mountain. Analcite seems to be the most common zeolite in such occurrences. White radiating compact fibers of zeolite (probably thomsonite) makes up as much as 30 percent of the rock in places on Maskelynite Peak and on the cliff that forms the eastern edge of the central mountain. There are undoubtedly other concentrations of zeolites that were not seen because of the reconnaissance nature of the mapping. Microscopic zeolites are common in many samples of anorthosite from the central mountain.

Zeolites also occur as crystals on joint surfaces in outcrops away from the central mountain. It is unlikely that such occurrences would contain enough zeolites to warrant exploitation.

The Manicouagan structure has been relatively inaccessible in the past. The flooding of the Manicouagan reservoir and the building of a road from Manicouagan 5 dam to Gagnon improves accessibility either by barge or by truck. This might permit the development of these unique deposits of zeolites.

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