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Ontario Geological Survey

Report 166

**Geology of the
Sudbury–Manitoulin Area
Districts of Sudbury and Manitoulin**

By

K.D. Card

1978



Ontario

**Ministry of
Natural
Resources**

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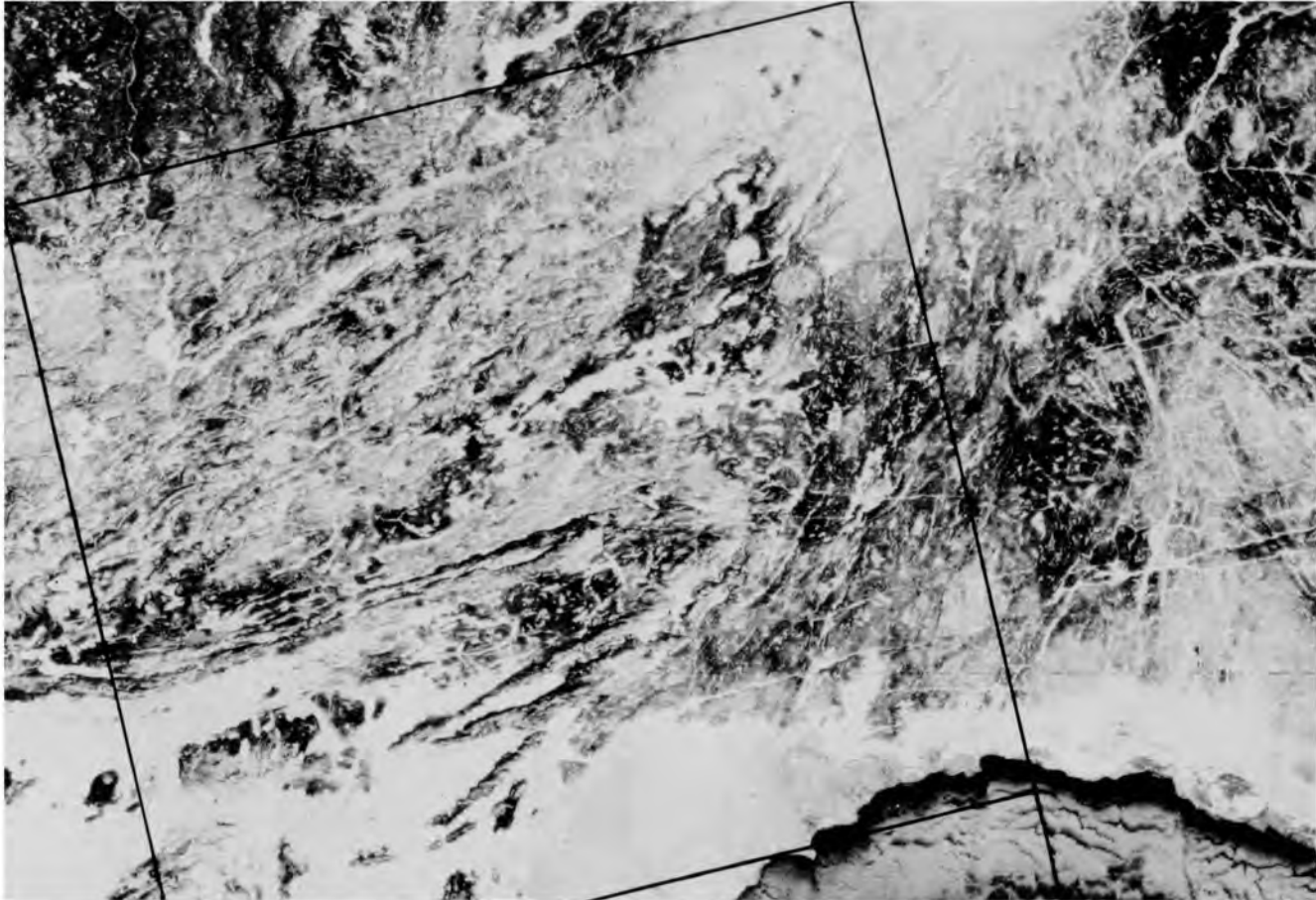


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Frontispiece—ERTZ Image of Sudbury–Manitoulin Area. Map area is outlined by dark line. "North" direction is toward top of, and parallel to the left hand margin of the image.

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A collection of rock samples and thin sections representative of the rock units described in this report are available for reference at the Department of Mineralogy and Geology, Royal Ontario Museum, Toronto.

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Review Geologist - Guy Kendrick

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GEOLOGICAL MAP

(back pocket)

Map 2360 (coloured)–Sudbury and Manitoulin Area, Districts of Sudbury and Manitoulin.

Scale 1 inch to 2 miles (1:126,720).

CHARTS

(back pocket)

Chart A (uncoloured); Figure 35

Chart B (uncoloured); Figure 32

Chart C (uncoloured); Figures 2 and 31

Chart D; Table 4

ABSTRACT

The Sudbury-Manitoulin map-area, some 2,250 square miles (5830 km²) in extent, is located immediately southwest of Sudbury, Ontario, in the North Shore of Lake Huron region (Latitudes 45°52'30"N to 46°30'N, Longitudes 81°W to 82°W). It includes parts of three geological subdivisions of the Precambrian Shield: the Superior, Southern, and Grenville Provinces; and the Precambrian rocks are bordered on the south by flat-lying Paleozoic strata which represent the northern margin of the Michigan Basin.

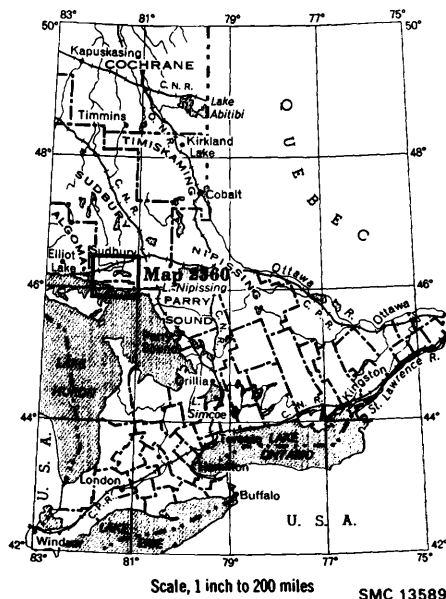


Figure 1—Key map showing location of the Sudbury-Manitoulin Area.

The Superior Province in the north is occupied mainly by Early Precambrian felsic plutons emplaced during or after the Kenoran Orogeny some 2,500 m.y. or more ago. These rocks were affected by Middle Precambrian deformation and metamorphism as is evidenced by cataclastic cleavage and granulation, retrograde mineral alterations, dike swarms, and the general lowering of the apparent radiometric ages on these Early Precambrian rocks from about Latitude 47° southwards.

The Southern Province comprises a thick (up to 40,000 feet; 12 000 m) sequence of Middle Precambrian supracrustal strata of the Huronian Supergroup which were deposited some 2,300 m.y. or more ago in fault-initiated, intracratonic basins superimposed on subsided Early Precambrian crustal blocks.

Basal volcanic accumulations of metamorphosed tholeiitic basalt, rhyolite, and pyroclastic rocks probably represent fissure eruptions controlled by early faulting along the margin of the developing depositional basins. These volcanic strata are formally subdivided herein into the Elsie Mountain, Salmay Lake, Stobie, and Copper Cliff Formations. Swarms of mafic dikes and layered Gabbro-Anorthosite Intrusions are spatially, and probably genetically, related to the volcanic accumulations.

The Huronian metasediments are dominantly coarse clastic accumulations derived mainly from the Superior Province craton to the north and deposited, for the most part, in water in fluvial-deltaic and marine neritic environments. The sequence is characterized by the following; laterally persistent

sheets of poorly sorted conglomerate of glacial or turbidite origin, turbidite-type greywacke and laminated pelitic rocks, and by thick units of relatively well-sorted quartz-feldspar sandstone with abundant crossbedding. Uranium-bearing quartz-pebble conglomerate lenses are present locally near the base of the sequence. A persistent carbonate-rich unit, the Espanola Formation, occurs in the central part; and mature orthoquartzites characterize several of the uppermost formations.

The Huronian strata are cut by mafic and felsic intrusions of several ages, including the Creighton Pluton (2,200 m.y.), Nipissing Diabase (2,150 m.y.), the Sudbury Nickel Irruptive (1,840 m.y.), the Grenville Front Plutons (1,600-1,730 m.y.), and the late diabase dikes (1,200-1,500 m.y.).

The map-area lies at the eastern end of the Penokean Fold Belt of the Southern Province, and is adjacent to the Grenville Front Tectonic Zone. The Southern Province rocks were deformed and metamorphosed during a protracted series of events which began before the emplacement of the Nipissing Diabase some 2,150 m.y. ago, and culminated approximately 1,700 to 1,800 m.y. ago with deformation and regional metamorphism. Deformation resulted in formation of east-west to north-east-southwest-trending doubly plunging folds arranged in an "en echelon" pattern, in major fault sets trending east-west, northeast and northwest, and in several generations of minor tectonic elements. Regional metamorphism was of the low pressure-intermediate type, and occurred at grades ranging from low greenschist to low amphibolite facies. Later events in the Southern Province, such as faulting, emplacement of felsic plutons, and retrograde metamorphism, are concentrated along the Grenville Front, and are probably attributable to Middle and Late Precambrian orogenic activity occurring mainly within the nearby Grenville Province.

The "Sudbury Event", either caused by explosive volcanism or meteorite impact, occurred about 1,800 m.y. ago, and resulted in excavation of a large crater, deposition of the Whitewater Group mainly within this crater, and formation of breccia, shatter cones, and microscopic shock metamorphic phenomena in the country rocks. This event probably also triggered emplacement of the Sudbury Nickel Irruptive, and its rich nickel-copper sulphide ores from depth.

The Grenville Province in the southeast is occupied by Middle Precambrian clastic metasediments, probably approximately equivalent in age to the Huronian sequence, and by Middle to Late Precambrian felsic plutons. These rocks suffered deformation and high rank regional metamorphism during the Middle and Late Precambrian. The Grenville and Southern Provinces are separated by a major northeast-trending structure, the Grenville Front Tectonic Zone, which represents a wide zone of faulting, mylonitization, flowage, and thrusting of the mobile Grenville sequence against the relatively rigid Southern Province Block. In its early stages, the Grenville Front probably constituted a paleogeographic hinge line and sedimentary facies boundary.

The region was subjected to faulting during the Late Precambrian and possibly Early Paleozoic, and some of these late faults may represent the westward continuation of the Ottawa-Bonnechere-Lake Nipissing Graben Structure.

The Precambrian rocks are bordered on the south by flat-lying Ordovician-Silurian marine limestone, dolostone, and shale. Continental glaciation during the Pleistocene Era resulted in erosion, in changes in the levels of the Great Lakes, and in deposition of a discontinuous cover of unconsolidated till, gravel, sand, and clay.

There are numerous metallic and industrial mineral deposits in the area of actual or potential economic value. Producing and past-producing mines associated with the Sudbury Nickel Irruptive include the Clarabelle, Copper Cliff North, Creighton, Crean Hill, Victoria, Worthington, and Totten Mines of INCO. These mines are, or have been, major producers of nickel, copper, iron, platinum, palladium and other commodities. In addition, there are numerous other nickel-copper and copper deposits associated with the Nickel Irruptive, with Nipissing Diabase Intrusions, and with Huronian metasediments and metavolcanics. Several of these have been in production, and potential for future production is good.

A number of occurrences of uranium and thorium occur in oligomictic quartz-pebble conglomerate bodies near the base of the Huronian sequence, and Agnew Lakes Mines Limited has outlined a deposit of this type in Hyman Township with future potential for production. Several other deposits probably warrant further exploration work.

Gold has been produced from several deposits, notably the Long Lake Mine in Eden Township, the McMillan Mine in Mongowin Township, and the Bousquet Mine in Curtin Township.

The orthoquartzites of the Lorrain and Bar River Formations represent major sources of high purity silica for metallurgical purposes and glass manufacture. Two quarries, the Lawson Quarry of INCO and the Badgeley Island Quarry of Indusmin Limited, are currently in production. Sand and gravel reserves are probably adequate for construction purposes, and the Paleozoic strata may have potential for cement manufacture.

Geology
of the
Sudbury-Manitoulin Area
Districts of Sudbury and Manitoulin

by

K.D. Card¹

INTRODUCTION

The Sudbury-Manitoulin map-area, located on the North Shore of Lake Huron in the Districts of Sudbury and Manitoulin, covers about 2,250 square miles (5830 km²) from Latitudes 45°52'30"N to 46°30'N and Longitudes 81°00'W to 82°00'W. It includes the area extending from Sudbury in the east to Webbwood in the west, the coast and islands of Lake Huron in the Whitefish Falls-Killarney-French River area, and the northeastern part of Manitoulin Island.

Access to various points is provided by Highway 17 (Sudbury to Webbwood), Highway 68 (Espanola to Manitoulin Island), Highway 69 (Sudbury south), Highway 144 (Sudbury north), Highway 549 (from Highway 17 to Lake Panache), Highway 643 (from Highway 69 to Long Lake), and Highway 637 (from Highway 69 to Killarney), by numerous township and private roads, and by water courses such as Lake Panache, Lake Huron, the Spanish River, and Agnew Lake.

The map-area includes parts of three geological provinces of the Canadian Shield (Stockwell *et al.* 1970). Early Precambrian felsic plutonic rocks of the Superior Province are exposed in the northwest. Middle Precambrian supracrustal rocks of the Huronian Supergroup constitute the central part of the area, the Southern Province. The Huronian rocks were deformed, metamorphosed, and intruded by mafic and felsic plutons, notably the Sudbury Nickel Irruptive, Nipissing Diabase, and Creighton and Grenville Front "granites", during the Middle Precambrian. Middle Precambrian metasediments and Middle to Late Precambrian felsic plutons of the Grenville Province, which were highly deformed and metamorphosed during the Middle to Late Precambrian, occur in the southeastern part of the area. To the south, the Precambrian rocks are bordered and overlain by flat-lying Paleozoic strata of Ordovician-Silurian age which represent the northern margin of the St. Lawrence Lowlands and the Michigan Basin (see Figure 1).

¹Geologist, Division of Mines, Toronto. Manuscript approved for publication by Chief Geologist, 11 Feb. 1975.

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Sudbury-Manitoulin Area

The area covered by the present report has been of interest to geologists and prospectors for over 100 years. The nickel-copper sulphide deposits associated with the Sudbury Nickel Irruption are the most economically important deposits of this type known, and since their discovery in 1883 have produced approximately 12 billion dollars worth of nickel, copper, cobalt, selenium, tellurium, platinum metals, gold, silver, iron ore, and sulphur. In addition, major amounts of silica and some gold have been produced from deposits in the Southern Province, and occurrences of base metals, silver, uranium, and tungsten also occur in this province. Occurrences of base metals, kyanite, and feldspar are present in the rocks of the Grenville Province immediately east of the present map-area.

An understanding of the regional geology is a prerequisite to deciphering the genesis of any mineral deposit, and in this context, the Sudbury-Manitoulin area includes numerous complex geological problems, many of which have a bearing on the genesis of the mineral deposits previously outlined. The map-area is located in a region where three tectonic provinces converge, a region which has had a protracted history of repeated deformation, metamorphism, and igneous intrusion. Problems associated with the following are discussed in this report: (1) the stratigraphy of the Huronian Supergroup, especially the relationship between the basal volcanic sequence and the overlying "shelf-type" sediments; (2) the nature of the contact between the Superior Province plutonic rocks and the Southern Province supracrustal sequence; (3) the age and origin of the rocks of the northwest Grenville Province; (4) the age and nature of the contact between the Southern and Grenville Provinces; and (5) the genesis of the "Sudbury structure" which includes the Sudbury Nickel Irruption, its ore deposits, rocks of the Whitewater Group, and phenomena such as shatter cones and breccias.

This report represents a synthesis of information gathered by the author and his assistants during systematic mapping in the period 1959 to 1970 of Hyman and Drury Townships (Card 1965), the Denison -Waters area (Card 1968a), the Espanola-Whitefish Falls area (Card 1976a), the McGregor Bay-Bay of Islands area (Card 1976b), the Louise-Eden area (Card *et al.* 1975), and Dunlop and Shakespeare Townships (Card and Palonen 1976). Valuable information was gained from the mapping of other townships, including data on Creighton, Fairbank, and Trill Townships (Thomson 1956), Baldwin Township (Thomson 1952), Broder Township (Grant *et al.* 1962), Porter Township (Ginn 1961), Nairn and Lorne Townships (Ginn 1965), Lake Panache-Collins Inlet area (Frarey and Cannon 1969), and Hallam, May, Harrow, and McKinnon Townships (Robertson and Siemiatkowska 1972).

Geological information on parts of McKim, Stobie, Denison, Graham, and Waters Townships was provided by The International Nickel Company of Canada Limited, of Drury Township by Falconbridge Nickel Mines Limited, of Hyman Township by Agnew Lake Mines Limited, and of Vernon Township by Texas Gulf Sulphur Company Incorporated. In addition, information was gained from these studies, especially those of Henderson (1967) in Eden and Tilton Townships, of Casshyap (1967) on the Huronian rocks of the Espanola-Whitefish Falls area, and of Innes (1972) on the stratigraphy and petrology of the Huronian volcanic rocks in the Sudbury area.

During the 1971 and 1972 field seasons, the writer and assistants carried out mapping in previously unmapped portions of the area, including parts of Ver-

non, Bigelow, Truman, and Roosevelt Townships, remapped selected areas in Baldwin, Hyman, Drury, Stobie, and McKim Townships, and measured stratigraphic sections at a number of selected localities (Card, Innes, and Debicki 1977).

Information on the Paleozoic strata of the Manitoulin Island area was taken from Liberty (1972), on magnetics from the Federal-Provincial Aeromagnetic Map Series (GSC 1965a, b, c; ODM-GSC 1972), on gravity from the work of Popelar (1971), and on surficial geology from Boissonneau (1965; 1968). Radiometric age studies by Fairbairn *et al.* (1960; 1965; 1968; 1969), Van Schmus (1965; 1971), Krogh and Davis (1969; 1972), Krogh *et al.* (1971), and Gibbins *et al.* (1972) provided valuable information on the absolute and relative ages of rock units and events.

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Unless otherwise stated, all chemical analyses in this report were done by the Mineral Research Branch, Division of Mines, and the author is most appreciative of the valuable contribution these data represent.

History, Resources, and Development

The history of human activity in this region began far back in antiquity, as Lee (1957) has described tool-working sites around Sheguiandah on Manitoulin Island which are at least 9,000 and possibly as much as 30,000 years old. Early man may have inhabited these sites before the last great glacial ice advance. The "Route of the Voyageurs", the main transcontinental canoe route used by fur traders and explorers such as La Verendrye, Champlain, and McKenzie during the 1600s, passes through the area. There were Indian villages on Manitoulin Island, Great Cloche Island, and at Killarney when these early explorers arrived. Indian graveyards have been discovered on Wardrope and Great Cloche Islands (Greenman 1951). Trading posts were established in the late 1700s and early

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1800s on Great Cloche Island by the North West Company, and on the North Shore of Lake Huron and at Whitefish Lake on I.R.6 by the Hudson's Bay Company.

Lumbering was the dominant industry of the region in the late 1800s and early 1900s, and was based on immense stands of virgin pine. Lumbering and the production of pulp, and paper are still of vital importance to the economy of the region, but are overshadowed by the mining and smelting of the Sudbury ores.

The nickel-copper sulphide deposits of the Sudbury area were discovered in 1883 during construction of the transcontinental line of the Canadian Pacific Railway. One of the railway rock cuts passes through part of what is now the Murray Mine orebody. This discovery of nickel at Sudbury was preceded by the finding of nickel-bearing sulphide minerals on the North Shore of Lake Huron by Alexander Murray in the 1840s (Murray 1847), and indeed, indications of magnetic materials were noted in 1856 by the surveyor, Salter, near the present-day Creighton Mine. For further information on the history of the area, the interested reader is referred to the Report of the Royal Ontario Nickel Commission (Knight 1917), and to Robertson and Card (1972).

The city of Sudbury, the administrative centre of the Sudbury District, and surrounding municipalities have a combined population of over 100,000 people. Two mining companies, The International Nickel Company of Canada Limited and Falconbridge Nickel Mines Limited, are the area's largest employers of manpower in their mines and smelting operations. These operations also generate much employment in the support and service industries. Sudbury is an important distribution centre for goods and services to much of northeastern Ontario.

The town of Espanola on the Spanish River is a pulp and paper manufacturing town, and a tourist and supply centre for the surrounding area. Whitefish Falls, located at the mouth of the Whitefish River in a very scenic setting, is an important tourist centre. The Lawson Quarry of The International Nickel Company of Canada Limited, an operation producing high-grade silica for use in the Sudbury-area smelting operations, is located nearby. Little Current on Manitoulin Island has good harbour facilities for the numerous pleasure craft which travel the Great Lakes each summer, and for larger lake boats bringing in goods such as coal, and taking away products such as iron ore pellets from the Sudbury operations. Killarney is also in a scenically beautiful area, has harbour and other facilities which attract numerous tourists each year, and has a nearby quarrying operation, the Indusmin Limited quarry on Badgeley Island which produces high-grade silica for glass manufacture. A few commercial fishermen operate out of Killarney and Little Current. Private summer cottages and tourist resorts are present on some of the lakes, notably Panache and Agnew Lakes, and on the islands in McGregor Bay, Bay of Islands, Frazer Bay and Killarney Bay of Lake Huron. The Government of Ontario has recently established Killarney Provincial Park which includes parts of the townships of Killarney, Roosevelt, Stalin, and Carlyle, in the southeastern part of the area.

Farming, mainly mixed dairy farming, is important in some localities, notably along Highway 17 from Sudbury to Webbwood and on Manitoulin Island.

Previous Geological Work

Early reconnaissance mapping carried out by Logan (1849), Murray (1847), Barlow (1893), Bell (1891;1892) and others delineated the major geological features of the area, especially along the North Shore of Lake Huron. Coleman (1905a; 1914), working around Sudbury, outlined the Sudbury Nickel Irruptive and its associated ore deposits, and subdivided the supracrustal rocks of the Southern Province into several formations. Coleman considered most of the Southern Province rocks south of the South Nickel Irruptive, which he termed the "Sudbury Series", to be younger than the rocks of the Grenville Province to the south, and older than the Huronian rocks to the north and west. He correlated the "Sudbury Series" with the Early Precambrian "Timiskaming Series".

Collins and his co-workers (Collins 1925; 1936) carried out extensive mapping in the North Shore of Lake Huron region, and outlined the general sequence of rock units and events, especially the stratigraphy of the Huronian sequence. Collins was undecided as to whether Coleman's "Sudbury Series" was Early Precambrian, or a part of the Huronian sequence older than his "Bruce Series".

Cook (1946) considered most of Coleman's Sudbury Series to be Huronian, and postulated that a fault separated a lower, pre-Huronian mafic volcanic sequence, which he called the "Stobie Group", from the overlying Huronian Copper Cliff rhyolite, McKim greywacke, and Ramsay Lake conglomerate.

Thomson (1952), working in Baldwin Township, recognized the conformable nature of the metavolcanic-metasedimentary sequence in that area, and suggested that extensive revisions of Collin's stratigraphic sequence were needed in the Sudbury-Espanola area. Thomson (1962) later concluded that most of the metasediments and metavolcanics of this area are of pre-Huronian age.

Ginn (1960; 1961; 1965), working in Porter, Nairn, and Lorne Townships, concluded that the felsic plutonic rocks of the "Birch Lake granite" are Early Precambrian in age, in contrast to some earlier workers, notably Tolman (1929), who regarded these rocks as post-Huronian and equivalent to the Grenville Front granites to the south. Ginn also recognized the similarity of the stratigraphic sequence in this area with the sequence outlined by Roscoe (1957) in the Huronian rocks around Blind River and Elliot Lake. Ginn concluded that an unconformity separated the metavolcanics from the metasediments in Baldwin and Porter Townships. Ginn's conclusions regarding the age of the granites and correlation of the metasediments with the Huronian rocks were supported by succeeding workers, including Card (1965; 1976b) and Young and Church (1966).

Recent work by Card and Palonen (1976) and Card, Innes, and Debicki (1977), has established that the metavolcanics in the map-area are conformable with the Huronian metasediments, and are part of the Huronian Supergroup, thus confirming Roscoe's (1969) suggestion. Huronian metavolcanics have now been recognized at a number of other localities, including the Elliot Lake, Cutler-Massey, and Thessalon areas (Frarey and Roscoe 1970; Robertson 1970a,1970b).

Interpretation of the sequence of deformational, metamorphic, and igneous intrusive events in the Southern Province, and of the relationship of these to or-

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ogenic events in the neighbouring Superior and Southern Provinces, has been assisted greatly by radiometric age determinations by the following; Van Schmus (1965), Lowdon *et al.* (1963), Fairbairn *et al.* (1960), Fairbairn *et al.* (1969), and Gibbins *et al.* (1972) and others. Card (1964) recognized the following: that the metamorphism which affected both the Huronian supracrustal rocks and Nipissing Diabase Intrusions in the Agnew Lake area is of regional extent and not caused by igneous intrusions, that irregularities in apparent metamorphic grade are related to irregular distribution of thermal metamorphic energy and to lithologic differences, not to differences in age of various rock units; and that the sequence of deformational-metamorphic events is far from being simple.

Much of the work in the Southern Province in recent years has been directed toward specific problems. Examples would include the following: studies of Huronian sedimentology and mode of deposition by Casshyap (1967; 1968; 1969; 1971), Palonen (1971; 1972), Lindsey (1967; 1969; 1971), and Young (1966; 1969; 1970; 1973); the petrology of igneous rocks such as the Nipissing Diabase (Card and Pattison 1973), the Mongowin Pluton (Card 1968b); fenites (Siemiakowska 1971), and the Huronian volcanic rocks (Innes 1972). The results of much of this work are summarized in papers by Frarey and Roscoe (1970), and Card *et al.* (1972).

The gneissic rocks of the Grenville Province were regarded by some early workers as dominantly metasedimentary, by others as mainly igneous. Quirke (1924) and Quirke and Collins (1930), concluded that gneisses of the northwestern part of the Grenville Province represent highly metamorphosed Huronian rocks, and that the "Grenville Front granites" which intrude the metasediments of both the Grenville and Southern Provinces define a Late Precambrian orogenic-plutonic event, the Killarney Orogeny.

Phemister (1960; 1961) and Grant *et al.* (1962), working in both the Southern and Grenville Provinces south of Sudbury, concluded that the Southern Province metasediments are pre-Huronian, and that the northwest boundary of the Grenville Province is in some places a fault, in other places an irregular metamorphic boundary wherein quartz-rich metasediments of the Southern Province pass by metamorphic-metasomatic transition into partly granitized paragneisses of the Grenville Province.

Henderson (1967), Brown (1968), Frarey and Cannon (1969), and others working along the Grenville Front in the Sudbury-Killarney area, disagreed with Phemister and Grant concerning the age of the Southern Province rocks, assigning these to the Huronian, and also refuted the widespread granitization postulated by Phemister.

Recent mapping by Lumbers (1971a,b; 1975) in the North Bay-Sudbury region and by Card *et al.* (1975) southwest of Sudbury has led to the conclusion that structures within the Grenville Front Tectonic Zone are dominantly of Late Precambrian age, and are superimposed on pre-existing structures in both the adjacent Grenville and Southern Provinces. Lumbers found that the only mappable boundary within this gradational tectonic zone is a fault, or series of faults, which bring highly metamorphosed gneisses of the Grenville Province into contact with relatively little metamorphosed rocks of the Southern Province. The Grenville Front Tectonic Zone has had a long history of repeated deformation and igneous intrusion extending well into the Middle Precambrian, and possibly coincides with a paleogeographic hinge line separating a miogeosynclinal-type

Huronian facies to the northwest from a eugeosynclinal-type facies to the southeast.

Early work on the Sudbury Nickel Irruptive, the Whitewater Group of the Sudbury Basin, and the rocks outside the Irruptive was carried out by Coleman (1905a), Knight (1923), Phemister (1925), Coleman *et al.* (1929), and Burrows and Rickaby (1929, 1934). Many of the early workers considered the Nickel Irruptive and Whitewater Group to be Late Precambrian in age, the Irruptive representing a folded sill or lopolith emplaced along an unconformity at the base of the Whitewater Group.

Williams (1956), and Thomson and Williams (1959) concluded that the Sudbury Nickel Irruptive represents a ring-dike intrusion and that the lower part of the Whitewater Group, the Onaping Formation, is a glowing avalanche deposit produced by explosive volcanism. Stevenson (1972) identified much of the brecciated material in the basal Onaping as quartzite, not rhyolite as concluded by Thomson and Williams (1959). Hawley (1962) summarized much of the earlier work, and gave an excellent description of the Sudbury ores.

Recent studies by Souch *et al.* (1969), Stevenson and Colgrove (1968), and Naldrett *et al.* (1970) have demonstrated that the Sudbury Nickel Irruptive is a layered intrusion, and that the ore deposits are associated with a particular part of the Irruptive, an inclusion-bearing basal unit termed the "sub-layer".

Geochronologic studies by Fairbairn *et al.* (1960; 1969) and Gibbins *et al.* (1972) have established that the Sudbury Nickel Irruptive and Whitewater Group are of Middle Precambrian age.

Studies by Fairbairn and Robson (1944), Speers (1957), and Card (1968a) on the Sudbury-type breccias outlined their general distribution and characteristics. Dietz (1964) suggested that the enigmatic breccias, along with the shatter cones so prevalent about the Sudbury structure, are the products of meteorite impact. Studies by Guy-Bray *et al.* (1966) of the shatter cones and by French (1967) and Peredery (1972), particularly in the Onaping Formation, have provided abundant evidence of phenomena of shock metamorphic origin. French (1970) suggested that meteorite impact triggered magmatic activity, resulting in the emplacement of the Sudbury Nickel Irruptive. A symposium on Sudbury geology (Guy-Bray 1972) presents further discussion of Sudbury as an astrobleme.

Gravity studies have been carried out in the Sudbury area by Popelar (1971), and paleomagnetic studies of the Sudbury Nickel Irruptive have been carried out by Sopher (1963) and others. The magnetic characteristics of the area are shown on Geological Survey of Canada Map 7067G, Sudbury (1965c). The Paleozoic geology of Manitoulin Island is shown on Ontario Division of Mines Map 2247 (Liberty 1972) and the regional surficial geology is described by Boissonneau (1965; 1968).

Physiography

The map-area is located at the contact between the southern part of the Canadian Precambrian Shield and the northern part of the Western St. Lawrence Lowlands. The Shield terrain consists of deformed rocks of Precambrian age, and is rugged in detail, but relatively even on a larger scale. The Western St.

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Lawrence Lowlands consist of undeformed Paleozoic strata which form a plain-like topography broken by cuestas.

The physiographic features of the area were formed over a long period of time, probably in excess of 1,000 million years, by various geological processes. An erosion surface, apparently of relatively low relief (approximately 300 to 1,000 feet; 90 to 300 m) was developed on Early Precambrian rocks before the deposition of the Huronian rocks. Following orogenesis and uplift in the Middle and Late Precambrian, and prior to deposition of Middle Ordovician strata, the Precambrian rocks were eroded to form a surface of low relief comparable to that of the present-day surface. This Late Precambrian-Phanerozoic surface was partly buried by Paleozoic rocks, and has been locally exhumed by post-Paleozoic erosion. Pleistocene continental glaciation has imparted features of erosion, such as scouring of the bedrock, and of deposition to the terrain. Throughout most of the map-area, Pleistocene surficial deposits form only a thin, discontinuous mantle over bedrock, and only in the northwest are they of sufficient extent and thickness to locally control drainage and subdue bedrock topography.

The recent history of the region is one of gradual uplift, isostatic rebound followed withdrawal of the Pleistocene glaciers some 10,000 to 12,000 years ago. The present Lake Huron shoreline is an emergent one, and changes in the levels of various glacial Great Lake stages are recorded by abandoned beaches. Lewis (1970) estimated that Manitoulin Island has been uplifted at a rate of 2.2 mm per year over the past 5,000 years.

The Sudbury-Manitoulin area includes parts of three physiographic subdivisions of the Canadian Shield (Bostock 1970); (1) the Abitibi Upland, which corresponds to the Superior Province; (2) the Penokean Hills, which correspond to the Southern Province; and (3) the Laurentian Highlands which correspond to the Grenville Province.

The Abitibi Upland, underlain by crystalline Early Precambrian rocks is a broad, rolling surface which within the map-area has an average elevation of about 1,200 feet (360 m) above sea level, a maximum elevation of about 1,400 feet (430 m) and an average relief of about 100 feet (30 m).

The Penokean Hills, underlain by folded Middle Precambrian strata, show that bedrock lithology and structure strongly control the topography. Sandstone units are generally resistant to erosion, and consequently form high, bare ridges; conglomeratic, pelitic, and calcareous rocks are less resistant, and consequently generally stand at lower elevations. Fault structures form narrow valleys or cliffs. The La Cloche Hills along the North Shore of Lake Huron, formed of sandstone of the Lorrain Formation, are topographically rugged, reach a maximum elevation of 1,783 feet (543.5 m) above sea level, and have an average relief of about 600 feet (180 m). Inland, the topography is more subdued, and the surface, which averages about 800 feet (240 m) above sea level, has a maximum relief of about 200 feet (60 m). In the Agnew Lake area and around the Sudbury Nickel Irruptive, the topography is again rugged, with maximum elevations of about 500 feet (150 m).

The Laurentian Highlands subdivision, which is underlain by highly deformed and metamorphosed rocks of the Grenville Province, is a topographically subdued surface which slopes southwestward toward Georgian Bay. In the

northeast, the average elevation of this surface is about 900 feet (270 m) above sea level, and in the southwest, about 700 feet (200 m). Maximum relief is about 100 feet (30 m).

The topography of Manitoulin Island, which represents the northwestern part of the St. Lawrence Lowlands, is generally flat and subdued, although some erosion-resistant Paleozoic formations form scarps several hundred feet high. The maximum elevation is about 1,075 feet (327 m) above mean sea level.

The major drainage systems in the Southern and Superior Provinces are the Spanish River, and its main tributary the Vermilion River, which drain the northern and western parts of the map-area into the North Channel of Lake Huron. The Whitefish River drains Lake Panache and other lakes in the central part of the area into the Bay of Islands of Lake Huron. The Mahzenazing, Beaverstone, and French Rivers discharge into northern Georgian Bay, and are the main drainage systems in this part of the Grenville Province. The drainage pattern is disrupted throughout the region, giving rise to numerous lakes, ponds, and swamps.

The proportion of exposed bedrock is high, probably amounting to about 50 percent of the area. Locally, as in the northwest, there are extensive, relatively thick deposits of unconsolidated Cenozoic sediments; bedrock outcrops are essentially absent in these areas. Excellent rock exposures along the North Shore of Lake Huron and on the offshore islands are probably attributable to a combination of erosion-resistant formations, and the scouring action of Pleistocene glaciers and post-glacial lakes. Abundant rock exposures around Sudbury are caused by the destruction of vegetation allowing uncontrolled erosion and removal of much of the unconsolidated surficial materials.

The topography of the Sudbury-Manitoulin map-area is shown on the following maps of the Surveys and Mapping Branch, Department of Mines and Technical Surveys, at a scale of 1:50,000: Collins Inlet (41 H/14E, 41 H/14W), published in 1965; Little Current (41 H/13E, 41 H/13W), published in 1964; Whitefish Falls (41 I/4E, 41 I/4W), Lake Panache (41 I/3E, 41 I/3W), Espanola (41 I/5E, 41 I/5W), Copper Cliff (41 I/6E, 41 I/6W). [The Whitefish Falls, Lake Panache, Espanola and Copper Cliff Maps have been superseded by the following maps published in 1975 at a scale of 1:50,000: Lake Panache (41 I/3); Whitefish Falls (41 I/4); Espanola (41 I/5); and Copper Cliff (41 I/6)].

GENERAL GEOLOGY

Geological Setting

The rocks of the Sudbury-Manitoulin area were formed by a variety of geological processes during the Early (greater than 2,500 m.y.), Middle (2,500 m. y. to 1,600 m.y.), and Late Precambrian (1,600 to 600 m.y.), and Early Phanerozoic. These rocks range in age from more than 2,500 m. y. to less than 500 m.y. In addition, the bedrock is partly covered by unconsolidated Cenozoic sediments, mainly the products of continental glaciation during the Pleistocene Epoch which began some 1 million years ago (Table 1).

Sudbury-Manitoulin Area

TABLE 1 | LITHOLOGIC UNITS AND EVENTS, SUDBURY-MANITOULIN AREA.

PHANEROZOIC CENOZOIC	Approximate Radiometric Age (M.Y.)
QUATERNARY	
RECENT	
Swamp, lake, stream deposits	
PLEISTOCENE	
Continental glaciation; erosion; deposition of sand, gravel, clay	0.1 to 1
<i>EROSION</i>	
<i>FAULTING</i>	
PALEOZOIC	
ORDOVICIAN-SILURIAN	
Limestone, dolostone, shale	
<i>EROSION-LIPPALEAN INTERVAL</i>	
<i>UNCONFORMITY</i>	
PRECAMBRIAN	
GRENVILLE PROVINCE	
LATE PRECAMBRIAN	
<i>FAULTING AND UPLIFT</i>	
LATE PEGMATITE DIKES ^c	1000
High Rank regional metamorphism and deformation (Grenville Orogeny)	1200
MIDDLE TO LATE PRECAMBRIAN	
FELSIC PLUTONIC ROCKS - quartz monzonite, granodiorite, tonalite, pegmatite	1400
MAFIC INTRUSIVE ROCKS - amphibolite, metagabbro	
<i>INTRUSIVE CONTACT</i>	
METASEDIMENTS - Biotite and quartz-feldspar gneiss, coarse clastic, siliceous, and calcareous metasediments	
<i>FAULTING</i>	
SOUTHERN PROVINCE	
LATE PRECAMBRIAN	
MAFIC INTRUSIVE ROCKS	
Diabase dikes ^a	
Amphibolite, metagabbro, trap, lamprophyre dikes ^b	1200-1400?
Fenite Breccia	
MIDDLE TO LATE PRECAMBRIAN	
MONGOWIN PLUTON - peridotite, granophyric trondhjemite	1770

Table 1 - continued

	Approximate Radiometric Age (M.Y.)
EDEN LAKE PLUTONS - trondhjemite, diorite, gabbro	
GRENVILLE FRONT PLUTONS - quartz monzonite, quartz diorite, granodiorite	1600-1730
<i>INTRUSIVE CONTACT</i>	
Regional metamorphism and deformation ("Hudsonian-Penokean" Orogeny)	
MIDDLE PRECAMBRIAN	
SUDBURY NICKEL IRRUPTIVE - norite, gabbro, granophyre	1840
<i>INTRUSIVE CONTACT</i>	
WHITEWATER GROUP - Onaping Formation, tuff-breccia	
Sudbury Event - explosive volcanism or meteorite impact ? Sudbury Breccia etc.	1840-2000
NIPISSING DIABASE - gabbro, metagabbro, granophyre	2150
<i>EARLY DEFORMATION</i>	
CREIGHTON PLUTON - quartz monzonite, granite	2200
<i>INTRUSIVE CONTACT</i>	
HURONIAN SUPERGROUP	
COBALT GROUP	
Bar River Formation - sandstone, siltstone	
Gordon Lake Formation - siltstone, argillite, sandstone	
Lorrain Formation - sandstone, minor conglomerate and siltstone	
Gowganda Formation - conglomerate, argillite, siltstone, sandstone	
<i>LOCAL DISCONFORMITY</i>	
QUIRKE LAKE GROUP	
Serpent Formation - sandstone, siltstone, limestone, conglomerate	
Espanola Formation - limestone, dolostone, siltstone, sandstone	
Bruce Formation - conglomerate, sandstone, siltstone	
<i>LOCAL DISCONFORMITY</i>	
HOUGH LAKE GROUP	
Mississagi Formation - sandstone, siltstone, argillite, conglomerate	
Pecors Formation - siltstone, argillite, sandstone	
Ramsay Lake Formation - conglomerate, sandstone, siltstone	
<i>LOCAL DISCONFORMITY</i>	
ELLIOT LAKE GROUP	
McKim Formation - argillite, siltstone, sandstone	
Matinenda Formation - sandstone, siltstone, argillite, conglomerate	
Copper Cliff Formation - rhyolite, dacite, felsic intrusions, porphyry, crystal tuff, and pyroclastics, minor metabasalt and metasediments	
Stobie Formation - metabasalt, fragmental mafic metavolcanics, mafic schist, metasediments	
Salmay Lake Formation - metabasalt, fragmental mafic metavolcanics, metasediments	
Elsie Mountain Formation - metabasalt, minor metasediments	

continued next page

Table 1 – continued

MAFIC INTRUSIVE ROCKS

Gabbro Anorthosite Plutons - gabbro, metagabbro, anorthositic
gabbro, gabbroic anorthosite, syenite
- amphibolite and metagabbro dikes

INTRUSIVE CONTACT; FAULTING; EROSION

EARLY PRECAMBRIAN

SUPERIOR PROVINCE

FELSIC PLUTONIC AND MIGMATITIC ROCKS

"BIRCH LAKE BATHOLITH" - quartz monzonite, granodiorite, granite, +2500 m.y.
quartz diorite and migmatitic granitic rocks

Kenoran Orogeny

^aDiabase dikes of more than one age may be present. Some dikes in the Grenville Province may be of Early Paleozoic age.

^bSome are pre-regional metamorphism (Penokean-Hudsonian); others are post-metamorphism.

^cNot shown on map.

The rocks of the Superior Province, exposed in the northwestern part of the map-area, are mainly Early Precambrian felsic plutonic rocks, presumably emplaced during the Kenoran Orogeny some 2,500 m.y. or more ago (Stockwell *et al.* 1970). The felsic plutons are cut by mafic dikes and layered Gabbro-Anorthositic Intrusions of late Early Precambrian or early Middle Precambrian age.

The Southern Province, in the central part of the area, is occupied mainly by clastic metasediments and metavolcanics of the Huronian Supergroup that were deposited during the early part of the Middle Precambrian. The contact between the Southern Province supracrustal rocks and the Superior Province felsic plutonic rocks is a deformed unconformity.

The Huronian rocks were affected by several deformational-metamorphic events, mainly during the early Middle Precambrian when they were folded and faulted to nearly vertical positions, thrust against the relatively rigid Superior Province block, and metamorphosed under conditions corresponding to the greenschist and amphibolite facies of regional metamorphism. These rocks were intruded by a variety of mafic and felsic plutons, such as the early Middle Precambrian Nipissing Diabase and Creighton Pluton, the Middle Precambrian Grenville Front Plutons, and the Late Precambrian diabase dikes of the Sudbury Swarm.

The southwestern part of the Sudbury Nickel Irruptive, a layered mafic-felsic intrusion of Middle Precambrian age, is exposed in the northeastern part of the map-area where it has intruded rocks of the Superior and Southern Prov-

inices and rocks of the Middle Precambrian Whitewater Group of the Sudbury Basin. Associated with the Sudbury Nickel Irruptive are major deposits of nickel and copper, and display phenomena of enigmatic origin such as shatter cones and Sudbury-type breccias.

The Grenville Province to the southeast is occupied by Middle Precambrian clastic metasediments, probably equivalent in age to the Huronian rocks of the Southern Province, and by Middle to Late Precambrian felsic plutons. These rocks were highly deformed and metamorphosed (in the almandine-amphibolite facies), mainly during the Late Precambrian, although there is some evidence for Middle Precambrian deformation and metamorphism associated with plutonic activity. The Grenville and Southern Provinces are separated by a major north-east-trending tectonic zone, the Grenville Front Tectonic Zone, one of the major regional structures of the Canadian Shield (Lumbers 1971b). In the Sudbury area, the Grenville Front Tectonic Zone is up to 20 miles (32 km) wide, and is characterized by northeast-trending foliations and southward-plunging lineations; these structural elements are superimposed upon pre-existing structures in both the adjacent Southern and Grenville Provinces. Although there is evidence of Middle Precambrian deformation and metamorphism within the Grenville Front Tectonic Zone, the major deformation is apparently of Late Precambrian age. During the Late Precambrian, the Grenville Province rocks were faulted and compressed against the relatively rigid Southern Province block, bringing highly deformed and metamorphosed rocks on the southeast into juxtaposition with mildly deformed and metamorphosed rocks on the northwest. During deposition of the early Middle Precambrian supracrustal sequences, the zone may have constituted a paleogeographic boundary or hinge line separating a miogeosynclinal-type sedimentary facies to the northwest from a eugeosynclinal-type facies to the southeast. The Grenville Front Tectonic Zone was also the locus of intrusive igneous activity during the Middle and Late Precambrian, with the emplacement of felsic plutons and mafic dikes.

Following Late Precambrian regional metamorphism and plutonism in the Grenville Province, the region was subjected to faulting during the Late Precambrian and Early Paleozoic. Lumbers (1971a,b) concluded that mafic stocks and lamprophyre dikes that occur in the Grenville Province to the east of the map-area are of Early Paleozoic age, and are related to an east-trending graben structure in the Lake Nipissing area.

Superior Province

EARLY PRECAMBRIAN

Felsic Plutonic and Migmatitic Rocks

Felsic plutonic rocks of general quartz monzonite composition exposed in the northwestern part of the map-area were named the "Birch Lake granite" by Tolman (1929) for the area around Birch (now Gough) Lake, Gough Township.

Sudbury-Manitoulin Area

These rocks were emplaced during the Early Precambrian, some 2,500 m.y. or more ago (Van Schmus 1965), and constitute the southern, exposed margin of the Superior Province. They also constitute the basement upon which the succeeding Middle Precambrian supracrustal sequences were deposited.

Tolman (1929) and Collins (1936) concluded that the Birch Lake Batholith is younger than the Huronian rocks, mainly on the basis of the occurrences of metasedimentary and mafic igneous xenoliths within the batholith, and on the similarity of these "granites" to the post-Huronian Killarney granites.

More recent work by Ginn (1960) and Card (1965) has established that the Birch Lake Batholith is older than the Huronian metasediments. Much of the field evidence for a pre-Huronian age of the batholith is negative, particularly the lack of any phenomena indicative of intrusive relationships. Even Tolman (1929) remarked upon the "regularity" of the granite-metasediment contact, the lack of apophyses of granite, and the absence of contact effects. The nature of the granite-metasediment contact is obscured by shearing and faulting, but the original unconformity is preserved at several localities in Vernon, Porter, and Hyman Townships (Ginn 1960; Card 1965).

A number of small felsic bodies, most of which are too small to be shown at the present map-scale, apparently intrude the Huronian rocks in Baldwin, Porter, and Hyman Townships (Ginn 1960; Thomson 1952). Investigation of these by Ginn (1960) and the writer has established that most are compositionally different from the Birch Lake quartz monzonite and are not genetically related to this intrusion. Some are felsic hypabyssal intrusions, flows, and pyroclastic units related to the Huronian volcanic accumulations, others represent zones of feldspathization of the Huronian metasediments, and still others are felsic differentiates of mafic intrusions. Those bodies in western Hyman and eastern Shakespeare Townships probably represent exposures of the pre-Huronian granitic basement along faults and in the axial zones of folds.

In Hyman and Drury Townships, Card (1965) concluded that whereas in the west the contact between the Huronian metasediments and the Birch Lake granite represents a deformed unconformity, in the east, these same granitic rocks apparently intrude rocks of the metavolcanic group. Furthermore, no evidence could be found for an unconformity between the metasediments and metavolcanics. Further work in the region has led to a solution of this conundrum with the recognition of a group of layered, sill-like Gabbro-Anorthosite Plutons which occur locally at the base of the Huronian sequence and intrude the Birch Lake Batholith. Age relationships between the mafic plutons and the granitic rocks are complicated because the contact zones consist of ramifying mafic intrusions and large xenoliths of granitic rocks, many of which show the effects of partial fusion and remobilization. The problem in Drury Township arose because of the failure to distinguish the Gabbro-Anorthosite Plutons from the metavolcanics and to recognize the true age relationships of this intrusion with the older granitic rocks.

The Birch Lake Batholith shows the effects of the Middle Precambrian deformation and metamorphism which also affected the younger Huronian rocks. These effects are concentrated near the granite-metasediment contact and include development of joints, shear zones, quartz veins, and breccia, local development of augen gneiss and mylonite, and pervasive cataclasis and alteration of primary minerals of the batholith. Mafic dike swarms are prevalent in the south-

ern part of the batholith, and, like the deformational-metamorphic effects, decrease in abundance northward. Emplacement of the dike swarm is probably related to the brittle deformation of the granitic rocks, and some may be genetically related to basal Huronian volcanic accumulations. Van Schmus (1965) has demonstrated in areas to the west that the effects of Middle Precambrian orogenic events, in the form of lowering of apparent radiometric age of the Superior Province rocks, extend northward to about Latitude 47° (Figure 2, Chart C, back pocket).

The Birch Lake Batholith consists of leucocratic granitic rocks with a few, scattered xenoliths of biotite- and hornblende-rich mafic rocks, granitoid gneiss, and quartz-rich metasediments ranging from a few inches (5 cm) to a few hundred feet in maximum dimension. Minor amounts of pegmatite in the form of dikes and irregular patches are also present. The granitic rocks range in composition from granodiorite to granite, but quartz monzonite is by far the most abundant rock type.

The Birch Lake quartz monzonite is a massive to gneissic equigranular to porphyritic, medium- to coarse-grained rock consisting of approximately equal proportions of quartz, plagioclase, and perthitic microcline with minor amounts of biotite, chlorite, muscovite, apatite, tourmaline, sphene, iron-titanium oxides, and sulphide minerals (Table 2). The porphyritic texture is formed by perthitic microcline phenocrysts up to several cm in length. The plagioclase, originally oligoclase in average composition, is intensely saussuritised and most of the samples studied also show evidence of cataclasis and granulation.

Although quartz monzonite varies from red to pink to grey, from medium to very coarse grained, and in texture from equigranular to porphyritic, its mineralogical and chemical composition is relatively uniform (Figure 3 and Table 2). This compositional uniformity, as well as intergradational contact relationships, indicate that the varieties of quartz monzonite are co-magmatic and emplaced contemporaneously. The colour variations are mainly caused by the degree of alteration of the feldspars and by hematite staining, although Tolman (1929) found that the red varieties contain slightly more potassic feldspar than do the grey varieties of quartz monzonite.

There are some dike-like or irregular masses of pink, equigranular, and porphyritic granite throughout the batholith which probably represent late-stage intrusions.

Hybrid granitic rocks, including gneissic and migmatitic granodiorite, quartz monzonite, and diorite in northern Drury Township and adjacent Trill Township, are part of the "Levack gneiss complex", a belt of high-rank metamorphic gneisses adjacent to the north range of the Sudbury Nickel Irruptive (see GSC 1946a).

The hybrid granitic rocks are of highly variable composition, ranging from diorite or quartz diorite to quartz monzonite, and contain appreciable amounts of mafic material in the form of mafic layers, schlieren, and sharply defined inclusions. The gneisses and migmatites are also intruded by dike-like and irregular masses of relatively homogeneous quartz monzonite and granite. In the Leinster-Bowell area to the north, the "Levack gneiss complex" locally shows mineral assemblages indicative of metamorphism in the pyroxene granulite facies (Card and Meyn 1969), but if such assemblages did exist in the present map-area, retrograde metamorphism has destroyed them.

Sudbury-Manitoulin Area

TABLE 2 | CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF ROCKS OF THE BIRCH LAKE BATHOLITH, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Sample Number	Modal Analyses in percent				
	A		B		C
	Average	Range	Average	Range	Average
Quartz	30.1	23-40	29.0	21-45	32.1
Potassic Feldspar	28.1	24-43	47.0	38-54	16.0
Plagioclase	35.9	24-46	17.0	10-22	45.0
Biotite					
Chlorite	3.5	0.5-8.5	5.8	3-6	6.4
Muscovite	1.6	0.5-3	0.5	0-3	
Accessories	0.8	0-2.5	0.7	0-1	0.5
Plagioclase Composition	Albite-oligoclase		Albite-oligoclase		Albite-oligoclase

Sample Number	Major Components in percent			Trace Elements in ppm (for Sample 1)	
	1	2	3		
SiO ₂	72.80	72.01	71.63	Ba	1000
Al ₂ O ₃	14.20	17.70	16.00	Co	.4
Fe ₂ O ₃	0.40	0.28	0.07	Cr	20
FeO	0.86	1.11	1.08	Cu	.6
MgO	0.65	0.37	0.40	Ga	30
CaO	0.65	.094	1.48	Ni	.5
Na ₂ O	3.84	2.64	3.06	Pb	15
K ₂ O	4.58	4.02	4.76	Sr	150
H ₂ O ⁺	0.64	0.52	0.56	U	10
H ₂ O ⁻	0.07	0.22	0.22	Y	30
CO ₂	0.20	1.02	0.97	Zn	30
TiO ₂	0.18	0.13	0.13	Zr	.5
MnO	0.03	0.01	-	Be	.5
P ₂ O ₅	0.04	0.15	-		
S	0.01	0.03	-		
ZrO ₂	8.50	0.07	-		
Total	99.10	100.96	100.26		
Specific Gravity	2.62	N.D.	N.D.		

Notes

- A 30 quartz monzonites, Shakespeare, Baldwin, Dunlop, Porter, Hyman, and Drury Townships.
- B 4 granites, Shakespeare, Baldwin, and Hyman Townships.
- C 2 gneissic granodiorites, Drury and Shakespeare Townships.

Abbreviations

- Not detected
- N.D. Not detected

Table 2 - continued

Norms in weight percent			
Sample Number	1	2	3
Apatite	0.094	0.35	0.00
Pyrrhotite	0.028	0.83	0.00
Ilmenite	0.348	0.25	0.25
Orthoclase	27.577	23.93	28.55
Albite	33.073	22.47	26.26
Anorthite	3.016	3.71	7.45
Corundum	1.869	7.70	3.16
Acmite	0.000	0.00	0.00
Magnetite	0.590	0.41	0.10
Hematite	0.000	0.00	0.00
Wollastonite	0.000	0.00	0.00
Enstatite	1.648	0.93	1.01
Ferrosilite	0.984	1.50	1.74
Quartz	30.773	38.68	31.49
Diopside	0.00	0.00	0.00
Colour Index	3.57	3.08	3.10
Normative Plagioclase Composition	7.92	13.45	21.09

Notes - Chemical Analyses and Norms

1. Porphyritic quartz monzonite, Shakespeare Township.
2. Red quartz monzonite, Bigelow Township (From Tolman, 1929).
3. Grey quartz monzonite, Hyman Township (From Tolman, 1929).

ORIGIN OF THE GRANITIC ROCKS

The granitic rocks of the Birch Lake Batholith were probably emplaced during the Kenoran Orogeny (Stockwell *et al.* 1970) some 2,500 m.y. or more ago as relatively homogeneous, magmatic, intrusions at moderate (mesozonal) crustal levels. Variations in grain size and texture are probably attributable to variations in cooling history for the most part, although there is evidence locally for granitic intrusions of more than one age. Isotopic studies by Fairbairn *et al.* (1965) in the area west of Sudbury indicate that the Birch Lake intrusions have a low initial Sr^{87}/Sr^{86} ratio ($0.706 \pm .001$), indicating little or no contamination by radiogenic crustal materials. The gneissic and migmatitic rocks on the other hand probably represent highly metamorphosed and metasomatized Early Precambrian rocks, mainly volcanic and related sedimentary rocks into which the magmatic rocks were emplaced.

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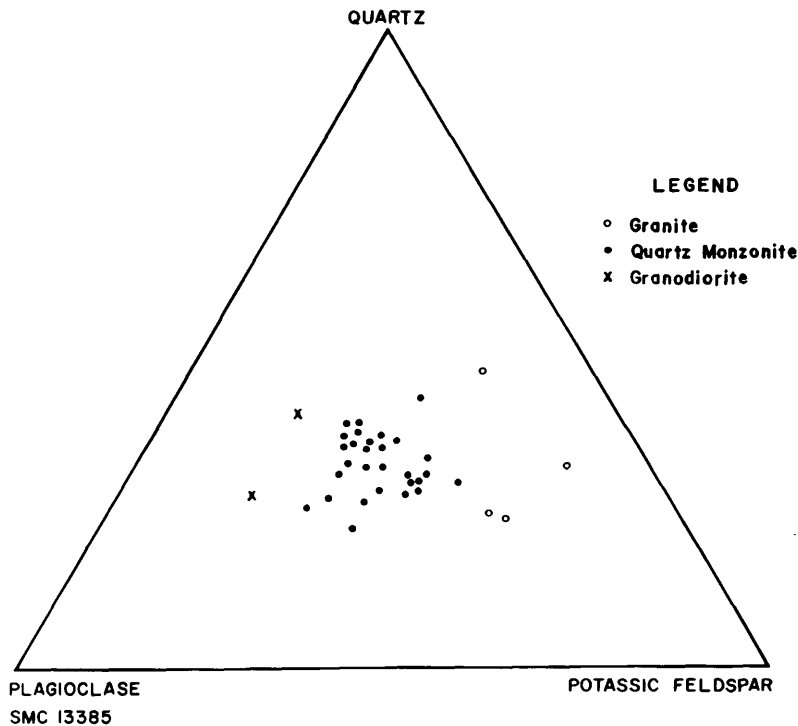


Figure 3—Ternary diagram showing modes of quartz, potassic feldspar, and plagioclase of felsic plutonic rocks of the Birch Lake Batholith; Sudbury-Manitoulin Area.

Southern Province

MIDDLE PRECAMBRIAN

Mafic Intrusive Rocks

Layered Gabbro-Anorthosite Plutons, swarms of mafic dikes, and sill-like bodies of amphibolite occur in the northern part of the map-area at, and near, the contact between the Superior Province felsic plutonic rocks and the Southern Province supracrustal sequence. These mafic bodies intrude the Early Precambrian rocks, and are spatially associated with the Middle Precambrian volcanic accumulations. Their absolute age is unknown, but field relations indicate that these mafic bodies were emplaced at about the same time as the Huronian volcanic rocks during the early part of the Middle Precambrian.

GABBRO-ANORTHOSITE PLUTONS

Layered, sill-like or lopolithic bodies of gabbro-anorthosite occur along the Huronian-pre-Huronian contact in May, Baldwin, Shakespeare, Dunlop, Drury, and Hyman Townships where they intrude granitic rocks of the Birch Lake Batholith. Their contacts with the granitic rocks are irregular, and numerous dikes and apophyses of gabbro extend outward into the batholith. The mafic plutons show chilled marginal zones containing granitic xenoliths, many of which show evidence of partial melting and remobilization.

The contact relationships are not well-defined between the Gabbro-Anorthosite Plutons and the overlying Huronian rocks which are mainly composed of metavolcanics. In most localities, there appears to be a gradation from coarse-grained gabbro-anorthosite, through medium-grained massive mafic rocks of basaltic composition which could represent either intrusions, thick flows, or both, to metabasaltic flows with intercalated metasediments. On the western shore of Agnew Lake near the boundary between Shakespeare and Dunlop Townships, gently dipping pebbly sandstone of the Matinenda Formation overlies sheared mafic rocks which grade westward into a coarse-grained gabbro-anorthosite. This contact may represent a sheared unconformity.

The Gabbro-Anorthosite Plutons consist of amphibolite, gabbro, metagabbro, anorthositic gabbro, and gabbroic anorthosite with minor amounts of syenitic and granitic material in the form of dikes and segregations. The mafic rocks are composed of variable proportions of plagioclase and feric minerals, with minor amounts of quartz, granophyre, biotite, chlorite, sphene, and iron-titanium oxides (Table 3). The plagioclase, originally a calcic variety (labradorite-bytownite) has been extensively saussuritized. The feric minerals, mainly actinolite and blue-green hornblende, probably represent the alteration products of pyroxenes. Remnant augite is present in some of the rocks examined microscopically. These coarse to very coarse grained rocks display equigranular, porphyritic, and glomeroporphyritic textures; rapid variations in grain-size and texture are characteristic of them.

The syenitic dikes and segregations are equigranular, medium grained, and consist mainly of albite with minor biotite, amphibole, chlorite, muscovite, epidote, sphene, and iron-titanium oxides. The granitic varieties are similar except, for the presence of quartz which commonly forms granophyric intergrowths with alkali feldspar.

Chemical analyses and normative compositions of typical gabbro-anorthosite rocks are given in Table 3. These, and plots of various compositional parameters show that they are subalkaline and tholeiitic, and are compositionally similar to the Huronian mafic volcanic rocks. In Figure 5a (weight percent SiO_2 versus weight percent $\text{Na}_2\text{O} + \text{K}_2\text{O}$), the gabbro-anorthosite rocks are closely grouped with the mafic volcanic rocks in the subalkaline field and in Figure 5b (weight percent Al_2O_3 versus normative plagioclase composition), the gabbroic rocks are grouped with the metabasalts in the tholeiitic field (see Figure 5a and 5b). Gabbroic anorthosite and syenite (albitite), both of which are strongly enriched in plagioclase, are in the calc-alkaline field.

Magmatic layering is present in all of the plutons but is best developed and

Sudbury-Manitoulin Area

TABLE 3 | **CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF EARLY MAFIC INTRUSIVE ROCKS, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.**

Major Components in Weight Percent						
Sample Number	1	2	3	4	5	6
SiO ₂	52.00	51.80	51.40	55.40	64.30	48.76
Al ₂ O ₃	14.40	18.80	16.80	22.30	17.80	23.59
Fe ₂ O ₃	1.22	1.43	2.74	1.98	0.06	4.26
FeO	7.23	5.63	8.41	3.18	1.67	3.24
MgO	8.60	6.90	3.74	2.11	0.80	3.78
CaO	10.70	11.00	10.60	9.90	3.34	11.78
Na ₂ O	2.62	1.64	2.13	3.24	9.23	2.81
K ₂ O	0.39	0.43	0.89	0.64	0.79	0.49
H ₂ O ⁺	1.56	1.69	1.21	0.69	0.41	1.32
H ₂ O ⁻	0.07	0.08	0.08	0.06	0.14	-
CO ₂	0.06	0.20	0.26	0.25	2.36	0.08
TiO ₂	0.36	0.19	1.37	0.55	0.23	0.06
P ₂ O ₅	0.04	0.02	0.07	0.02	0.05	0.06
S	0.01	0.01	0.05	0.01	0.01	-
MnO	0.18	0.12	0.18	0.08	0.06	0.07
Total	99.44	99.94	99.93	100.41	101.25	100.33
Specific Gravity	2.98	2.83	2.97	2.85	2.57	2.91

Trace Elements in ppm						
Ba	--	150	200	250	--	--
Co	40	40	50	16	6	6
Cr	250	100	40	80	10	10
Cu	30	30	150	40	8	8
Ga	15	15	20	30	10	10
Ni	130	230	80	60	20	20
Pb	10	10	10	10	10	10
Sc	40	20	25	20	--	--
Sr	300	300	250	300	250	250
V	100	100	400	200	20	20
Y	--	20	20	20	--	--
Zn	70	50	100	40	20	20
Zr	30	50	40	40	50	50
Be	--	--	--	--	3	3

Norms in weight percent						
Quartz	0.00	5.36	6.58	9.29	0.63	0.00
Corundum	0.00	0.00	0.00	0.00	0.00	0.00
Orthoclase	2.36	2.60	5.35	3.81	4.75	2.94
Albite	22.68	14.16	18.32	27.58	79.42	24.09
Anorthite	26.99	43.55	34.21	44.68	4.89	50.99
Diopside	14.77	6.68	7.69	2.40	4.37	3.53
Hypersthene	7.20	3.06	7.95	1.35	5.18	2.95
Enstatite	14.81	14.44	5.91	4.18	0.00	2.80
Ferrosilite	8.27	7.59	7.00	2.70	0.00	2.68
Forsterite	0.18	0.00	0.00	0.00	0.00	3.58
Fayalite	0.11	0.00	0.00	0.00	0.00	3.78
Wollastonite	0.00	0.00	0.00	0.00	0.09	0.00

Table 3 – continued

Sample Number	1	2	3	4	5	6
Magnetite	1.81	2.12	4.04	2.89	0.09	2.34
Ilmenite	0.70	0.37	2.65	1.05	0.44	0.17
Chromite	0.00	0.00	0.00	0.00	0.00	0.02
Apatite	0.09	0.05	0.17	0.05	0.12	0.14
Pyrrhotite	0.03	0.03	0.14	0.03	0.03	0.00
Differentiation Index	25.04	22.12	30.25	40.68	84.80	27.03
Colour Index	47.85	34.26	35.23	14.57	10.08	21.83

Abbreviations

-- Present below detection limits

- Not detected

Notes

1. Metagabbro, Baldwin Township.
2. Partly altered pyroxene-bearing anorthositic metagabbro, Shakespeare Township.
3. Anorthositic metagabbro, Shakespeare Township.
4. Gabbroic anorthosite, Shakespeare Township.
5. Syenite (albitite) Baldwin Township.
6. Gabbroic anorthosite, Drury Township.

Modal Analyses (Volume Percent)

Sample Number	A	B	C	D	E	F	G	H	I
Plagioclase	41.0	23.6	56	68	81.4	8.0	22	51	12
Amphibole	34.8	60.0	40	15	-	74.9	28	28	49
Pyroxene	3.1	-	-	-	-	-	-	-	-
Quartz	-	-	1	3	-	-	6	-	-
Granophyre	12.5	2.7	-	-	-	-	-	-	-
Biotite	-	7.8	-	-	-	-	-	-	-
Chlorite	-	-	2	9	11.7	-	8	x	3
Muscovite	-	-	-	-	-	5.1	-	x	11
Epidote	x	-	-	-	-	-	31	21	24
Sphene	8.6	5.9	1	5	4.3	-	-	-	-
Iron-Titanium Oxides	-	-	-	-	2.6	1.0	1	-	1
Calcite	x	-	-	-	-	11.0	4	-	-
Zircon	-	-	-	-	x	-	-	-	-
Apatite	-	-	-	-	x	-	-	-	-
Plagioclase Composition	An _{60±5}	Labradorite	-	-	Albite	-	-	-	-

Abbreviations

- Not detected

x Trace amounts

Notes

- (A) Partly altered pyroxene gabbro, Shakespeare Township.
- (B) Mafic metagabbro, Shakespeare Township.
- (C) Metagabbro (average of 3), Shakespeare and Dunlop Townships.
- (D) Anorthositic gabbro and gabbroic anorthosite (average of 4).
- (E) Syenitic (albitite) segregation, Dunlop Township.
- (F) Amphibolite, Drury Township.
- (G) Metagabbro, Drury Township.
- (H) Anorthositic gabbro, Drury Township.
- (I) Porphyritic mafic dike (average of 2), Drury Township.



OOM9572

Photo 1—Layering in gabbro-anorthosite, Dunlop Township.

preserved in the Dunlop body (Photo 1). Individual layers range in thickness from a few inches (5 cm) to several hundred feet (90 m), and are expressed by variations in modal composition, grain size, and texture. Some layers display oriented tabular plagioclase grains; others have a graded appearance due to gradual increase in the proportion of plagioclase from bottom to top.

In the Dunlop Township Gabbro-Anorthosite Pluton, the attitude of the layering is crudely conformable with the contacts of the body, indicating that it is possibly a funnel-shaped lopolithic intrusion. Gravity measurements (Popelar 1971) show that there is a close correlation between gabbro-anorthosite bodies and positive gravity anomalies, an indication that these intrusions have considerable mass.

The Gabbro-Anorthosite Plutons represent magmatic intrusions emplaced at relatively high crustal levels in the form of sill-like or lopolithic bodies. Magmatic differentiation, mainly gravitative settling of early formed plagioclase, was operative during emplacement. The spatial and chemical relationships between the plutons and the Huronian mafic volcanic accumulations indicate a genetic relationship between the two.

MAFIC DIKES

Metamorphosed mafic dikes of several petrographic varieties, and probably of several ages, intrude the Birch Lake Batholith and the Gabbro-Anorthosite

Plutons. Most dikes apparently do not penetrate the overlying Huronian metasediments and are considered to be older. Locally, as in northeastern Porter Township, mafic dikes intrude the Birch Lake Batholith and the Huronian metasediments, and are consequently correlated with the Middle Precambrian Nipissing Diabase Intrusions.

The dikes, which range in thickness from about 5 to 100 feet (1.5 to 30 m), commonly occur as swarms of several, approximately parallel dikes. Dike sets striking northwest, east-west, and northeast are present. These preferred orientations indicate control of dike emplacement by pre-existing structures such as joints in the host rocks. Contacts of the dikes with the granitic rocks are sharp and regular. The wall rocks show little or no evidence of contact metamorphism.

Most of the dikes are dark green to black, fine- to medium-grained metagabbro or amphibolite consisting of hornblende (35 to 80 percent), plagioclase (15 to 50 percent), and biotite (0 to 15 percent) with minor amounts of quartz, chlorite, apatite, epidote, sphene, iron-titanium oxides, and sulphide minerals. Plagioclase, originally a calcic variety, is altered to albite, white mica, epidote, and carbonate. The porphyritic dikes are mineralogically similar except for ovoid crystals of saussuritized plagioclase up to 1½ inches (4 cm) in maximum dimension, and in some dikes, amphibole crystals of similar dimensions. Porphyritic dikes are especially common in and around the Gabbro-Anorthosite Plutons, and are probably related to these intrusions.

In summary, the mafic dikes are high-level intrusions emplaced mainly during the early part of the Middle Precambrian along the southern margin of the Superior Province. Some dikes, mainly the porphyritic dikes, are similar petrographically to the Gabbro-Anorthosite Plutons, and are probably genetically related to them. Other dikes may represent feeder dikes for the Huronian mafic volcanic accumulations. The mafic dikes, Gabbro-Anorthosite Plutons, and Huronian mafic volcanic accumulations probably represent early intrusive-extrusive activity associated with faulting and the initial development of the Southern Province depositional basin.

AMPHIBOLITE INTRUSIONS

Sill-like bodies of amphibolite occur within the lower part of the Huronian Supergroup, mainly in the Elsie Mountain and Stobie Formations. Most are of too limited extent to be shown at the present map-scale, although the one shown in McKim Township is up to 600 feet (180 m) in outcrop width. Amphibolite, a coarse to very coarse grained rock, consists mainly of blue-green hornblende and actinolite. These intrusions are probably closely related in time and genesis to the mafic volcanic accumulations in which they occur.

Huronian Supergroup

The Middle Precambrian supracrustal rocks of the Huronian Supergroup form part of a fold belt, the Penokean Fold Belt of the Southern Province, which

Sudbury-Manitoulin Area

is approximately 200 miles (320 km) long and up to 40 miles (64 km) wide along the North Shore of Lake Huron in Ontario (Figure 1). The sequence was first recognized and named the "Huronian Series" by Murray and Logan (Logan 1849) and is of historical significance as the first valid stratigraphic subdivision within the Canadian Shield.

The term "Huronian" was first used in a time-stratigraphic sense to denote not only this one specific sequence, but also any other coeval sequences. This resulted in the application of the name "Huronian" to numerous other little metamorphosed supracrustal rock units overlying crystalline basements. Most of these correlations have since proven to have little or no validity.

Church and Young (1970) argued that the term "Huronian" should be retained as a time-stratigraphic term because it serves a useful purpose in correlating Middle Precambrian sequences throughout the Great Lakes region. However, such correlations are tenuous, if not incorrect. For example, correlation of the upper part of the Huronian sequence in Ontario with the lower part of the Animikie sequence in the Lake Superior region of Michigan on the basis of some litho-stratigraphic similarities is apparently invalidated by radiometric evidence which indicates that the Animikie is several hundred million years younger than the Huronian (Van Schmus 1972). Roscoe (1969) has pointed out the difficulty of establishing time-stratigraphic correlations between widely separated supracrustal sequences in Precambrian terranes, or even, for that matter, of establishing the absolute ages of individual sequences. This makes it difficult to use terms such as "Huronian" in other than a rock-stratigraphic sense. Furthermore, application of the term "Huronian" in a time-stratigraphic sense to the various Middle Precambrian supracrustal sequences of the Great Lakes region probably serves only to mask their true age relationships.

In this report, "Huronian Supergroup" will be used in accordance with the recommendation of the Federal-Provincial Committee on Huronian stratigraphic nomenclature as a rock-stratigraphic term to designate the Middle Precambrian supracrustal rocks of the Lake Huron region which are younger than Superior Province basement granitic rocks and older than the Nipissing Diabase Intrusions (Robertson *et al.* 1969). The Huronian Supergroup includes all the formations so designated by Collins (1925) as well as newly recognized units which concordantly underlie and overlie these formations. This results in the inclusion of the following in the Huronian Supergroup: the "Sudbury Series", a volcanic-sedimentary sequence in the Sudbury area, and two units at the top of the succession, the Gordon Lake and Bar River Formations (Frayre 1967) which were not formally named by Collins. The Whitewater Group of the Sudbury Basin will, however, be excluded because of its isolated position and apparent younger radiometric age.

The rocks of the Huronian Supergroup were deposited between 2,500 m.y. ago, the approximate minimum radiometric age of the Early Precambrian basement upon which the Huronian sequence rests unconformably, and 2,150 m.y. ago, the age of the intrusive Nipissing Diabase (Van Schmus 1965; Fairbairn *et al.* 1969). Direct dating of Huronian volcanic and sedimentary rocks indicates that these rocks were deposited about 2,300 to 2,400 m.y. ago (Knight 1967; Fairbairn *et al.* 1969).

The Huronian Supergroup records rapid deposition by facies migration of mainly immature to submature clastic sediments which were derived from a

granitic terrane to the north, and were deposited in the form of a southward-thickening wedge on the south flank of the Superior Province craton. Deposition mainly occurred in shallow to moderately deep water in a fault-initiated basin superimposed on subsiding Early Precambrian crustal blocks. Volcanic accumulations in the lower part of the succession probably represent fissure-type eruptions associated with deeply penetrating faults which bounded the depositional basin in its early stages of development.

The Huronian Supergroup thickens southward, and in the Sudbury-Manitoulin map-area attains a total cumulative thickness of approximately 40,000 feet (12 000 m). Most of the Huronian sequence displays a cyclical repetition of three major rock types, conglomerate, pelitic rocks, and sandstone, which, following, Roscoe (1969) and Robertson *et al.* (1969), permits subdivision of the Supergroup into four groups of lithostratigraphic formations as portrayed in Figure 4. The Elliot Lake, Hough Lake, and Quirke Lake Groups constituting the lower part of the succession generally correspond to the "Bruce Series" of Collins (1925); the upper part of the succession, the Cobalt Group, is essentially identical to Collins' "Cobalt Series".

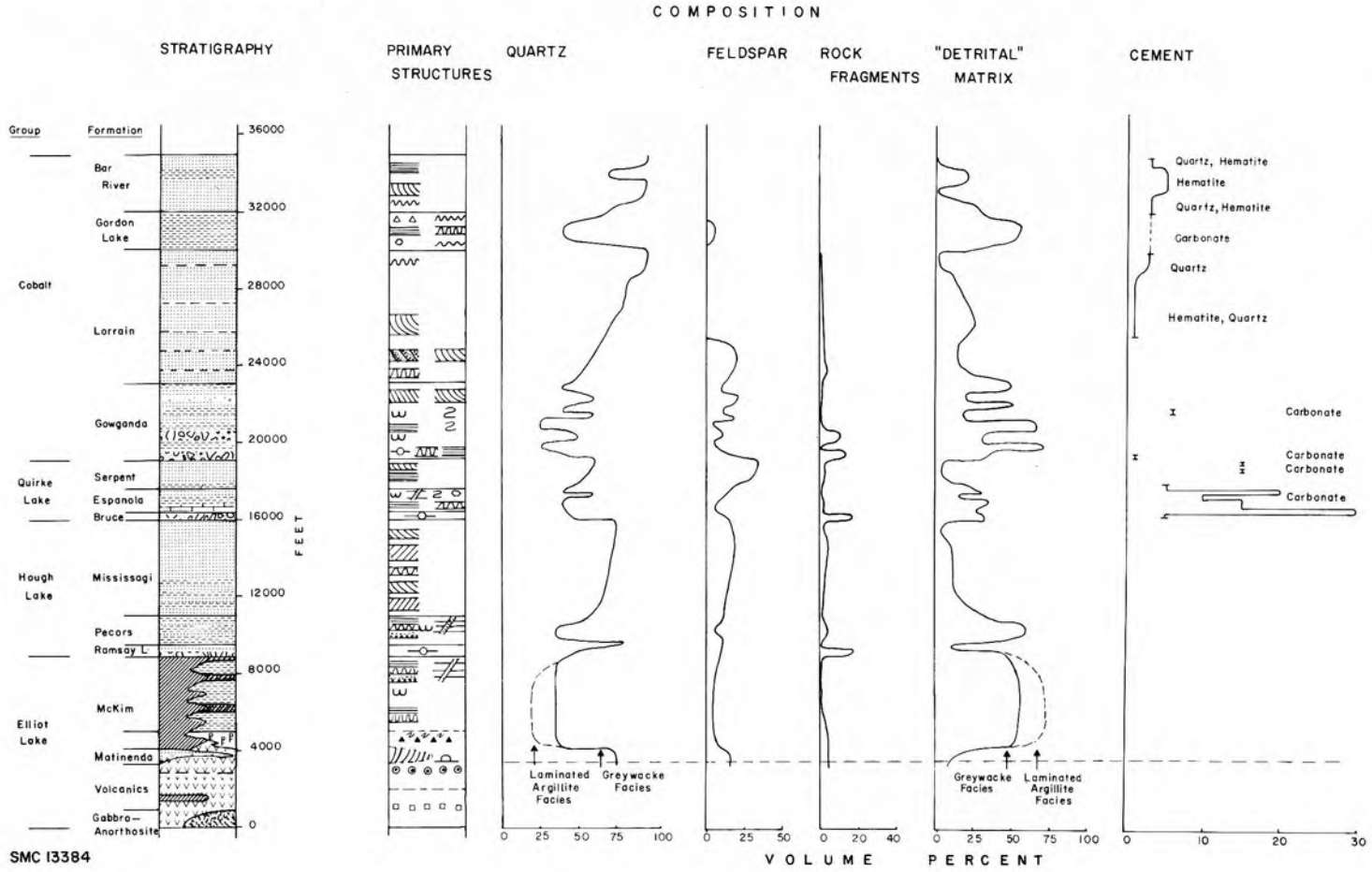
The basal part of the Elliot Lake Group lies nonconformably on an irregular erosion surface formed on the Early Precambrian basement rocks, and is conformably to disconformably overlain by the Hough Lake Group which is in turn conformably to disconformably overlain by the Quirke Lake Group. On a regional scale, the paleolimits of successively younger formations occur progressively further northward, and where the younger formations overlap Early Precambrian basement, they too lie on an irregular erosional unconformity (Roscoe 1969).

The Elliot Lake Group, with a total cumulative thickness of about 8,500 feet (2600 m), comprises an interfingering sequence of quartz-feldspar sandstone and conglomerate (Matinenda Formation), greywacke and siltstone (McKim Formation), and locally, accumulations of volcanic rocks. Near Sudbury and around Agnew Lake, the lower part of the group consists of several thousand feet of subalkaline, tholeiitic, mafic and felsic metavolcanics with intercalated metasediments. These rocks are, in this report, formally subdivided into the Elsie Mountain, Salmay Lake, Stobie, and Copper Cliff Formations. The Hough Lake and Quirke Lake Groups each comprise cyclical repetitions of lower conglomeratic units (Ramsay Lake and Bruce Formations), middle pelitic units (Pecors and Espanola Formations), and upper sandstone units (Mississagi and Serpent Formations).

The sandstone formations of the lower part of the Huronian succession are relatively uniform, southeastward-thickening wedges of coarse, immature to submature quartz-feldspar sandstone characterized by abundant crossbedding. The pelitic units consist mainly of siltstone and greywacke that typically display thin, laminated bedding and structures indicative of deposition by turbidity currents, including graded beds and Bouma divisions. The Espanola Formation is characterized by the presence of abundant carbonate minerals. The relatively thin, sheet-like conglomeratic formations are typically massive, unbedded, and consist mainly of polymictic paraconglomerate with lenses of sandstone and siltstone locally.



























The Cobalt Group, which encompasses the Gowganda, Lorrain, Gordon Lake, and Bar River Formations, has a maximum preserved cumulative thick-

Huronian Supergroup.



SMC 13384

LEGEND

LITHOLOGIES	PRIMARY STRUCTURES
 Quartz-feldspar sandstone	 Parallel lamination.
 Siltstone, greywacke	 Ripple-drift cross-lamination.
 Pebbly sandstone.	 Ripples.
 Limestone.	 Planar crossbedding.
 Conglomerate.	 Festoon crossbedding.
 Laminated argillite.	 Graded crossbedding.
 Felsic pyroclastic rocks.	 Bouma layering.
 Mafic volcanic rocks.	 Sedimentary dykes.
 Gabbro-anorthosite.	 Ball and pillow structures.
	 Slump folds.
	 Drop stones.
	 Desiccation cracks.
	 Sedimentary breccia.
	 Pyroclastic breccia.
	 Flow layering.
	 Amygdules.
	 Phenocrysts.

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Figure 4—Generalized stratigraphy, sedimentology, and primary structures of the Huronian Supergroup; Sudbury-Manitoulin Area.

Sudbury-Manitoulin Area

ness of about 17,000 feet (5000 m) in the map-area. In the south, the Gowganda Formation conformably overlies older Huronian rocks of the Serpent Formation, but in the north in Vernon Township, the Gowganda Formation locally rests unconformably on Early Precambrian basement.

The Gowganda Formation is a heterogeneous assemblage of conglomerate, argillite, siltstone, greywacke, and quartz-feldspar sandstone. The formation is divisible into a lower sequence of intercalated conglomerate, siltstone, argillite, and greywacke, and an upper sequence of sandstone and siltstone. The Lorrain Formation is a remarkably thick (approximately 8,500 feet; 2600 m) sequence of sandstone, feldspar-rich in the lower half and notably quartz-rich in the upper half. The Bar River Formation is lithologically similar to the upper part of the Lorrain Formation, and the intervening Gordon Lake Formation consists of thinly bedded siltstone with subordinate sandstone.

Definition of Terms

Sandstone—a sedimentary rock composed mainly of sand-size (0.06 to 2 mm) fragments. Included are quartz sandstone (orthoquartzite), quartz-feldspar sandstone (arkose, feldspathic quartzite), and silty sandstone (protoquartzite, subgreywacke, greywacke).

Orthoquartzite—a sandstone composed of more than 95 percent quartz and less than 10 percent matrix. The matrix consists of silt-size quartz (or quartz and feldspar) and phyllosilicate minerals.

Protoquartzite—a sandstone composed mainly of quartz and feldspar with 10 to 20 percent matrix.

Subgreywacke—a sandstone intermediate in composition between orthoquartzite and greywacke composed mainly of quartz, feldspar, and rock fragments with 20 to 30 percent matrix.

Greywacke—a sandstone with more than 30 percent matrix.

Feldspathic quartzite—a sandstone with less than 10 percent matrix and 5 to 25 percent feldspar.

Arkose—a sandstone with less than 10 percent matrix and more than 25 percent feldspar.

Coarse-grained sandstone—a sandstone in which most of the sand-sized grains are over 1 mm in diameter.

Medium-grained sandstone—a sandstone in which most of the sand-sized grains range in size from ¼ to 1 mm.

Fine-grained sandstone—a sandstone in which most of the sand-sized grains are less than ¼ mm in diameter.

Polymictic conglomerate—a conglomerate with pebbles of more than one rock-type.

Oligomictic conglomerate—a conglomerate with pebbles of a single rock-type.

Paraconglomerate—a conglomerate with a disrupted framework (pebbles do not touch each other). Paraconglomerates generally contain over 50 percent matrix.

Orthoconglomerate—a conglomerate with an intact framework (pebbles touch each other). Orthoconglomerates generally contain over 70 percent pebbles.

Pelite—metamorphosed, fine-grained (mudstone, siltstone) clastic sediment.

Thick bedded—sedimentary bedding over 3 feet (0.9 m) thick.
Medium bedded—sedimentary bedding 1 to 3 feet (0.3 to 0.9 m) thick.
Thin bedded—sedimentary bedding less than 1 foot (0.3 m) thick.

ELLIOT LAKE GROUP

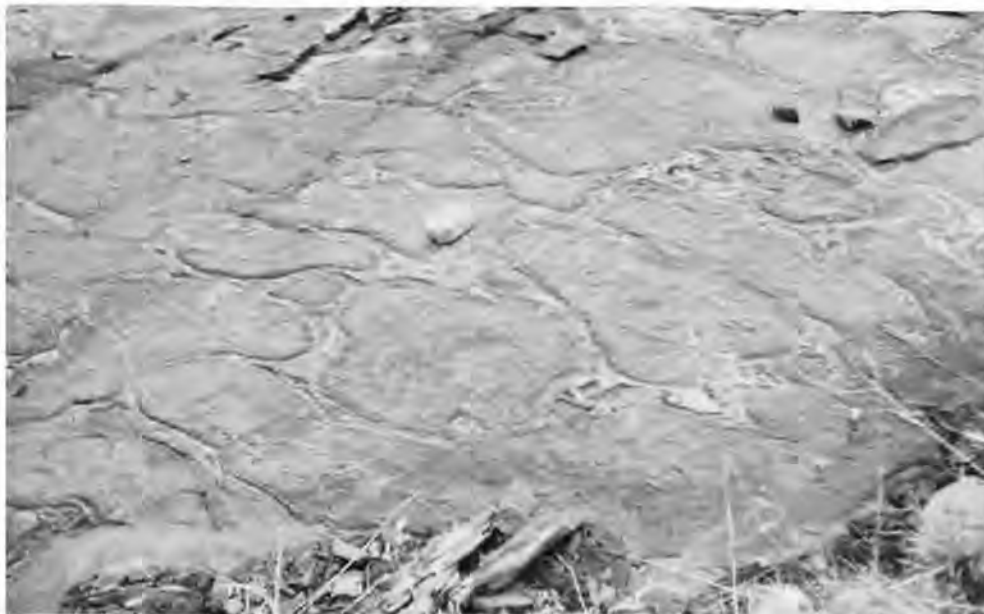
Elsie Mountain Formation

The Elsie Mountain Formation, consisting mainly of metamorphosed basalt flows, is exposed south of the Sudbury Nickel Irruptive, and forms a belt extending eastward from Drury Township to, and beyond, McKim Township in the northeastern corner of the map-area. These flows dip vertically for the most part, and as far as can be determined, face uniformly southward. In addition, there are isolated xenoliths of metamorphosed mafic igneous rocks ranging from a few inches to about 5 miles (8 km) in maximum dimensions enclosed within the Creighton Pluton which are probably correlative with the Elsie Mountain Formation. The Elsie Mountain Formation represents the lower part of Coleman's (1905a) "Sudbury Series" and corresponds approximately to the lower part of the "Stobie Group" of Cook (1946). The formation is named after a hill, "Elsie Mountain" located south of the Elsie and Murray Mines and north of the city of Sudbury in lot 12, concessions IV and V, McKim Township. Thick metabasalt flows with well preserved amygdules and pillows form the hill.

The Elsie Mountain Formation is intruded by the Sudbury Nickel Irruptive, the Creighton Pluton, and, possibly, by a Gabbro-Anorthosite Pluton, with the consequence that its base is nowhere preserved. The upper contact of the formation with the metabasalts and metasediments of the overlying Stobie Formation is conformable and gradational, and it is placed arbitrarily where intercalated metasediments, especially sulphide-bearing varieties, first appear in appreciable amounts (greater than 15 percent). Within the map-area, the formation has a maximum preserved thickness of about 3,300 feet (1000 m).

The Elsie Mountain Formation consists mainly (approximately 90 percent) of mafic igneous rocks which are dominantly thick metabasalt flows, although mafic intrusions are also present. Metamorphic recrystallization and structural deformation have made distinction of extrusive and intrusive phases difficult in the field. The metabasalt flows range in thickness from approximately 75 feet to 300 feet (23 to 90 m), and flow thicknesses decrease upward and westward in the formation. Over 90 percent of the flows are massive or foliated and show no primary internal structure or texture. However, porphyritic flows with large (1 inch to 3 inches; 2.5 to 8 cm) phenocrysts of plagioclase occur in the lower part of the formation. Amygdaloidal and pillowed flows occur throughout the formation. Although the original grain size has been modified by metamorphic recrystallization and growth of porphyroblasts of amphibole and garnet, some flows display primary variations in grain size from fine to medium grained in the upper parts, to medium to coarse grained in the lower parts.

The amygdules, which consist mainly of quartz with variable amounts of carbonate, chlorite, amphiboles, and iron oxides, are up to a centimetre in diam-



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Photo 2—Pillowed mafic metavolcanics, Elsie Mountain Formation, Waters Township.

eter and are concentrated near flow tops or about pillow selvages. The pillows, which are commonly tectonically flattened, are up to about 3 feet (0.9 m) in maximum dimension, and are surrounded by narrow ($\frac{1}{2}$ to 2 inches; 1.3 to 5 cm) fine-grained dark-coloured selvages (Photo 2).

In east-central Graham Township, there is a unit of pillow breccia which consists of subrounded metabasalt fragments about 2 to 4 inches (5 to 10 cm) in diameter with thin chilled margins or selvages in a medium-grained tuffaceous matrix. A few other units displaying indistinct layering and fragmental textures may also represent mafic tuffaceous rocks, which, like the pillow breccias, are probably the product of submarine explosive volcanic activity.

Metabasalt of the Elsie Mountain Formation is a mainly medium- to coarse-grained, dark green to black, equigranular or foliated rock consisting of amphiboles (hornblende, actinolite), plagioclase (An_{20} to An_{40}), quartz and chlorite with lesser amounts of biotite, epidote, clinozoisite, carbonate, apatite, sphene, sericite, sulphide minerals, and iron-titanium oxides (Table 4, Chart D, back pocket). These minerals represent the products of metamorphic recrystallization under conditions corresponding to the greenschist and amphibolite facies of regional metamorphism, of the original igneous mineral assemblage, which probably mainly consisted of calcic plagioclase and pyroxene.

Metasediments, which constitute approximately 10 percent of the formation, are mainly light-coloured, aluminous metapelite and metasandstone which form thin (30 to 60 feet; 9 to 18 m) intercalations that are persistent along strike for up to 10 miles (16 km). These rocks are thin bedded, 1 inch to 1 foot (2.5 to 30 cm) thick, and consist mainly of quartz and muscovite with some plagioclase (al-

bite-oligoclase), chlorite, amphibole, and iron-titanium oxides. Altered staurolite or andalusite porphyroblasts are conspicuous in some beds. There are also a few thin units of metamorphosed siltstone and greywacke near the top of the formation.

Modal and chemical analyses of typical rocks of the Elsie Mountain Formation are given in Table 4, and plots of various chemical indices (Figure 5a and b) show that the metabasalts are subalkaline, tholeiitic, and average to slightly potassic in composition. The petrology, chemistry, and chemical variations of the Huronian volcanic rocks as a group will be discussed in a later section of this report.

Salmay Lake Formation

The Salmay Lake Formation, a sequence of metamorphosed mafic metavolcanics and metasediments which forms part of the basal Huronian succession in Hyman, Porter, Shakespeare, Baldwin, and May Townships, was named by Robertson (1970a) for its occurrence around Salmay Lake which is located a few miles (8 km) west of the present map-area. Collins (Geological Survey of Canada Map 291A - Espanola; Collins 1925) mapped parts of the formation as pre-Huronian schistose, volcanic, and sedimentary rocks, and other parts as intrusive Nipissing Diabase. The Salmay Lake Formation is probably correlative with the "Spragge Group" of the Cutler area to the west (Robertson 1970b) and with the Elsie Mountain and Stobie Formations of the Sudbury area.

The Salmay Lake Formation is approximately 1,500 feet (450 m) thick at Salmay Lake (west of the map-area in May and Salter Townships), and consists of massive, porphyritic, and amygdaloidal basalt, andesite, and diabasic flows with minor mafic pillow lava and rhyodacite, and intercalations of greywacke and Matinenda-type quartz-feldspar sandstone and quartz-pebble conglomerate (Robertson and Siemiatkowska 1972). In Baldwin Township, where the formation is up to 5,000 feet (1500 m) thick, Thomson (1952) attempted to distinguish between mafic extrusive and intrusive parts of the sequence, apparently mainly on the basis of grain size. Although mafic intrusions are present in the sequence, the author is convinced on the basis of his work in Baldwin Township that much of the material previously mapped by Thomson as intrusive diabase actually consists of thick flows. In Baldwin Township, the formation consists of a lower sequence of mafic flows and pyroclastic rocks with abundant intercalations of quartz-feldspar sandstone and polymictic conglomerate, overlying gabbro-anorthosite, and overlain by a thick sequence of mafic flows and intrusions with minor amounts of mafic pyroclastic rocks, felsic metavolcanics, and metasediments. Some of the metasediments in the lower part of the formation are lithologically similar to parts of the Matinenda Formation.

In southwestern Shakespeare and adjacent Gough Townships, the basement granitic rocks are unconformably overlain by a thin (100 feet; 30 m) sequence of quartz-feldspar sandstone and quartz-pebble conglomerate, correlated in this report with the Matinenda Formation, which is succeeded by some 600 feet (180 m) of mafic volcanic rocks. In southeastern Shakespeare Township, a thin (50 feet; 15 m) sequence of pelitic metasediments containing scattered granitic fragments, and fine-grained chert-like orthoquartzite overlies gabbro-anorthosite

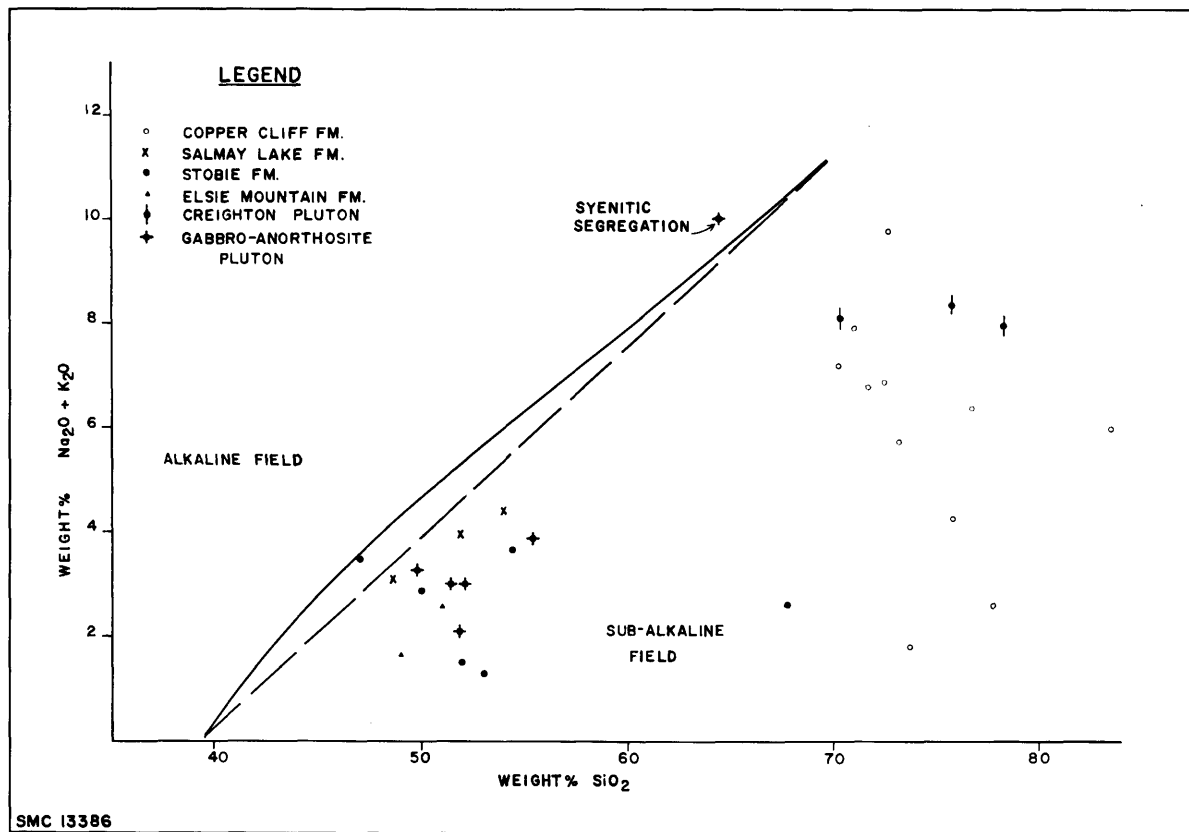


Figure 5a—Weight percent SiO_2 versus weight $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram for rocks from the Huronian Metavolcanics, Creighton Pluton, and Gabbro-Anorthosite Intrusions; Sudbury-Manitoulin Area.

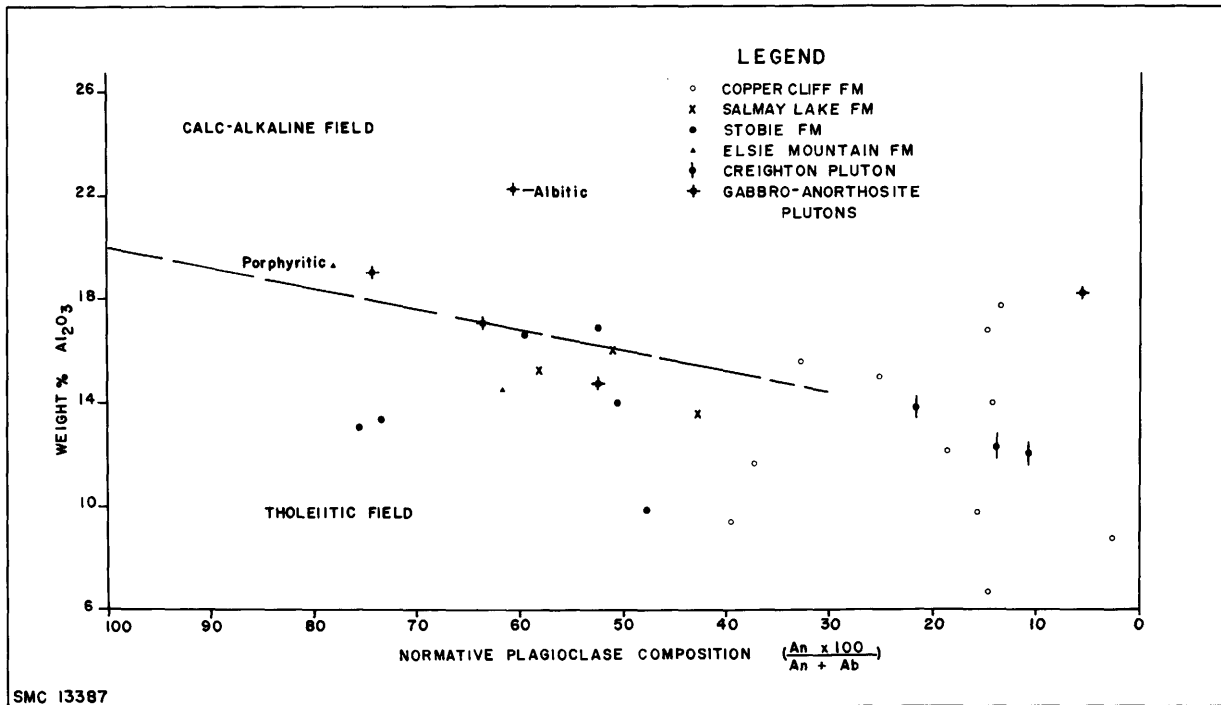


Figure 5b—Weight percent Al_2O_3 versus normative plagioclase composition for rocks from the Huronian Metavolcanics, Creighton Pluton, and Gabbro-Anorthosite Intrusions; Sudbury-Manitoulin Area.

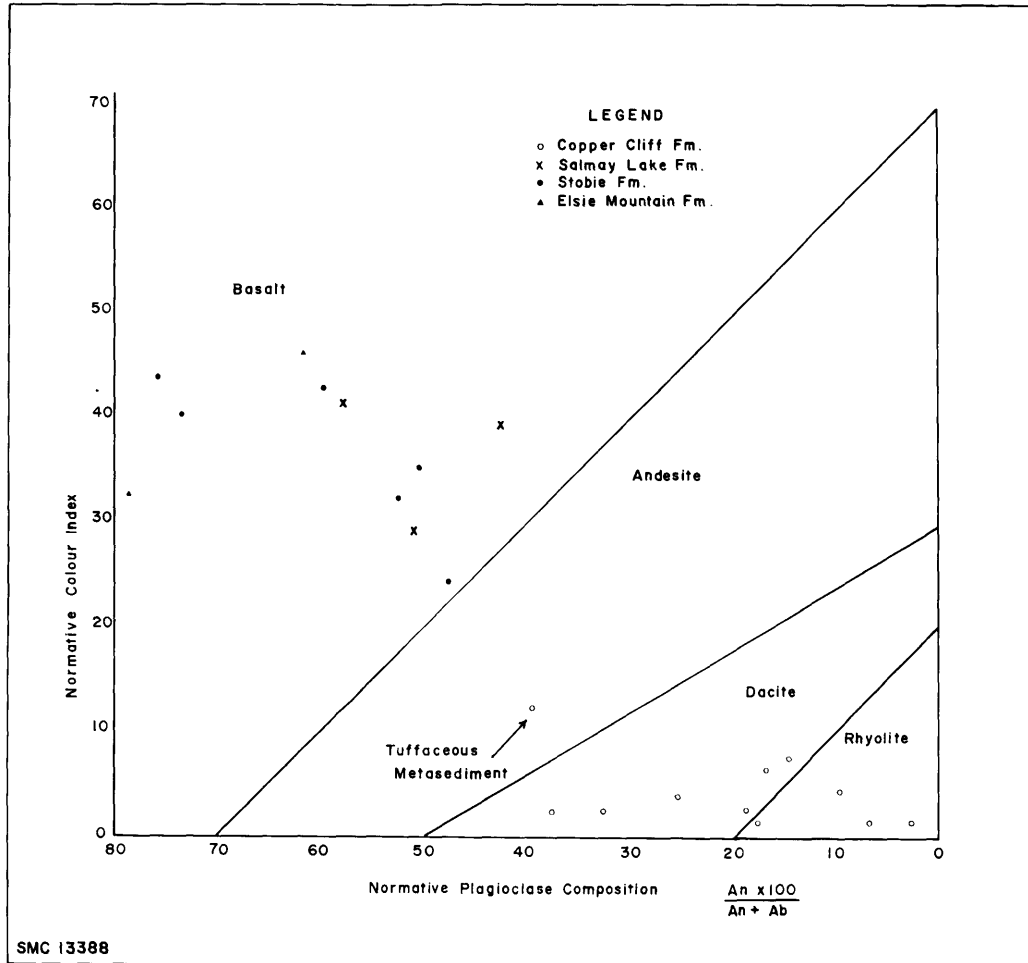


Figure 5c—Normative colour index versus normative plagioclase composition diagram for Huronian Metavolcanics, Sudbury-Manitoulin Area.

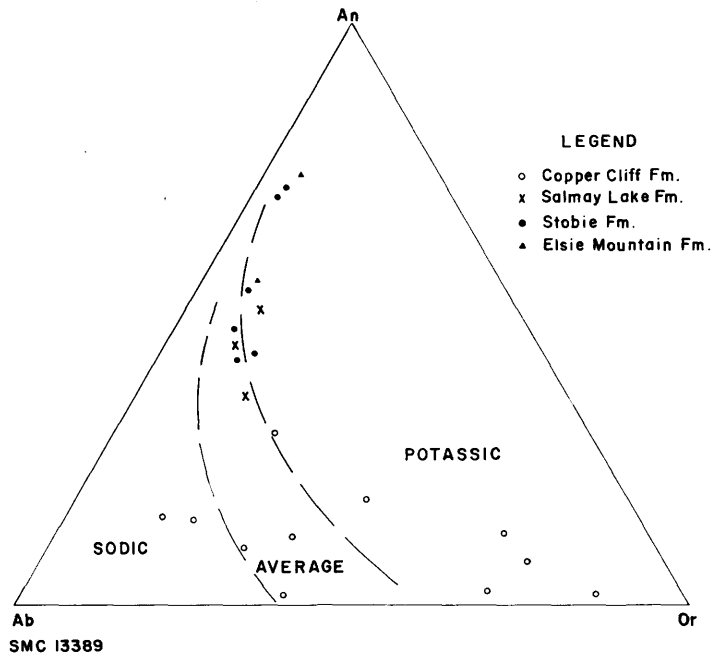


Figure 5d—Ternary diagram showing percentage of normative anorthite, albite, and orthoclase in samples of Huronian Metavolcanics; Sudbury-Manitoulin Area.

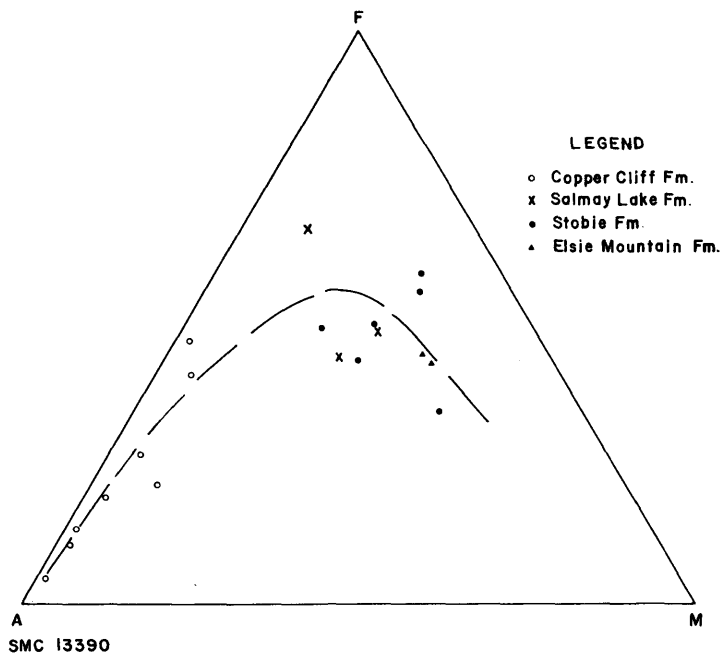


Figure 5e—AFM diagram for Huronian Metavolcanics; Sudbury-Manitoulin Area.

Sudbury-Manitoulin Area

rocks and is succeeded by about 1,000 feet (300 m) of medium-grained mafic rocks which were probably thick flows or intrusions. These rocks are overlain by some 1,500 feet (450 m) of intercalated mafic flows, pelitic metasediments, quartz-feldspar sandstone, and conglomerate. In southwestern Hyman and adjacent Porter Townships, interstratified mafic flows (and intrusions ?), pelitic metasediments, quartz-feldspar sandstone, and conglomerate are correlated with the Salmay Lake Formation on the basis of lithologic similarity and stratigraphic position. These rocks, especially the mafic metavolcanics and pelitic and conglomeratic metasediments, have been metamorphosed to amphibolite, feather amphibolite, garnet amphibolite, and biotite-garnet schist. These rocks are conformably overlain by metamorphosed sandstone and conglomerate of the Matinenda Formation.

The contact of the Salmay Lake Formation with basement granitic rocks is exposed in May Township, southwestern Shakespeare and adjacent Gough Townships, and in northeastern Shakespeare Township. Robertson (1970a) described the contact in May Township as regular and sharp with no evidence that the granite has intruded the overlying supracrustal rocks, some of which are conglomeratic and contain granitic cobbles and boulders similar to the underlying granite. The contact where seen in Shakespeare and Gough Townships is essentially similar to that described by Robertson (1970a).

The nature of the contact between the Salmay Lake Formation and the Gabbro-Anorthosite Plutons is not well-defined. Robertson (1970a) described the contact in May and Salter Townships as sharp and intrusive in some places, and as apparently gradational in others. In Shakespeare and Baldwin Townships, Card and Palonen (1976) described the contact as gradational from coarse-grained, layered gabbro-anorthosite to medium-grained, massive mafic rocks which could either represent intrusions or thick flows, to fine- and medium-grained, commonly amygdaloidal mafic flows and intercalated metasediments.

The contact of the Salmay Lake Formation with the Matinenda Formation is conformable and gradational with extensive interstratification of Salmay Lake-type metavolcanics and Matinenda-type metasediments. The complex interstratification of these rock units has made it difficult to distinguish the two formations at the present map-scale. In practice, the author has assigned mappable units of quartz-feldspar sandstone in dominantly metavolcanic sequences to the Matinenda Formation, and mappable units of metavolcanics in dominantly quartz-feldspar sandstone (Matinenda-type) sequences to the Salmay Lake Formation (and to the Stobie Formation in the east).

The mafic metavolcanics of the Salmay Lake Formation are lithologically and petrographically similar to their counterparts in the Elsie Mountain and Stobie Formations, and include mainly fine- to medium-grained dark green to black, massive and foliated metabasalt. Amygdaloidal varieties are common; pillowed and porphyritic flows are rare. These rocks are composed mainly of amphiboles and plagioclase altered to saussurite, with lesser amounts of quartz, biotite, chlorite, epidote, garnet, carbonate, sphene, iron-titanium oxides, and sulphide minerals. The amygdules, some of which display concentric mineral zoning, consist of quartz, plagioclase, chlorite, and amphibole. The analyzed samples are subalkaline, tholeiitic, normal to slightly potassic, metabasalts (Table 4, Figure 5).



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Photo 3—Mafic tuff, Salmay Lake Formation, Baldwin Township.

Fragmental mafic metavolcanics include agglomerate, and bedded mafic to felsic tuff. The agglomerate units consists of mafic volcanic fragments in a basaltic or andesitic commonly amygdaloidal matrix, and are interstratified with fine- to medium-grained, poorly bedded mafic to intermediate tuff which forms lenses up to 3 feet (1 m) thick (Photo 3). The thin-bedded chert-like orthoquartzite and fine-grained pelitic rocks in Shakespeare and Baldwin Townships probably represent metamorphosed chert and ash-tuff. An analysis of a recrystallized, chert-like orthoquartzite is given in Table 4 (analysis 33), and this rock locally contains appreciable amounts of pyrite, chalcopyrite, and cubanite.

Lenses of conglomeratic rocks of various types are present throughout, but are concentrated in the basal and upper parts of the Salmay Lake Formation. The most abundant type is a greenstone-pebble conglomerate, consisting of abundant (up to 80 percent) angular to rounded rock fragments in a greywacke or siltstone matrix. The rock fragments, which average about 3 inches (8 cm) in maximum dimension and range up to 1 foot (30 cm) in maximum dimension, consist mainly of mafic metavolcanics (75 percent) but gabbroic, granitic, felsic volcanic, quartzose, and metasedimentary types are also present. Garnet and biotite porphyroblasts of metamorphic origin are abundant in both the matrix and mafic rock fragments. In the upper part of the Salmay Lake Formation, thin lenses of pebbly sandstone consisting of small angular fragments of metasediments and metavolcanics in a quartz-feldspar sandstone matrix are present as well as lenses of polymictic conglomerate consisting of scattered pebbles and cobbles of quartz with lesser amounts of metavolcanics, and metasedimentary

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rock fragments in a schistose pelitic matrix. The other metasediments are similar to their counterparts in the Stobie Formation, including metamorphosed pelitic rocks and greywacke, probably tuffaceous in part, and quartz-feldspar sandstone similar to that of the Matinenda Formation.

Stobie Formation

The Stobie Formation, which is part of Coleman's (1905) "Sudbury Series" and corresponds to the upper part of Cooke's (1946) "Stobie Group", extends eastward from Hyman Township to, and beyond McKim Township in the northeastern corner of the map-area. The formation takes its name from the Stobie Mine in McKim Township in the north of the map-area where rocks of the Stobie Formation are well exposed.

The Stobie Formation is approximately 2,800 feet (850 m) thick in the eastern part of the area. Its thickness increases westward to possibly as much as 5,000 feet (1500 m) in Denison and Drury Townships, and then decreases rapidly and is absent west of central Hyman Township. The Stobie Formation is intruded by the Creighton Pluton, by a coarse-grained amphibolite body in McKim Township, and, possibly, by a Gabbro-Anorthosite Pluton in Drury Township. Throughout most of the map-area, The Stobie Formation lies conformably above the Elsie Mountain Formation. However, in eastern Hyman and western Drury Townships where the Stobie Formation either overlaps the Elsie Mountain Formation, or represents the western facies equivalent of the Elsie Mountain Formation, the Stobie Formation lies nonconformably upon Early Precambrian basement granitic rocks. In Drury and Denison Townships, Stobie mafic metavolcanics are intercalated with rocks of the Matinenda and McKim Formations. The contact between the Stobie Formation and the overlying Copper Cliff Formation is apparently conformable throughout the map-area, and locally, as in central Waters Township, there is interstratification of mafic flows, felsic flows, and pyroclastic rocks, and pelitic metasediments in a transitional contact zone between the two formations. No evidence could be found for a major fault between the two units as was postulated by Cooke (1946).

A xenolith or roof pendant of Stobie-type rocks approximately 3.5 miles (5.6 km) long and 1 mile (1.6 km) wide occurs within the Creighton Pluton in Snider Township. This body is locally referred to as the "Snider quartzite". It consists of metamorphosed, schistose, interstratified mafic flows, some of which contain large amygdules or spherulites, mafic tuff, siltstone, greywacke, and some quartz-feldspar sandstone.

The Stobie Formation consists of a steeply dipping, south-facing sequence of the following: interstratified mafic igneous rocks that are mainly mafic flows, tufts, and, probably, mafic intrusions; and metasediments, including sulphide-rich siltstone and greywacke, quartz-feldspar sandstone, and conglomerate. The proportion of metavolcanics decreases upward in the formation from about 80 percent in the lower part to less than 50 percent in the upper part of the formation. The thickness of individual flows also decreases upward from an average of about 75 feet (22.9 m) in the lower part to about 5 feet (1.5 m) in the upper portions.



ODM9575

Photo 4—Intercalated mafic metavolcanic flow (right) and metasediment (left) of the Stobie Formation, Graham Township. The centre bed is rich in sulphide minerals.

The Stobie Formation is characterized by the presence of a number of cyclic repetitions of mafic flows and metasedimentary units. A typical cycle consists of a basal flow overlain by a sulphide-bearing siltstone or greywacke unit which is in turn overlain by relatively sulphide-free pelite, and in some cycles, by quartz-feldspar sandstone (Photo 4). The sulphide-bearing metasedimentary units are commonly 1 to 10 feet (0.3 to 3 m) thick, but several 50 to 100 feet (15 to 30 m) thick units are present. The contacts between flows and overlying metasediments commonly have a disrupted or stirred appearance. These stirred tops display crude layering and consist of metavolcanic and metasedimentary fragments in a dark-coloured matrix composed mainly of amphibole, quartz, feldspar, and mica. The stirred tops may be the result of extrusion of flows into a basin experiencing rapid sedimentation with brecciation of flow tops and mixing of volcanic and sedimentary materials at the flow-sediment interface. These mixed zones may also represent tuffaceous deposits.

The volcanic rocks of the Stobie Formation are lithologically similar to those of the underlying Elsie Mountain Formation, consisting of massive and foliated, fine- to coarse-grained metabasalt, some units of which have well-developed pillows, and abundant amygdules. Metabasalts consist essentially of amphibole, plagioclase, quartz, and chlorite with lesser amounts of epidote, mica, iron-titanium oxides and sulphide minerals (see Table 4). Chemical analyses and normative calculations show that the Stobie metavolcanics are subalkaline, tholeiitic metabasalts, although some amygdaloidal and porphyritic flow samples ana-

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lyzed approach calc-alkaline andesite compositions (see Table 4, and Figure 5).

Fragmental metavolcanics are present, especially in the western part of the formation. Brecciated flow tops are sporadically distributed; in east-central Denison Township there are several units consisting of angular fragments of metabasalt, 3 to 6 inches (8 to 20 cm) in maximum dimension, in a fine-grained mafic matrix. Also, conformable, massive, or poorly stratified units consisting of scattered flattened pumice-like fragments in a mafic silty or sandy clastic matrix probably represent water-laid tuff and agglomerate.

Within the map-area, metasediments present include siltstone, greywacke, quartz-feldspar sandstone, and very coarse grained quartz sandstone or grit. Siltstone and greywacke, the dominant metasediments in the eastern part of the area, are probably tuffaceous, at least in part, and consist of quartz, feldspar, micas, chlorite and amphibole, with appreciable amounts of sulphide and iron-titanium oxide minerals. Some of the aluminous metapelite beds are rich in staurolite, muscovite, and garnet. Quartz-feldspar sandstone which is prominent in the western part of the area, is a medium-bedded, commonly crossbedded, moderately well-sorted rock consisting mainly of quartz, feldspars, and micas. The conglomerate or grit beds are composed of large (up to 1 cm), rounded, quartz granules in a finer grained matrix of quartz and muscovite. The quartz-rich sandstone is lithologically similar to rocks of the Matinenda Formation, and like them, probably has a granitoid provenance.

Reconnaissance work northeast of the map-area has revealed the presence of several other types of metasediments within the Stobie Formation. Beds of polymictic conglomerate a few inches to about 10 feet (3 m) thick are intercalated with greywacke, quartz-feldspar sandstone, and mafic flows in Blezard Township. The polymictic conglomerate consists of pebbles and cobbles of metabasalt, quartz, and granite in a greywacke matrix, and locally displays excellent pebble imbrication (Photo 5). Relatively thick (approximately 1,000 feet; 300 m) sections of medium- to thick-bedded quartz-feldspar sandstone, siltstone, and quartz-pebble conglomerate lithologically similar to rocks of the Matinenda Formation are present in Garson Township [northeast of the map-area]. These rocks are in the upper part of the Stobie Formation where they conformably overlie pelitic metasediments and metabasalt flows, and are overlain by pelitic metasediments, mafic flows, and rocks of the Copper Cliff Formation.

Sulphide-rich pelitic metasedimentary intercalations between metabasalt flows are abundant in the middle and upper parts of the Stobie Formation throughout much of the area. Individual units are generally less than 10 feet (3 m) thick, but are persistent along strike for long distances. Zones of sulphide-rich metasediments can be traced from Denison Township to Graham Township, a distance of some 15 miles (24 km). Sulphide minerals occur in these metamorphosed siltstone and greywacke (tuffaceous?) units as disseminations, stratiform layers, and veinlets along joints and foliation surfaces. The amounts, forms, and types of sulphide minerals vary systematically within the previously described volcanic flow-metasedimentary rock cycles (Innes 1972). The amount of sulphide increases rapidly from the upper part of a flow into the stirred top unit, reaches a maximum of 5 to 10 percent in the overlying, well-bedded pelitic metasediments, and decreases toward the top of the metasedimentary sequence; especially where quartz-feldspar sandstone forms this top. Disseminated pyrite and



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Photo 5—Conglomerate and greywacke of the Stobie Formation, Blezard Township. Note the imbricate arrangement of the pebbles.

pyrrhotite (up to 5 percent) with minor (less than 1 percent) chalcopyrite are present in the upper parts of some flows. In the stirred tops, disseminated pyrite, pyrrhotite, and chalcopyrite are present in nearly equal proportions (up to about 1 percent each). Pyrrhotite (up to 10 percent) and minor chalcopyrite (generally less than 2 percent) occur as thin stratiform layers in the overlying well-bedded pelitic rocks. Disseminated pyrite with some chalcopyrite is present in the middle and upper parts of these sulphide-bearing units. Innes (1972) found textural evidence for sulphide-silicate and sulphide-oxide reactions in these rocks, and suggested that metallic elements such as iron and copper were extracted from the ferromagnesian and iron oxide minerals by H_2S -rich gases of volcanic exhalative origin. The resulting sulphides were then deposited in the overlying volcanogenic sediments.

Copper Cliff Formation

Felsic metavolcanics of the Copper Cliff Formation form a northeast-trending belt extending from Graham Township to and beyond McKim Township. The formation takes its name from the area around the town of Copper Cliff and the Copper Cliff Mine where it is well exposed. Rocks comprising the formation were referred to variously as granite, syenite, and felsite in the earliest reports.

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Coleman (1905), who recognized their layered and fragmental character and concluded that such rocks have a metasedimentary origin, termed the unit the "Copper Cliff arkose", and included it with his pre-Huronian "Sudbury Series".

Burrows and Rickaby (1934) recognized that the unit is mainly of volcanic origin, and stated that it is conformable with the rocks above and below.

Cooke (1946) concluded the following: that the Copper Cliff Formation is of volcanic origin, including both flows and pyroclastic rocks; that the contact between the Copper Cliff Formation and overlying McKim Formation is conformable, but that the lower contact with the Stobie Formation is faulted. Cooke placed the Copper Cliff Formation at the base of the Huronian sequence.

Phemister (1956) described the Copper Cliff Formation as a relatively homogeneous, sill-like granitic intrusion emplaced at a high crustal level. He concluded that although the upper and lower contacts of the unit are generally conformable to the strata on either side, crosscutting relationships are present locally. Phemister could find no evidence of Cooke's fault at the base of the Copper Cliff Formation, and concluded that formations above and below were parts of the same stratigraphic sequence interrupted by the intrusive Copper Cliff "granite".

In view of such widely divergent views on practically every aspect of the geology of this enigmatic formation, the author is somewhat hesitant about expressing his own conclusions regarding its age and genesis. However, these conclusions are as follows:

- (1) The Copper Cliff Formation consists mainly of volcanic rocks, and although felsic hypabyssal intrusions and metasediments are present, these are relatively minor. At least half of the rocks constituting the formation are felsic pyroclastic rocks, the remainder are mainly felsic flows.
- (2) The main part of the Copper Cliff Formation is conformable with the underlying and overlying rock units, which are respectively the Stobie and McKim Formations. Consequently, the Copper Cliff, like the Elsie Mountain Formation, is part of the Huronian Supergroup.
- (3) The Copper Cliff Formation represents the felsic end-member of the Sudbury area volcanic suite, which includes the Elsie Mountain and Stobie Formations.

The Copper Cliff Formation is up to approximately 2,500 feet (760 m) thick in central Waters and McKim Townships, and thins southwestward where it is truncated by the Murray Fault. A body of felsic rocks lying between the Stobie and McKim Formations in Graham Township is correlated tentatively with the Copper Cliff Formation on the basis of some lithological similarities and its stratigraphic position. This body could also represent a felsic intrusion because there are a number of felsic bodies, including hypabyssal dikes, small plutons, flows and pyroclastic lenses within the rocks of the Elsie Mountain and Stobie Formations throughout the area. The largest of these bodies, in Denison Township, have brecciated, chilled margins, and are clearly intrusive. These bodies have some petrographic and chemical similarities to rocks of both the main Copper Cliff Formation and to the nearby Creighton Pluton. Therefore, these bodies are tentatively correlated with the Copper Cliff Formation.

The contact of the Copper Cliff Formation with rocks of the underlying Stobie Formation is well exposed in Waters and McKim Townships, although it is

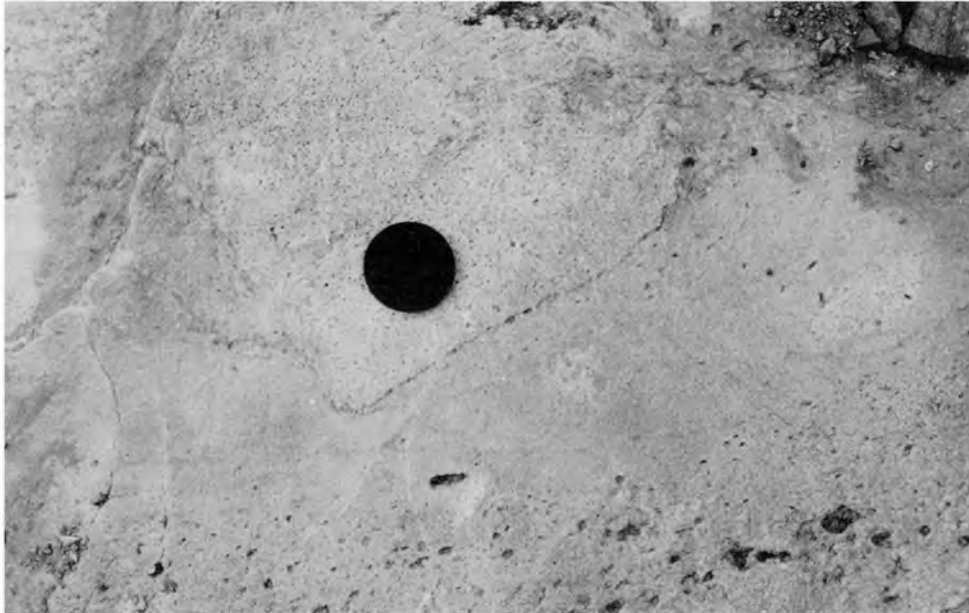
partly disrupted by Sudbury-type breccia bodies. The rocks of the two formations are foliated, as are most other rocks in the area, but there is no evidence for any large-scale fault movement at this contact. Nor could any evidence be discerned for an intrusive relationship between the Copper Cliff and Stobie Formations. The strata on either side of the contact are essentially parallel; and locally there is interstratification of mafic flows, pelitic metasediments, and felsic flows and pyroclastic rocks in a transitional contact zone. The contact between the Copper Cliff Formation and the overlying McKim Formation is essentially similar to the above with parallel stratification and transitional contact zones consisting of intercalated felsic pyroclastic rocks and tuffaceous greywacke and siltstone.

The felsic pyroclastic rocks and flows of the Copper Cliff Formation are grey to pink-coloured rhyolite and dacite. Most of these rocks are fine to medium grained, but locally coarser grained segregations, which Phemister (1956) termed pegmatite, have a coarse, granophyric texture with acicular amphibole crystals, and commonly, garnet porphyroblasts. In the writer's opinion, they represent zones of metamorphic recrystallization. There are also conformable stratiform lensoid bodies with a granophyric texture which may represent thoroughly welded, recrystallized pyroclastic units, and bodies of coarse crystal tuff or quartz-feldspar porphyry.

The rock types of the main part of the Copper Cliff Formation, in approximate order of abundance, are crystal tuff, or quartz-feldspar porphyry, tuff-breccia or lithic tuff, flow-layered rhyolite and dacite, massive rhyolite and dacite, and sulphide-rich crystal tuff. These rock units are lensoid and interstratified, probably extrusive for the most part, but some of the quartz-feldspar porphyry and massive rhyolite may represent hypabyssal intrusions. Near the top of the formation are conformable lenses of greywacke, probably tuffaceous, which consist of angular quartz and feldspar fragments in a dark-coloured, poorly sorted matrix. These lenses are interstratified with crudely bedded felsic tuffs and display graded bedding, ripples, and ripple-drift crossbedding attesting to deposition in water. The fragmental metavolcanics locally display crude stratification caused by variations in fragment size, packing, and composition, and to variations in matrix composition and texture. Some units show crude size grading of fragments (Photo 6). A fragmental rock type, termed "ghost fragment rhyolite" by the writer in the field, is relatively abundant, although difficult to recognize because of the compositional and textural similarity of fragments and matrix, both being equigranular rhyolite or dacite (Photo 7). The fragments are angular to rounded, and range in maximum dimension from a fraction of an inch to several feet (5 cm to 3 m). Some of the larger fragments have apparently been broken in place, because adjacent pieces have matching shapes and could be fitted together. Examination of thin sections reveals that the matrix is also fragmental, and that many of the smaller fragments are flattened and deformed, possibly as a result of welding.

Layering in the rhyolitic flows ranges in thickness mainly from a few mm to about 5 cm and is caused mainly by variations in grain size. Individual flow layers can seldom be traced for more than a few feet. Some flow-layered units ranging in thickness from 60 to 200 feet (18 to 60 m) can be traced over strike lengths of several miles. Burrows and Rickaby (1934) suggested that some of the flow-layered rhyolite may represent thoroughly welded tuff.

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Photo 6—Fragmental felsic metavolcanics, Copper Cliff Formation, McKim Township. Note the variation in size and packing of fragments, and, the large bomb-like fragments beneath the lens cap.



ODM9578

Photo 7—"Ghost fragment rhyolite" a fragmental felsic metavolcanic rock-type of the Copper Cliff Formation, McKim Township.

The felsic metavolcanics of the Copper Cliff Formation consist essentially of a fine- to medium-grained intergrowth of quartz, microperthite, plagioclase, and orthoclase. Minor amounts of muscovite, biotite, chlorite, amphibole, epidote, carbonate, and iron-titanium oxides are also commonly present. Pyrite and pyrrhotite constitute up to 5 percent of a sulphide-rich crystal tuff unit near the base of the formation. Quartz, feldspar, and amphibole crystals in the crystal tuffs and quartz-feldspar porphyries are commonly rounded, or flattened and broken, but some retain their euhedral shapes; some plagioclase phenocrysts show the complex zoning and twinning typical of volcanic feldspars. Modal and chemical analyses and normative calculations given in Table 4 and Figure 5 show that these rocks are subalkaline, tholeiitic, sodic, average, and potassic rhyolite, and dacite.

Petrology and Origin of the Metavolcanic Sequences

The Elsie Mountain, Salmay Lake, Stobie, and Copper Cliff Formations of the Elliot Lake Group represent local volcanic accumulations, which, with coevally deposited clastic metasediments, form the basal part of the Huronian Supergroup. The volcanic accumulation of the Sudbury area apparently represents a major mafic to felsic volcanic cycle beginning with a thick sequence of mafic flows (Elsie Mountain Formation) followed by thin mafic flows and abundant metasedimentary intercalations (Stobie Formation) and ending with felsic pyroclastic rocks and flows (Copper Cliff Formation). The Salmay Lake Formation is a sequence of essentially undifferentiated metabasalts and intercalated metasediments.

The Huronian volcanic accumulations are associated in space and time with mafic dike swarms in the exposed Early Precambrian basement rocks and with gabbro-anorthosite plutons. These mafic intrusions are probably genetically associated with the metavolcanics, emplaced during an early, intrusive stage of the igneous activity. The Creighton Pluton is also spatially, temporally, and probably genetically related to the Sudbury-area volcanic rocks, and may represent a high-level felsic pluton emplaced at a late intrusive stage of the igneous cycle.

The Huronian volcanic accumulations are spatially related to the Creighton and Murray Faults, members of a major east-west regional fault system. Early normal movement on faults of this system probably initiated the Huronian depositional basins and controlled emplacement of the volcanic rocks as fissure eruptions.

Chemical analyses and normative calculations of Huronian volcanic rocks show that they are subalkaline, tholeiitic, average to potassic metabasalt, dacite, and rhyolite in composition (Table 4, Figure 5). According to the classification system used, andesite is notably absent, although some of the rocks analyzed, especially those with abundant plagioclase phenocrysts, fall near or within the calc-alkaline field, and approach andesite in composition. AFM plots for the Sudbury area volcanic rocks are given in Figure 5e (in section "Elsie Mountain Formation").

In Figure 6, variations of petrographic indices, major oxides, and trace elements with stratigraphic height are plotted for analyzed rocks of the Elsie Mountain, Stobie, and Copper Cliff Formations. The variations in petrographic indices and oxides such as SiO_2 , Na_2O , FeO , CaO , and MgO support the field evidence that the mafic and felsic metavolcanics belong to the same episode of extrusive igneous activity. Major oxide variation trends of the intercalated metasediments generally match those of the metavolcanics thus supporting the field and petrographic evidence that the metasediments (with the exception of quartz-feldspar sandstone) are probably tuffaceous or represent clastic materials derived directly from the flows. The trace element variation diagrams show that a tendency for an inverse relationship between concentrations of some trace elements in the metavolcanics and in the metasediments. For example, in the Stobie Formation, high Cr and Ni concentrations in the metavolcanics correspond to low concentrations of these elements in the associated metasediments; maximum concentrations of copper in the metasediments correspond to minimum concentrations of copper in the metavolcanics.

The field evidence and chemical relationships previously cited, as well as petrographic evidence for sulphide-silicate and sulphide-oxide reactions, led Innes (1972) to conclude that the sulphide mineralization, especially in the Stobie Formation, is of volcanic exhalative origin: H_2S -rich vapour passed through the volcanic rocks, reacted with silicate and oxide minerals, and extracted copper and iron to form sulphide minerals which were then deposited in the associated volcanogenic sediments. Volcanic activity may have resulted in a local reducing environment which controlled deposition of the sulphide minerals. Of note is the close spatial and temporal relationship between Huronian volcanic accumulations and uranium-bearing clastic sedimentary rocks of the Matinenda Formation. Uraniferous quartz-pebble conglomerate was being deposited in the Agnew Lake area at the same time as volcanism was in progress to the east and west. A common attribute of both the volcanic accumulations and the uraniumiferous sedimentary rocks is the prevalence of sulphide minerals in them, and possibly these sulphide minerals all have a common, volcanic exhalative origin.

Isotopic analyses of metavolcanics of the Sudbury area by Knight (1967) show that they have an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.7048 ± 0.0014 , suggesting a complicated (contamination by crustal materials?) magmatic history. Volcanic rocks in the Spragge area, however, which are probably correlative with those near Sudbury, have an initial $\text{Sr}^{86}/\text{Sr}^{87}$ ratio of 0.7013 ± 0.0012 , suggesting a simple (uncontaminated) history. Some of the Sudbury-area material analyzed was actually tuffaceous or mixtures of tuffaceous and metasedimentary materials.

A comparison of the Huronian volcanic sequence with Early Precambrian volcanic assemblages is important because many previous workers have correlated the two, mainly on lithological grounds. The Huronian volcanic accumulations, like many of their Early Precambrian counterparts, consist mainly of mafic flows, felsic pyroclastic rocks and flows, and pyritic metasediments. The Sudbury area sequence shows the cyclicity common to many Early Precambrian "greenstone belt" successions. However, there are also some differences. The Huronian metavolcanics are slightly richer in K_2O than many of the Early Precambrian suites, possibly supporting the concept of increasing K_2O with time (Fahrig and Eade 1969). In the Huronian sequence of the Sudbury area, a slight decrease occurs in alumina with increasing stratigraphic height (Figure 6),

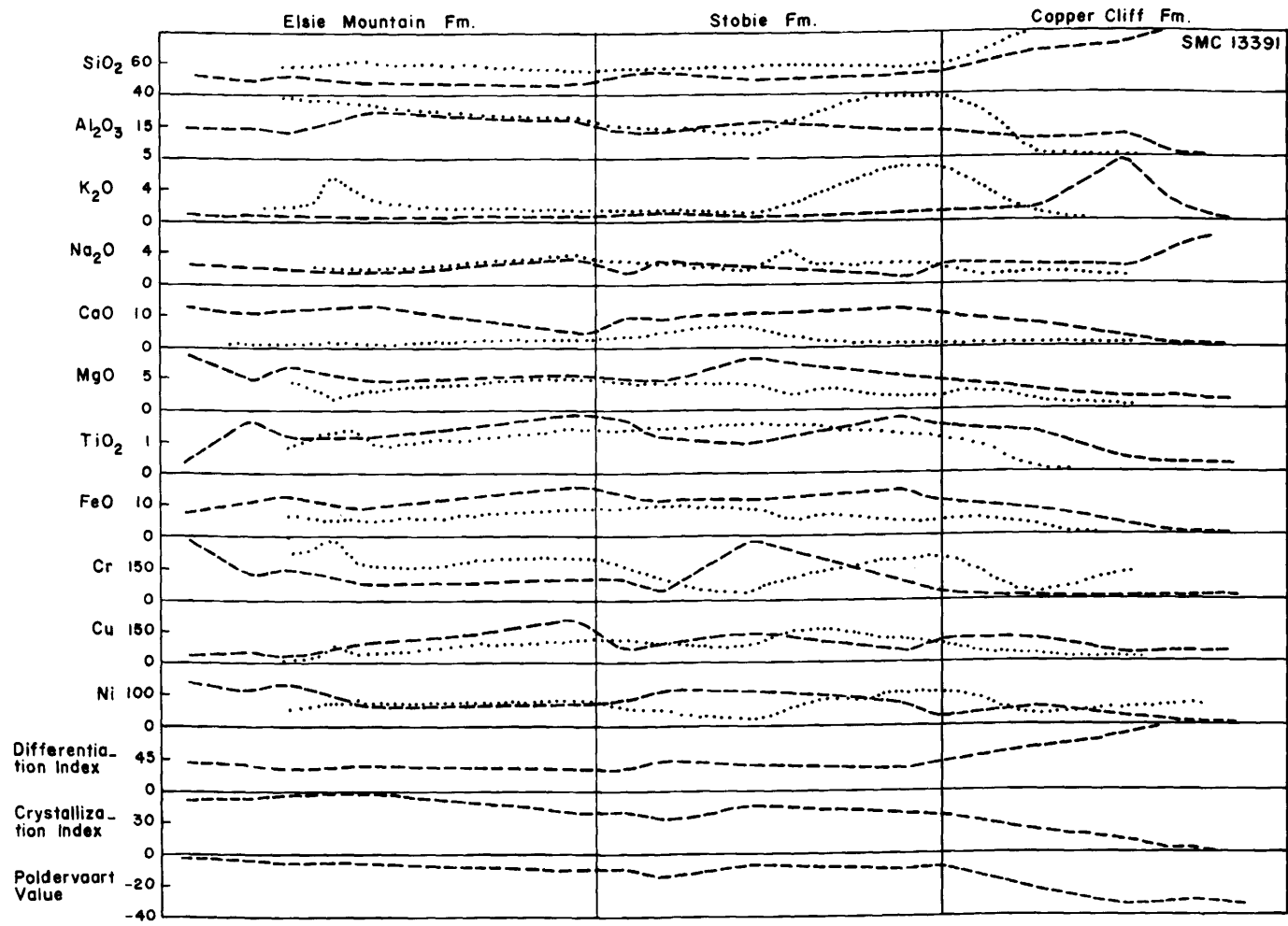


Figure 6—Variations in petrographic indices, major oxides, and trace elements with stratigraphic height in the Huronian metavolcanic sequence of the Sudbury-Manitoulin Area. Dashed lines represent Metavolcanics; dotted lines represent intercalated metasediments and tuffaceous metasediments. Major oxides are expressed in weight percent, trace elements in ppm, and petrographic indices in molecular percent.

whereas the opposite trend is present in many Early Precambrian suites (Baragar 1968). The lack of volcanic rocks of intermediate (andesitic) composition in the Huronian sequences contrasts with some of the Early Precambrian belts where andesite is an important component (Goodwin 1965). Many of the Early Precambrian volcanic suites are calc-alkaline or mixtures of calc-alkaline and tholeiitic rock types; the Huronian succession is tholeiitic. The association of mafic volcanic flows with shelf-type quartz-feldspar sandstone is common in the Huronian, and is apparently lacking in Early Precambrian sequences.

Age and Stratigraphic Relationships of the Metavolcanic Sequences

The controversies regarding the age of the metavolcanic accumulations in the Sudbury-Manitoulin map-area, and their stratigraphic relationships to both the Early Precambrian granite and to the Middle Precambrian clastic metasediments have been outlined previously. Essentially, the problems are centred around two factors: (1) the similarity of the metavolcanics and related rocks to Early Precambrian greenstone belt sequences, and their lack of similarity to the typical Huronian shelf-type sedimentary rocks; and, (2) the apparent lack of any significant boundary or unconformity between the metavolcanic sequences and the overlying clastic metasediments. Various workers have sought to resolve this dilemma in various ways such as invoking faults (Cooke 1946) or postulating unconformities (Collins 1936; Card 1965).

The available radiometric age data is inconclusive as to the time of deposition of the metavolcanics. Knight (1967) determined a Rb-Sr isochron age of $2,005 \pm 125$ m.y. for the "Sudbury Series" metavolcanics, but in this same area, Fairbairn *et al.* (1969) deduced Rb-Sr isochron "ages" of 1,800 to 2,200 m.y. for various Huronian formations. Since the Huronian Supergroup is intruded by Nipissing Diabase reliably dated at 2,150 m.y., the figures given for the metasedimentary and metavolcanic formations are probably metamorphic overprint ages rather than depositional ages. Fairbairn *et al.* (1969) also determined a Rb-Sr isochron age of $2,288 \pm 87$ m.y. for the Gowganda Formation, and Gibbins *et al.* (1972) have determined a Rb-Sr isochron age of $2,230 \pm 20$ m.y. for the main part of the Murray Granite, which like the Creighton Pluton, intrudes the Elsie Mountain and Stobie Formations. Knight (1967) obtained a Rb-Sr isochron date of $2,496 \pm 145$ m.y. for the Spragge group metavolcanics which are probably broadly correlative with the volcanic sequences of the Sudbury-Manitoulin map-area. The Superior Province granitic basement rocks yield minimum radiometric ages of about 2,500 m. y. (Van Schmus 1965). Consequently, the volcanic rocks of the Sudbury-Manitoulin area were probably deposited about $2,400 \pm 100$ m.y. ago.

Interpretation of the stratigraphic relationships of the volcanic sequences has depended on the distinction of mafic metavolcanics from Nipissing Diabase and other mafic intrusions, and on the nature of the contacts between the metavolcanics and the metasediments of the Matinenda and McKim Formations. The contacts between the metavolcanic sequences and the granitic rocks of the Superior Province are largely masked by mafic and felsic intrusions and by shearing, but where preserved, as at localities in Drury, Hyman, and May Town-

ships, represent a deformed unconformity.

Detailed investigation of the stratigraphy of the lower part of the sequence in the area between Sudbury and Hyman Townships has shown conformity between the metavolcanic and metasedimentary sequences that form the Elliot Lake Group. Volcanic flows, pyroclastic rocks, and pelitic metasediments typical of the Elsie Mountain, Stobie, and Copper Cliff Formations are interstratified with quartz-feldspar sandstone and conglomerate of the Matinenda Formation, and greywacke and siltstone of the McKim Formation. These relationships are shown diagrammatically in Figure 7.

In Waters Township near Sudbury, the lower part of the Huronian section preserved consists mainly of mafic flows with intercalations of siltstone, greywacke, quartz-feldspar sandstone, and conglomerate (Elsie Mountain and Stobie Formations) which are overlain by felsic flows and pyroclastic rocks (Copper Cliff Formation) and by thick-bedded turbidite-type greywacke (McKim Formation). Westward, the proportion of metasedimentary material increases rapidly, so that in central Drury Township, some 10 miles (16 km) to the west, the sequence consists of a lower metavolcanic unit with abundant, thick intercalations of quartz-feldspar sandstone, a middle unit consisting mainly of quartz-feldspar sandstone with some mafic flows, and an upper unit, the McKim Formation, consisting of approximately equal proportions of thick-bedded greywacke and thin-bedded siltstone and argillite. The trend continues westward, and in eastern Hyman Township some 20 miles (30 km) west of Waters Township, the lower part of the Huronian sequence consists of a thin, lower unit of mafic metavolcanics interbedded with quartz-feldspar sandstone and greywacke that is 1,000 to 2,000 feet (300 to 600 m) of sandstone, conglomerate, and pelitic rocks of the Matinenda Formation, and laminated argillite and siltstone of the McKim Formation. In addition to the trend for volcanic components to decrease westward, several other trends are evident. The amount of Matinenda-type feldspathic sandstone in the section decreases eastward; east of Denison Township, the Matinenda Formation can no longer be distinguished as a separate lithostratigraphic formation. In the McKim Formation, a distinct change from mainly thick-bedded, turbidite-type greywacke in the east, to mainly thin-bedded, laminated siltstone and argillite in the west occurs.

The unusual association of volcanic rocks and turbidite-type greywacke with relatively well-sorted quartz-feldspar sandstone may owe its origin to the simultaneous input of materials from different source areas into the same depositional basin. Quartz-feldspar sandstone was probably derived mainly from the Early Precambrian granitic terrane to the north, the metavolcanics were derived from fault-controlled vents marginal to the basin, and the turbidites were derived partly from the metavolcanics themselves, and partly from basement rocks uplifted as a result of volcanism and tectonism.

Matinenda Formation

Clastic metasediments of the Matinenda Formation, mainly quartz-feldspar sandstone with lesser amounts of siltstone, argillite, and conglomerate, occur in the northern part of the map-area where they unconformably overlie the Early

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Precambrian granitic basement, and are in conformable contact with rocks of the Salmay Lake, Stobie, and McKim Formations.

In May, and southern Shakespeare Townships, the formation is as much as 1,000 feet (300 m) thick. It consists of thin- to medium-bedded quartz-feldspar sandstone and minor pelitic rocks interstratified with volcanic rocks of the Salmay Lake Formation, and a thin, 100-foot (30 m) thick basal unit of sandstone and quartz-pebble conglomerate (Figure 7).

In Baldwin and adjacent Porter and Hyman Townships, the formation is as much as 1,000 feet (300 m) thick, and consists of a lower unit, approximately 200 feet (60 m) thick, composed of medium- to thick-bedded, coarse-grained quartz-feldspar sandstone, conglomeratic sandstone, quartz-pebble conglomerate and polymictic conglomerate, a middle unit of medium- to coarse-grained quartz-feldspar sandstone and an upper unit of thin- to medium-bedded quartz-feldspar and silty sandstone with argillaceous partings and interbeds. In the lower conglomeratic part, there are well-developed cycles each consisting of a lower silty sandstone unit 10 to 20 feet (3 to 6 m) thick, a middle coarse-grained, conglomeratic sandstone unit 20 to 30 feet (6 to 9 m) thick, and a unit some 20 to 60 feet (6 to 18 m) thick consisting of quartz-pebble conglomerate and coarse, pebbly sandstone. Some cycles are incomplete with the upper conglomeratic part missing, or with the coarse-grained, pebbly sandstone unit of one cycle resting upon a scour surface developed on the quartz-pebble conglomerate unit of the preceding cycle.

In central Hyman Township near the Agnew Lake Mine, the Matinenda Formation is about 700 feet (200 m) thick. It consists of thick-bedded quartz-feldspar sandstone with appreciable amounts of oligomictic and polymictic conglomerate in the lower and upper parts, thin-bedded laminated pelitic rocks and silty sandstone in the central part, and a few thin units of mafic igneous rocks which probably represent the westward extensions of the Stobie Formation mafic flows. The conglomeratic sections display the same cyclic repetitions of micaceous sandstone, coarse-grained pebbly sandstone, and quartz-pebble conglomerate as in Baldwin Township. The formation thins westward and northward from central Hyman Township, is absent in much of Dunlop, Porter, and Vernon Townships where rocks correlated with the Pecors and Mississagi Formations form the base of the sequence. In northern Vernon Township, a thin unit of quartz-feldspar sandstone is again present at the base of the sequence and is correlated with the Matinenda Formation.

Eastward the Matinenda Formation thickens to possibly as much as 2,000 feet (600 m) in eastern Hyman and Drury Townships, then thins rapidly eastward where it is intercalated with mafic metavolcanics, greywackes, and pelitic rocks of the Stobie and McKim Formations. East of central Denison Township, the Matinenda Formation cannot be distinguished as a separate lithostratigraphic formation. The Matinenda Formation in the area between Hyman and Denison Townships consists mainly of thin-bedded, fine- to medium-grained silty sandstone with abundant partings, interbeds, and units up to about 100 feet (30 m) thick of siltstone. However, there are also sections of thick-bedded or very thick-bedded (up to 15 feet; 5 m), coarse-grained pebbly sandstone with scattered quartz pebbles and granules and lenses of quartz-pebble and polymictic conglomerate.

These stratigraphic variations in the Matinenda Formation, which are es-



ODM9579

Photo 8—Coarse, pebbly feldspathic sandstone of the Matinenda Formation, Hyman Township.

essentially southward thickening and eastward thinning accompanied by rapid incoming of pelitic and volcanic rocks and facies change, are shown diagrammatically in Figure 7. These variations are accompanied by textural and compositional variations in the quartz-feldspar sandstone which exhibit general southward, eastward, and upward decreases in the following: (a) average grain size from about 1.5 mm to 0.5 to 1.0 mm; (b) in the amount of feldspar, from an average of about 20 percent to 10 percent; and (c) bedding thickness. The number of quartz-pebble conglomerate lenses also decreases, as does their average thickness from about 1 to 3 feet (0.3 to 1 m) in the north to 6 inches to 1 foot (15 cm to 0.3 m) in the south and east. Decreases in the amount and average grain size of detrital minerals such as monazite, and in the average and maximum size of quartz pebbles in the conglomerate lenses from north to south have been recorded by Young (1962).

Two types of sandstone are present in the Matinenda Formation, these are; medium- to thick-bedded, medium- to coarse-grained, poorly to moderately sorted, white, green, and pink feldspar-rich sandstone which is typically pebbly and associated with quartz-pebble conglomerate (Photo 8); and thin-bedded, fine- to medium-grained, poorly sorted grey, micaceous sandstone that is commonly associated with pelitic rocks (Photo 9). Sandstone of the first type is mainly arkose and feldspathic protoquartzite with minor orthoquartzite and of the second type, mainly subgreywacke and protoquartzite (Pettijohn 1956). The Matinenda sandstone consists of subangular to subrounded grains of quartz (average 75 per-



ODM9580

Photo 9—Thin-bedded silty sandstone of the Matinenda Formation, Drury Township.

cent; range 25 to 98 percent) and feldspars (average 10 percent; range 1 to 60 percent) in a matrix of phyllosilicate minerals and silt-size quartz and feldspars (average 10 to 15 percent; range 1 to 40 percent) (Figure 8). Rock fragments, mainly of granitic composition, are generally present in amounts of less than 5 percent, although some coarse conglomeratic sandstone contains 15 percent rock fragments. Angular chips of green and black siltstone, probably formed by disruption of silty partings or interbeds, are present locally. Average grain-size of feldspathic sandstone is approximately 1 mm, but very coarse varieties with quartz, feldspar, and rock fragments 5 mm or more in diameter are present. Average grain-size of the silty sandstones is approximately 0.1 mm, but these poorly sorted rocks have clastic grains ranging from less than 0.05 mm to greater than 1mm. The quartz probably has a plutonic or vein origin. Both potassic feldspar and plagioclase are present, the ratio of potassic feldspar to plagioclase ranging from about 1:1 to 10:1 and averaging 3:1. The feldspars are extensively sericitized. Sericite (a muscovite of metamorphic origin), with minor biotite and chlorite, are the dominant matrix components. Accessory minerals, including zircon, pyrite, pyrrhotite, monazite, apatite, sphene, ilmenite, and magnetite, are generally present in amounts of less than 1 percent.

Oligomictic quartz-pebble conglomerate of the Matinenda Formation consists of well-rounded, commonly tectonically flattened, quartz pebbles in a

Sudbury-Manitoulin Area

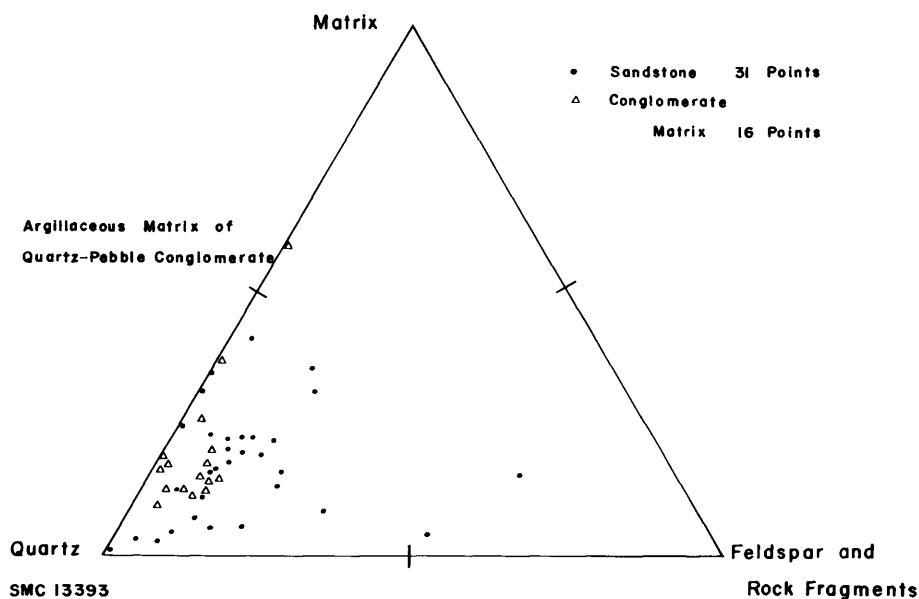


Figure 8—Triangular diagram showing mineralogical composition of rocks of the Matinenda Formation; Sudbury-Manitoulin Area.

poorly to moderately sorted, medium-grained to coarse-grained micaceous feldspathic sandstone matrix (Photo 10). The pebbles, which constitute 20 to 80 percent and average about 50 percent of the rock, are mainly grey, black, white, and reddish vein quartz, but minor chert, quartzite, and granitic pebbles are also present locally. The pebbles range in maximum dimension from less than ¼ inch to 12 inches (0.6 to 30 cm), but most are ½ inch to 1 inch (1 to 2.5 cm) in diameter. Compositionally and texturally the conglomerate matrix is similar to the associated feldspathic sandstones, except that accessory minerals, including ilmenite, zircon, monazite, apatite, garnet, tourmaline, sphene, uranothorite, uraninite, thoriumite, pyrrhotite, chalcopyrite, and galena are generally more abundant, constituting approximately 1 to 10 percent of the rock. Pyrite, in the form of euhedral crystals, anhedral grains, and granular aggregates, is commonly present in the conglomerate in amounts of 5 to 10 percent. The main uranium-bearing minerals are uraninite, uranothorite, and “brannerite” (Card 1959). Uraninite occurs as small (0.05 to 0.1 mm) euhedral crystals and rounded grains, typically closely associated with pyrite. “Brannerite”, which is actually a multi-phase mixture of uranium and titanium compounds, possibly a uraniumiferous leucocoxene, occurs as small (0.1 to 0.5 m) grains and diffuse aggregates. Thucholite, a uranium-bearing hydrocarbon, replaces uraninite in some of the conglomerate studied.

Polymictic paraconglomerate lenses occur especially where the basement rocks are granitic. Polymictic paraconglomerate consists of 15 to 30 percent granitic, quartz, and mafic igneous pebbles averaging 1 to 3 inches (2.5 to 8 cm) in diameter in a poorly sorted feldspathic sandstone (subgreywacke) matrix. Po-



ODM9581

Photo 10— Quartz-pebble conglomerate lens, Matinenda Formation, Hyman Township. Note the tectonic flattening of the pebbles.

lymictic orthoconglomerate units consisting of approximately 70 percent pebbles and cobbles of mafic volcanic, granitic, vein quartz, and metasedimentary derivation in a schistose pelitic or greywacke matrix typically occur in association with mafic metavolcanics.

Laminated argillite, a fine-grained (probably clay to fine silt size originally), dark grey to black rock commonly forms distinct units from a few feet to about 100 feet (30 m) in thickness. Siltstones, dark grey rocks rich in phyllosilicates and silt to fine-sand size quartz and feldspars, forms units up to several hundred feet (100 m) thick interbedded with sandstone, and as bedding plane partings in dominantly sandstone sequences.

Sedimentary structures in the Matinenda Formation include the following: festoon crossbedding, scour surfaces, and scour-and-fill structures, especially in the coarse-grained, conglomeratic sequences; and planar crossbedding, parallel laminations, and graded bedding, especially in the sandstone-siltstone sequences. Very fine, varve-like laminations are present in the argillite unit in Hyman Township, and coarse $\frac{1}{8}$ to 2 inch (0.3 to 5 cm) thick parallel and cross-laminations are common in the thick-bedded quartz-feldspar sandstone. Within the cycles previously described, planar crossbeds are characteristic of the lower silty sandstone, and festoon crossbeds of the middle and upper coarse-grained sandstone.

McKim Formation

Metamorphosed pelite and poorly sorted sandstone of the McKim Formation are exposed in a northeast-trending belt extending from May Township in the west to McKim Township in the northeast. These rocks conformably overlie, and are intercalated with quartz-feldspar sandstone, mafic and felsic volcanic rocks, and pelitic metasediments of the Matinenda, Stobie, Salmay Lake, and Copper Cliff Formations.

Three main facies were distinguished in the McKim Formation as follows; a greywacke facies, a laminated argillite-siltstone facies, and a quartz-feldspar sandstone facies. These facies alternate throughout the sequence, and locally repetitions occur of a cycle consisting of a lower thick-bedded, coarse greywacke unit, a middle unit of thin-bedded, fine- to medium-grained greywacke and siltstone, and an upper unit of laminated argillite and siltstone (Figure 7). Thin lenses of conglomeratic sandstone lithologically similar to their counterparts in the Matinenda Formation and Ramsay Lake Formation, as well as mafic meta-volcanic, possibly tuffaceous, rocks similar to those of the Stobie Formation occur near the top and bottom of the formation.

The greywacke facies consists of fine- to coarse-grained greywacke with subordinate sandy siltstone and siltstone. Bedding ranges in thickness from a few inches to approximately 10 feet (3 m). These rocks show ripples, cross-laminations, graded beds, Bouma divisions (Bouma 1962), slump structures, and clastic dikes (Photo 11). The laminated argillite-siltstone facies consists of laminated argillite with subordinate siltstone and sandy siltstone. Bedding rarely exceeds 6 inches (15 cm) in thickness and is commonly about 1 inch (2.5 cm) thick. The characteristic primary structure of this facies is a delicate, varve-like parallel lamination consisting of alternating light grey, silt to fine sand laminae and dark grey, pelitic laminae (Photo 12) which range from less than 1 to more than 20 mm in thickness, and commonly maintain a constant thickness over distances of at least 100 feet (30 m) along strike. The quartz-feldspar sandstone facies consists of fine- to medium-grained silty sandstone (protoquartzite, subgreywacke) which occurs as interbeds and units of about 50 feet (15 m) in thickness throughout the formation.

In Waters and McKim Townships, where the McKim Formation is approximately 6,000 feet (1800 m) thick, the greywacke facies constitutes approximately 70 percent of the formation and consists mainly of thick (1 to 10 feet; 0.3 to 3 m, average 2 feet; 0.6 m), greywacke beds, some of which display several Bouma divisions such as the "A" (graded greywacke), "B" (parallel laminated), "C" (ripple cross-laminated), and "D" (parallel laminated), or "E" (pelitic) units. The proportion of greywacke in the McKim Formation decreases westward across the map-area.

In Denison and Graham Townships, where the McKim Formation is about 8,000 feet (2400 m) thick, the greywacke facies constitutes approximately 50 percent, the laminated argillite-siltstone sandstone facies approximately 30 percent, and the quartz-feldspar sandstone facies, 20 percent. West of Denison Township, the greywacke facies constitutes only 20 percent of the formation, is characteristically thinly bedded, less than 1 foot (0.3 m) thick, and displays incomplete Bouma divisions such as A - B, or A - C combinations. In the eastern part of the



ODM9582

Photo 11—Thick-bedded greywacke facies of the McKim Formation, McKim Township. Note the Bouma divisions in the lower bed, and the flame and slump structures at the base of the overlying bed.



ODM9583

Photo 12—Thin-bedded laminated argillite-siltstone facies, McKim Formation, Denison Township.

Sudbury-Manitoulin Area

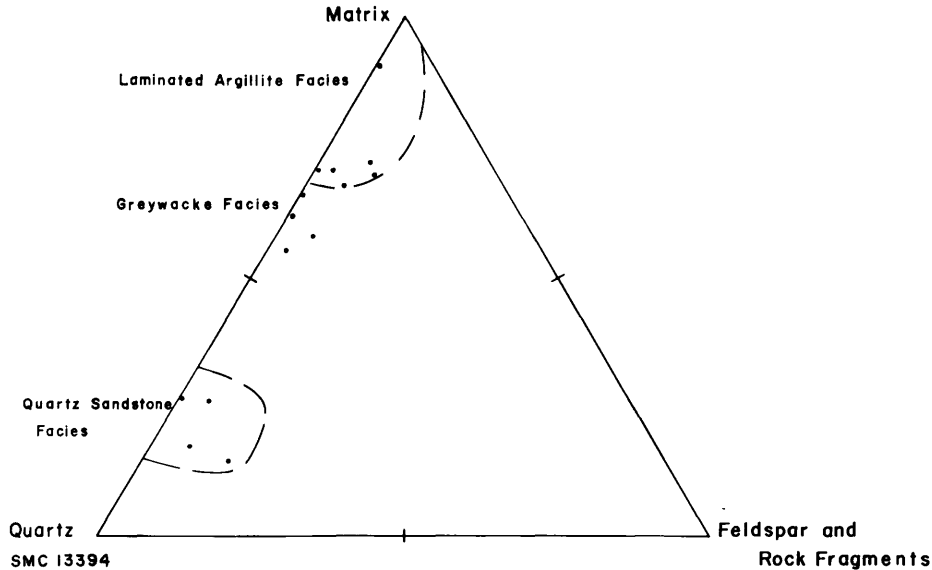


Figure 9—Triangular diagram showing mineralogical composition of rocks of the McKim Formation; Sudbury-Manitoulin Area.

map-area, where the laminated argillite-siltstone facies is subordinate to the greywacke facies, the former facies is concentrated in the middle part of the formation. In the central and western parts of the belt, where it is subordinate, the greywacke facies is concentrated in the lower part of the formation, especially in areas where volcanic rocks are intercalated with the sequence, and in the upper part of the formation immediately below the Ramsay Lake Formation.

Greywacke of the McKim Formation is a dark grey, poorly sorted rock composed of fine to very coarse sand size, angular to subrounded fragments of quartz (25 to 50 percent; average 35 percent), feldspars and rock fragments (5 to 15 percent), in an abundant (45 to 70 percent) matrix of micaceous minerals and silt size quartz and feldspars (Figure 9). Plagioclase and potassic feldspar are present, and plagioclase is the most abundant feldspar. Rock fragments, which are abundant (up to 15 percent) only in the thick-bedded, coarse-grained greywacke, include mafic metavolcanic, granitic, and metasedimentary varieties as shown in Figure 9. Muscovite is the chief micaceous mineral, but appreciable amounts of biotite, iron-rich chlorite, and amphibole are also present. Accessory minerals include sphene, ilmenite, magnetite, pyrite, pyrrhotite, epidote, zircon, and carbonate. Metamorphic porphyroblasts of staurolite, andalusite, chloritoid, and garnet are conspicuous in some localities.

Every gradation is present from greywacke through sandy siltstone to siltstone. Siltstone is a poorly sorted, grey rock consisting of silt- to fine-sand size angular grains of quartz and feldspars with abundant micas and chlorite.

The laminated argillite-siltstone is a grey to black rock consisting of silt-size angular grains of quartz (20 percent) and feldspars (10 percent) and abundant

micaceous minerals (70 percent). Muscovite is the dominant mica, but biotite and iron-rich chlorite are prominent, as well as porphyroblasts of garnet, chloritoid, staurolite, and andalusite. Chemical analyses given in Table 5, show that in comparison to "average shale" (Pettijohn 1957), the analyzed rocks are relatively rich in alumina, total iron, and titania, and poor in CaO, and have an average $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratio of about 17, an average $\text{CaO}/\text{Na}_2\text{O}$ ratio of 0.8, an average $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio of 2, and an average $\text{FeO}/\text{FeO}_2\text{O}_3$ ratio of 2.5.

Quartz-feldspar sandstone of the McKim Formation is poorly to moderately sorted and consists of fine- to medium-grained subangular to subrounded grains of quartz (60 to 80 percent), feldspars (up to 15 percent), and minor rock fragments in a silty matrix (10 to 30 percent) of muscovite, biotite, chlorite, quartz, and feldspars with minor sphene, iron-titanium oxides, and sulphide minerals. Plagioclase and potassic feldspar are present in approximately equal amounts.

HOUGH LAKE GROUP

Ramsay Lake Formation

The Ramsay Lake Formation, a relatively thin, sheet-like conglomeratic unit at the base of the Hough Lake Group, outcrops in the northern part of the map-area in two main outcrop belts, one north of the Baldwin Anticlinorium and the Murray Fault (see Map 2360, back pocket). The other belt south of these structures outcrops in the area extending from May Township in the west to McKim Township in the east. In addition, conglomeratic rocks tentatively correlated with the Ramsay Lake Formation occur in an area of complex structure and igneous intrusions at the eastern end of Lake Panache.

The contact between the Ramsay Lake and the underlying McKim Formation, considered by Coleman (1914) and Collins (1936) to mark the "great unconformity" between an Early Precambrian "Sudbury Series" and the Middle Precambrian Huronian rocks, is conformable. In most areas, this contact is abrupt with no evidence of erosion or angular discordance. However, at numerous localities a transitional contact zone up to 50 feet (15 m) thick exists between the two formations which consists of interbedded McKim-type greywacke and pelite and Ramsay Lake-type conglomerate.

The Ramsay Lake Formation is up to 200 feet (60 m) thick in Hyman Township in the northern part of the area, and thickens southward to an average of about 500 feet (150 m) in the belt extending from May to McKim Townships (Figure 10). Near Lake Panache, the formation is again less than 200 feet (60 m) thick, indicating that it may thin southward or eastward. The lateral variations in thickness are accompanied by lithological changes. In the thinner sections in the north, sandstone, pebbly sandstone, and siltstone comprise over 50 percent of the formation, whereas in the thicker southern sections, the formation consists mainly of polymictic paraconglomerate (80 to 90 percent).

In southern Graham Township, where the McKim-Ramsay Lake contact is a transition zone some 30 feet (9 m) thick consisting of interbedded, medium-grained greywacke, siltstone, conglomeratic greywacke, and polymictic paracon-

TABLE 5

CHEMICAL ANALYSES OF ROCKS OF THE McKIM FORMATION, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Major Components in Weight Percent																	
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻	CO ₂	TiO ₂	MnO	P ₂ O ₅	S	Total	S.G.
(1)	55.07	21.50	2.72	6.04	3.00	0.98	1.43	3.01	3.53	0.02	0.12	0.98	0.05	0.11	-	99.56	2.80
(2)	60.73	21.18	3.23	4.16	2.75	0.79	0.90	2.30	2.61	-	0.20	0.74	0.04	0.09	-	99.72	2.82
(3)	57.14	25.61	2.33	4.17	2.39	1.01	1.01	2.66	2.02	-	0.12	0.71	0.05	0.09	-	99.31	2.89
(4)	57.75	19.19	2.98	7.86	2.44	2.27	2.34	0.98	2.48	0.02	0.02	0.82	0.07	0.11	-	99.33	2.75
(5)	62.00	18.90	1.24	4.24	3.30	1.64	2.17	1.88	3.56	0.05	-	0.64	0.05	0.11	-	99.78	N.D.
(6)	54.60	23.90	1.32	5.20	3.60	0.82	0.90	4.12	3.78	0.04	-	0.96	0.04	0.18	-	99.46	N.D.
(7)	55.55	22.80	1.40	5.28	3.20	0.56	0.72	4.65	4.31	0.07	-	0.84	0.09	0.15	-	99.62	N.D.
(8)	60.40	22.40	4.11	3.97	2.77	0.01	0.86	2.54	2.81	0.12	0.18	0.98	0.06	0.08	0.01	101.30	2.96
(9)	65.60	16.30	0.74	5.45	2.67	0.89	1.41	-	2.42	0.26	0.04	0.79	0.07	0.12	-	96.76	2.76

Trace Elements in ppm														
(8)	Ba	Co	Cr	Cu	Ga	Ni	Pb	Sc	Sr	V	Y	Zn	Zr	Be
	500	10	200	15	20	80	15	20	100	200	30	15	150	3

Notes

- (1) Metapelite (laminated siltstone-argillite), lower greenschist facies metamorphism, Drury Township.
- (2) Metapelite (laminated siltstone-argillite), lower almandine-amphibolite facies metamorphism, Hyman Township.
- (3) Metapelite (laminated siltstone-argillite), lower almandine-amphibolite facies metamorphism, Hyman Township.
- (4) Fine-grained silty sandstone, upper greenstone facies metamorphism, Hyman Township.
- (5) Metapelite (laminated siltstone-argillite), upper greenschist facies, Merritt Township.
- (6) Metapelite (laminated siltstone-argillite), upper greenschist facies, Merritt Township.
- (7) Metapelite (laminated siltstone-argillite), lower greenschist facies, Merritt Township.
- (8) Metapelite (laminated siltstone-argillite), lower almandine-amphibolite facies, Shakespeare Township.
- (9) Greywacke, greenstone facies, Graham Township.

Abbreviations

- S.G. Specific Gravity
 N.D. Not determined
 - Not detected

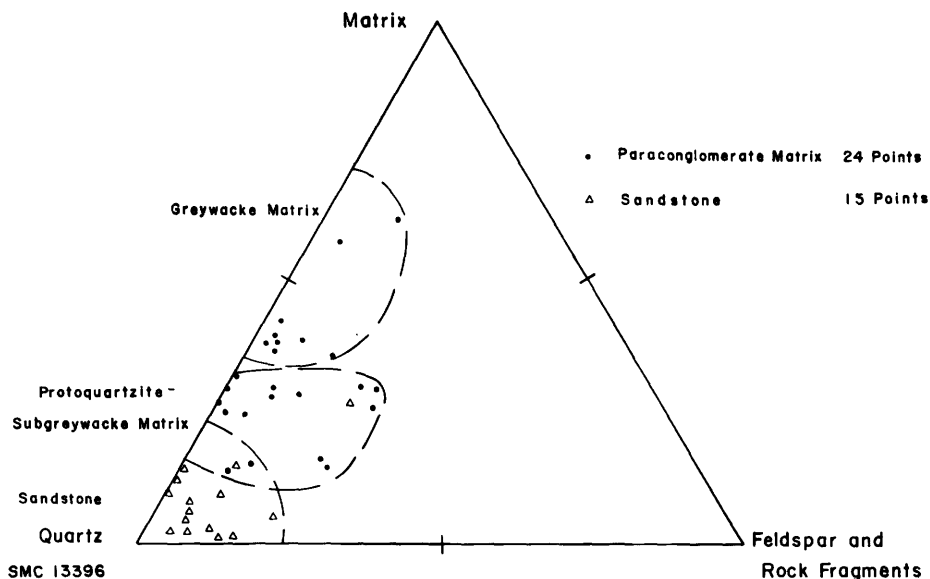


Figure 10—Triangular diagram showing mineralogical composition of rocks of the Ramsay Lake Formation; Sudbury-Manitoulin Area.

glomerate lenses; the Ramsay Lake Formation consists of some 500 feet (150 m) of polymictic paraconglomerate with a few interbeds of sandstone and siltstone overlain by about 50 feet (15 m) of sandstone and pebbly sandstone that pass upward into interbedded sandstone and siltstone of the overlying Pecors Formation. The upper sandstone-pebbly sandstone member is medium to thick bedded. Ginn (1965) reported the presence of ripples with maximum amplitudes of 6 inches (15 cm) and wavelengths of 2 feet (0.6 m) in this unit in Nairn Township. In the lower conglomeratic part of the formation, thick stratification units 10 to 40 feet (3 to 12 m) thick are poorly defined by variations in pebble content (from approximately 10 to 30 percent), and size (from less than 1 inch to about 4 feet; 2.5 cm to 1-2 m in maximum dimension), variations in matrix composition and textures, and by sandstone and siltstone interbeds. The thin sandstone interbeds are commonly disrupted to give contorted fragments and blocks with diffuse boundaries enclosed in massive conglomerate.

In Baldwin and Shakespeare Townships in the north, sandstone and conglomeratic rocks of the Ramsay Lake Formation abruptly overlie thin-bedded greywacke, siltstone, and laminated argillite of the McKim Formation. However, at several localities, there are beds 5 to 10 feet (1.5 to 3 m) thick in the upper part of the McKim Formation of very coarse grained quartz sandstone or grit consisting mainly of rounded grains and granules of quartz. These units are similar to some beds in the overlying Ramsay Lake Formation. The Ramsay Lake Formation consists of a lower unit of polymictic conglomerate and pebbly sandstone (40 to 60 feet; 12 to 18 m), a section of sandstone with siltstone and conglomeratic lenses 100 to 150 feet (30 to 45 m) thick, a unit of polymictic paraconglomerate 30 feet (9 m) thick, and an upper unit of sandstone and pebbly



ODM9584

Photo 13—Massive, polymictic paraconglomerate, Ramsay Lake Formation, Graham Township.

sandstone. These rocks display bedding, coarse parallel laminations, crossbedding, ripple marks, and, possibly, dropstones.

Polymictic paraconglomerate of the Ramsay Lake Formation is a buff-weathering rock containing 10 to 30 percent angular to rounded pebbles, cobbles, and boulders composed of the following: felsic igneous rocks (granitic and felsic volcanic), 25 to 60 percent; mafic igneous rocks (gabbro, mafic volcanic), 25 to 40 percent; and quartzose rocks (vein quartz, quartzite) 10 to 30 percent. The mineralogical composition of rocks of the Ramsay Lake Formation is given in Figure 10. The rock fragments are unsorted or poorly sorted, range from less than 1 inch (2.5 cm) to about 4 feet (1.2 m) in maximum dimension, and average 1 to 2 inches (2.5 to 5 cm) in maximum dimension. The conglomerate matrix, feldspathic subgreywacke and greywacke (Photo 13) is poorly to moderately sorted, and consists of fine- to coarse-grained (0.1 to 2 mm; average 0.5 mm) angular to rounded grains of quartz (25 to 75 percent), feldspars and rock fragments (up to 25 percent), and silt size quartz and feldspars with abundant phyllosilicates (20 to 50 percent). In addition, the conglomerate matrix characteristically contains appreciable amounts (5 to 15 percent) of well-rounded quartz grains and granules up to 1 cm in diameter. Plagioclase and potassic feldspars are present, and sand-size mafic igneous rock fragments are locally abundant (15 percent) in the matrix. Accessory minerals include pyrite, pyrrhotite, iron titanium oxides, zircon, apatite, sphene, leucoxene, and monazite. Chemical analyses of the conglomerate matrix (see Table 6) show that it has an average K_2O/Na_2O ratio of about 1.5, a CaO/Na_2O ratio of 0.25, and an Al_2O_3/Na_2O ratio of 6, indicating that it is relatively immature chemically as well as texturally.

Sandstone of the Ramsay Lake Formation is mainly moderately sorted feldspathic protoquartzite consisting of medium-grained subangular to subrounded quartz (75 percent), feldspars (10 percent), and interstitial micas (15 percent). The white, fine-grained sandstone interbeds and fragments consist mainly of rounded quartz grains (85 to 90 percent) with minor feldspar and micas. The coarse-grained quartz sandstones, which are present in the McKim Formation-Ramsay Lake Formation transition zone, form lenses within the Ramsay Lake Formation, and consist of well-rounded, well-sorted quartz grains and granules (70 percent) with interstitial white micas and fine-grained quartz.

The siltstone and greywacke interbeds are lithologically similar to rocks of the McKim and Pecors Formations, although some contain appreciable amounts of well-rounded quartz grains and granules.

Pecors Formation

Greywacke, siltstone, argillite, and quartz-feldspar sandstone of the Pecors Formation, which are lithologically similar to rocks of the McKim Formation, occur in three parts of the map-area: a discontinuous outcrop belt in Shakespeare, Porter, and Hyman Townships north of the Murray Fault and the Baldwin Anticlinorium; a relatively continuous belt south of the Murray Fault extending from May Township to McKim Township; and at the eastern end of Lake Panache in an area of complex structure and igneous intrusions. The contact between the Pecors and the underlying Ramsay Lake Formation is conformable and abrupt, or gradational through a thin stratigraphic interval. The contact of the Pecors Formation with the overlying Mississagi Formation is similarly conformable and gradational over a stratigraphic interval up to several hundred feet thick. In northern Porter Township, fine-grained, thin-bedded laminated argillite and siltstone of the Pecors Formation unconformably overlie granitic basement rocks (Ginn 1961), and in eastern Dunlop Township, Pecors argillite, siltstone, and sandstone are in contact with a Gabbro-Anorthosite Pluton. The latter contact is sheared, and although abrupt, there is no evidence that the gabbroic rocks intrude the metasediments (Card and Palonen 1976).

In the north, the formation is up to 500 feet (150 m) thick, has an average thickness of 200 to 300 feet (60 to 90 m), and is commonly missing entirely. Thin-bedded siltstone and argillite beds 1 to 6 inches (2.5 to 15 cm) thick are the dominant rock types with lesser amounts of fine-grained greywacke and quartz-feldspar sandstone. For example, in Shakespeare Township, the formation comprises the following: a lower, thin-bedded unit 100 to 200 feet (30 to 60 m) thick consisting of siltstone, argillite, and fine-grained greywacke with minor (10 percent) quartz-feldspar sandstone concentrated in the basal part, and an upper unit some 100 to 300 feet (30 to 90 m) thick consisting of laminated argillite, siltstone, and fine-grained greywacke with less than 10 percent quartz-feldspar sandstone in the lower part and 40 to 50 percent quartz-feldspar sandstone interbeds in the upper part. Bedding in the lower part of this member is approximately 1 to 4 inches (0.3 to 1.2 cm) thick. Parallel laminations, graded beds, and ripples are present in the lower and central parts of the formation, and planar crossbeds are prevalent in the sandstone of the upper parts.

Sudbury-Manitoulin Area

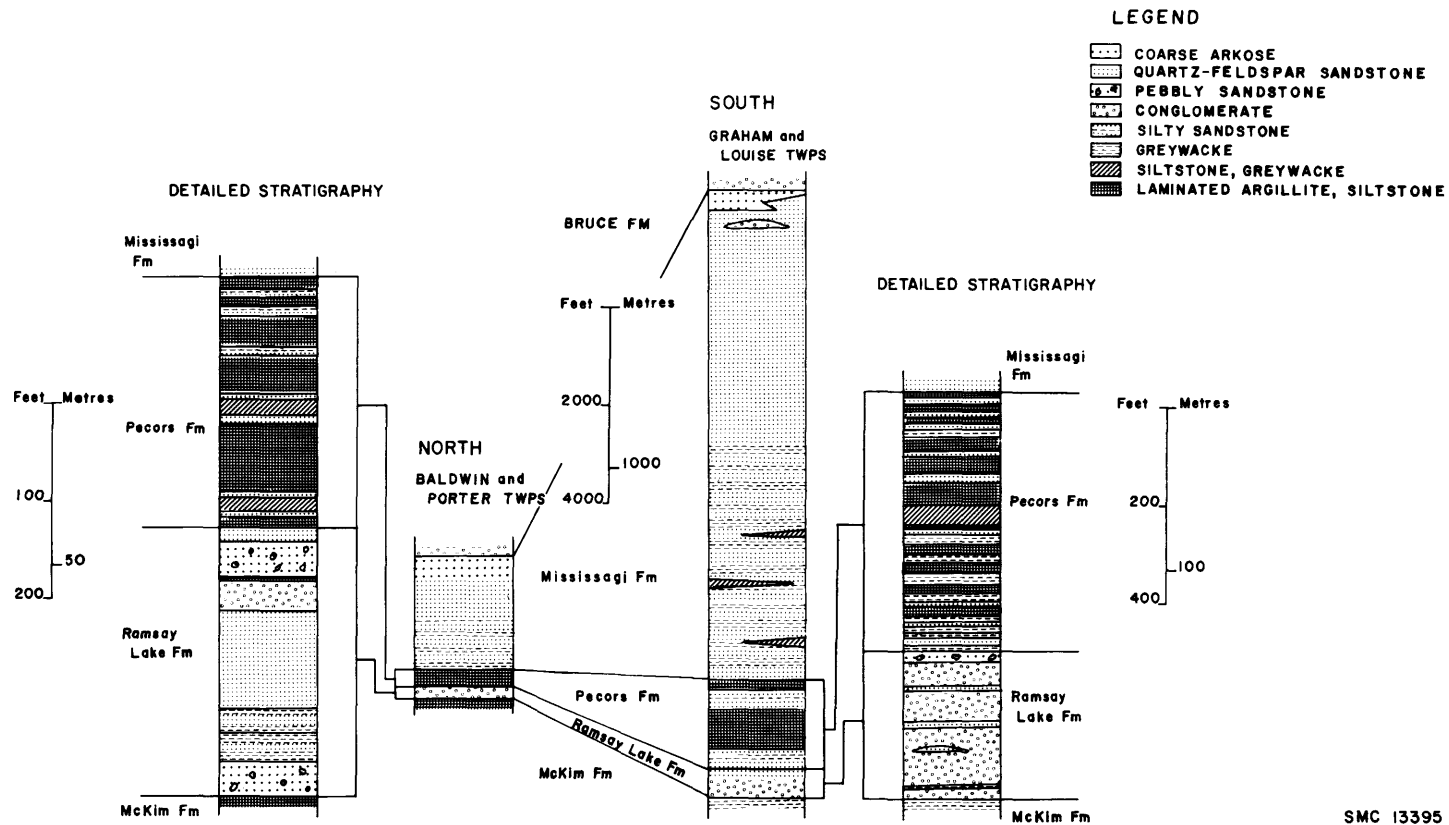
In the main outcrop belt extending from May Township to McKim Township, the Pecors Formation ranges in thickness from approximately 1,200 to 2,000 feet (360 to 600 m) and averages 1,500 feet (450 m) (Figure 10). Greywacke and siltstone are the dominant rock types, but there are also appreciable amounts of quartz-feldspar sandstone present in the lower and upper parts, and of laminated argillite in the central part. The formation is generally divisible into three intergradational units. A lower member 700 to 900 feet (200 to 270 m) thick consists of fine- to medium-grained greywacke, quartz sandstone, and siltstone. The proportion of quartz-feldspar sandstone in this member decreases upward from approximately 70 percent in the lower part to 10 percent at the top, and the bedding thickness similarly decreases from an average of about 1 foot (0.3 m) and a maximum of 6 feet (1.8 m), to an average of about 4 inches (10 cm) and a maximum of 3 feet (0.9 m). The middle member comprises some 400 to 500 feet (120 to 150 m) of thin-bedded siltstone, argillite, and fine-grained greywacke with less than 10 percent quartz-feldspar sandstone interbeds in the lower and upper parts. The upper member, which represents the transition into quartz-feldspar sandstone of the overlying Mississagi Formation, consists of 300 to 600 feet (90 to 180 m) of greywacke, siltstone, and quartz-feldspar sandstone, the proportion of sandstone increasing upward from about 10 to more than 50 percent.

In the Lake Panache area, where the Pecors Formation may be as much as 3,000 feet (900 m) thick, it consists of approximately equal proportions of fine-grained greywacke, siltstone, and sandstone. These lateral and vertical stratigraphic variations are shown diagrammatically in Figure 11.

Sedimentary structures present in the greywacke, siltstone, and argillite include graded bedding, ripples, cross-laminations, parallel laminations, ball-and-pillow structures, and clastic dikes. Some relatively complete Bouma sequences (Bouma 1962) are present, but more commonly, only partly developed sequences such as combinations of "B" (parallel laminated) and "C" (cross laminated) divisions or "A" (graded) and "B" divisions are developed (Photo 14). Quartz-feldspar sandstone displays crossbedding, typically of the planar variety.

Siltstone and argillite in the Pecors Formation are dark grey to black, fine-grained rocks consisting of phyllosilicate minerals and silt-size quartz and feldspar. The greywacke is fine to medium grained, poorly sorted, and consists of angular grains of quartz (30 to 60 percent), feldspars and rock fragments (10 percent), in an abundant (30 to 70 percent) matrix of phyllosilicate minerals and silty quartz and feldspar. The mineralogical composition of rocks of the Pecors Formation is shown in Figure 12. Quartz sandstone is poorly to moderately sorted, fine- to medium-grained subgreywacke and protoquartzite consisting of quartz (70 to 80 percent), feldspar and rock fragments (5 to 30 percent) and interstitial phyllosilicate minerals, quartz, and feldspar (10 to 30 percent). Recognizable rock fragments, mainly of granitoid composition, generally compose less than 5 percent of the rock. Plagioclase and potassic feldspar occur, with sodic plagioclase being the dominant species. Accessory minerals include pyrite, pyrrhotite, iron-titanium oxides, carbonate, zircon, apatite, sphene, and leucoxene.

A chemical analysis of a typical Pecors siltstone given in Table 6 shows it is chemically similar to analogous rocks of the McKim Formation having $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$, $\text{CaO}/\text{Na}_2\text{O}$, $\text{K}_2\text{O}/\text{Na}_2\text{O}$, and $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios of about 16, 1, 2, and 12 respectively.



SMC 13395

Figure 11—Diagram showing the generalized stratigraphy of the Hough Lake Group in the Sudbury-Manitoulin Area.

Sudbury-Manitoulin Area



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Photo 14—Thin-bedded siltstone and sandstone of the Pecors Formation, Graham Township. Note the ripple cross-lamination and "starved ripples".

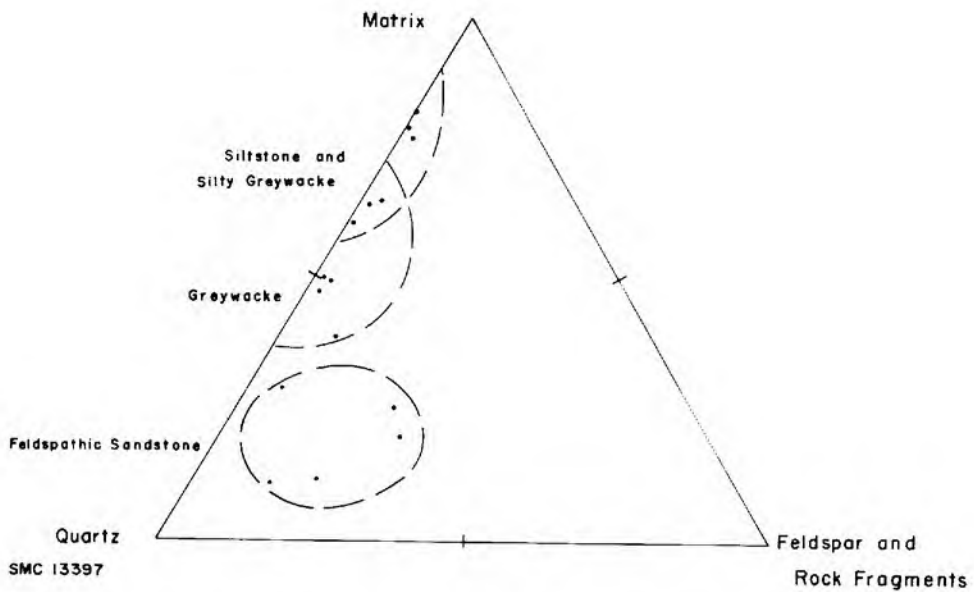


Figure 12—Triangular diagram showing mineralogical composition of rocks of the Pecors Formation, Sudbury-Manitoulin Area.

TABLE 6 | **CHEMICAL ANALYSES OF ROCKS OF THE HOUGH LAKE GROUP, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.**

Major Components in Weight Percent																
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻	CO ₂	TiO ₂	MnO	P ₂ O ₅	S	Total
(1)	88.90	5.44	0.26	0.92	0.32	0.19	0.60	2.11	0.81		-	0.19	0.01	0.04	-	99.79
(2)	74.25	10.39	0.26	5.32	2.12	0.51	2.15	1.28	2.26		0.27	0.49	0.05	0.15	-	99.50
(3)	83.55	8.05	1.08	0.98	0.65	0.34	1.25	2.65	1.06		0.26	0.20	0.08	0.04	-	100.19
(4)	62.60	19.60	0.42	5.35	3.40	1.01	1.20	2.17	2.49	0.12	0.12	0.93	0.07	0.08	-	99.44
Trace Elements in ppm																
	Ba	Co	Cr	Cu	Ga	Ni	Pb	Sc	Sr	V	Zn	Zr	Be			
(4)	500	20	250	50	35	70	30	20	300	100	100	120	3			

Notes

- (1) Paraconglomerate matrix, Ramsay Lake Formation.
- (2) Paraconglomerate matrix, Ramsay Lake Formation.
- (3) Paraconglomerate matrix, Ramsay Lake Formation.
- (4) Meta-siltstone, Pecors Formation.

Abbreviations

- Not detected

Mississagi Formation

The Mississagi Formation, the uppermost formation of the Hough Lake Group, is a thick sequence consisting of immature to submature, medium- to coarse-grained quartz-feldspar sandstone, with subordinate amounts of siltstone and argillite in the form of partings, interbeds, and units up to 200 feet (60 m) thick, and minor conglomerate lenses. Within the map-area, the Mississagi Formation forms three main outcrop areas, a northern area in the Porter and Vernon Synclines (Map 2360, back pocket), a central area extending from Harrow Township in the west to Eden and Broder Townships in the east, and a southern area exposed in the axial zones of the McGregor Bay Anticline in the Bay of Islands-McGregor Bay area.

The Mississagi Formation comprises a sequence of upward-coarsening sedimentary cycles composed mainly of sandstone with subordinate siltstone. Individual cycles are lensoid, vary in thickness from about 10 to 250 feet (3 to 70 m), and have sharp, non-erosional basal contacts. A typical complete Mississagi cycle, as described by Palonen (1971), is shown diagrammatically in Figure 13 and consists of the following units:

Unit A—Fine- to medium-grained feldspathic greywacke and subgreywacke with interbedded siltstone and sandy siltstone. The beds are generally less than 6 inches (15 cm) thick, are commonly graded or laminated, and crossbedding, where present, is of the planar type.

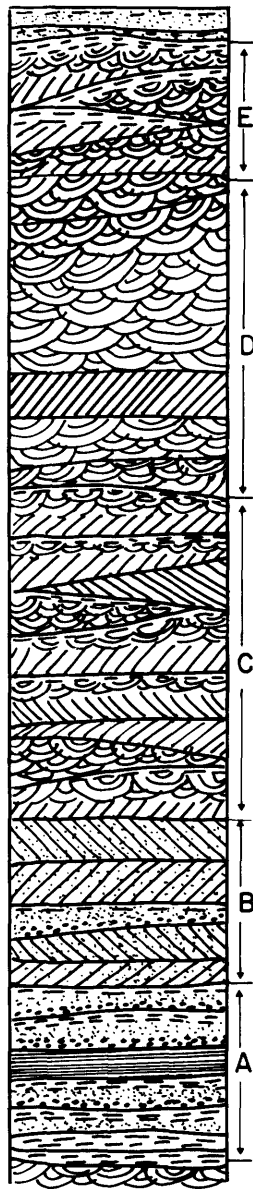
Unit B—Medium-grained quartz greywacke, subgreywacke, and feldspathic protoquartzite with minor siltstone. Beds are up to 1½ feet (0.5 m) thick and graded beds, planar crossbeds and graded planar crossbeds are present.

Unit C—Medium- to coarse-grained subarkose and arkose with minor pebbly siltstone partings. Beds average 2 to 3 feet (0.6 to 0.9 m) in thickness, are lenticular, and planar and trough crossbeds are present. Single beds generally display a distinctive crossbed pattern consisting of a lower single set of planar crossbeds up to 1 foot (0.3 m) thick which is truncated by a trough crossbedded coset up to 2 feet (0.6 m) thick. The sandstone beds are commonly overlain by sandy or pebbly siltstone with current ripples.




Unit D—Medium- to coarse-grained, thick-bedded (5 to 20 feet; 1.5 to 6 m) subarkose and arkose. Trough crossbedding is present throughout, and some beds up to 6 feet (1.8 m) thick represent individual sets of planar crossbeds.

Unit E—Subarkose with intercalated siltstone beds. Bedding in the sandstone is 2 to 3 feet (0.6 to 0.9 m) thick and both planar and festoon crossbeds are present. The siltstone is massive and commonly contains quartz and granitic pebbles up to 1 inch (2.5 cm) in diameter.

Rocks in the formation show a general upward increase in average grain size and in degree of sorting in the sandstone, and a corresponding decrease in the amount of silty material in the form of sandstone matrix and intercalations. Average grain size of the lower sandstones is approximately 0.2 to 0.3 mm, of the middle sandstones 0.3 to 0.5 mm, and of the upper sandstones 0.5 to 1.0 mm.



LEGEND

- 
 Siltstone and sandy and pebbly siltstone.
- 
 Feldspathic and quartz greywacke, subgreywacke and protoquartzite with laminated or graded beds and planar crossbedding.
- 
 Medium-to coarse-grained arkose and subarkose with planar and festoon crossbedding.

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Figure 13—Diagram of a sedimentary cycle in the Mississagi Formation (after Palonen 1971).



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Photo 15—Crossbedded sandstone of the Mississagi Formation, Merritt Township.

The silty matrix content of the lower sandstones is generally greater than 15 percent, whereas the middle and upper sandstones generally contain less than 15 percent matrix. The average thickness of the sedimentary cycles increases upward in the formation; units A and B are dominant in the lower cycles, units C and D are dominant in the cycles of the middle and upper parts of the formation. Unit E is developed only in the upper cycles.

The average thickness of bedding increases upward from about 6 inches (15 cm) to 2 feet (0.6 m) in the lower part, to 3 to 6 feet (0.9 to 1.8 m) in the upper part of the formation. Throughout much of the area, the uppermost 200 to 300 feet (60 to 90 m) of the formation, consists of coarse-grained, thick-bedded, (up to 20 feet (6 m) thick) arkose with festoon, planar, and graded planar crossbeds, and coarse, up to 2 inches (5 cm) thick laminations variously coloured in shades of pink, yellow, grey, green, and white (Photo 15). Scattered fragments of greenish and black siltstone or argillite and conglomeratic lenses are common in the upper half of the formation. The foregoing features indicate deposition in an environment of increasing energy and reworking.

The Mississagi Formation displays lateral variations in thickness and lithology. In the northern part of the map-area, the formation is approximately 2,000 feet to 3,000 feet (600 to 900 m) thick in Shakespeare and Porter Townships, and thins northward to a maximum of about 1,000 feet (300 m) in thickness in central Vernon Township. The formation consists mainly of medium- to coarse-grained feldspathic sandstone. Cycles are present, but are thin (10 to 100 feet; 3 to 30 m), and not well developed. Siltstone occurs mainly as sandstone matrix and partings.

In the central outcrop zone, the thickness of the Mississagi Formation varies from 5,000 to 7,000 feet (1500 to 2000 m) in the west to 8,000 to 10,000 feet (2400 to 3000 m) or more in the east (see Figure 11). Sedimentary cycles are thick, and relatively complete in the western and central parts of the belt, but the cycles are generally thinner (less than 100 feet ; 30 m) and less complete (commonly only units A, B, and C are developed) in the east. The amount of siltstone interbeds and members increases from less than 10 percent in the west to more than 20 percent in the east. A thick-bedded coarse arkose unit present at the top of the formation in the western and central parts of the outcrop zone gives way to thin- to medium-bedded feldspathic protoquartzite and subgreywacke as the formation is traced eastward. Several conglomeratic sandstone lenses approximately 50 to 200 feet (15 to 60 m) thick are present in the upper part of the formation in the central and eastern parts of the belt.

The Mississagi Formation exceeds 4,000 feet (1200 m) in thickness in the McGregor Bay area, where its base is not exposed, and consists of mainly feldspathic sandstone. Appreciable amounts of siltstone (approximately 20 percent) occur in the lower half of the formation. Some thin, less than 6-inch (15 cm) thick, conglomeratic sandstone lenses are present in the upper part. Silty sandstone units in the lower part may contain up to 2 percent hematite which forms grain coatings, irregular disseminations, and concentrations along fracture surfaces. Sedimentary cycles are generally well developed, and the upper coarse arkose unit is present.

Sandstone in the Mississagi Formation ranges in composition from orthoquartzite to arkose to greywacke (Figure 14). Most contain approximately 60 to 90 percent quartz, 5 to 20 percent feldspar and rock fragments, and 5 to 30 per-

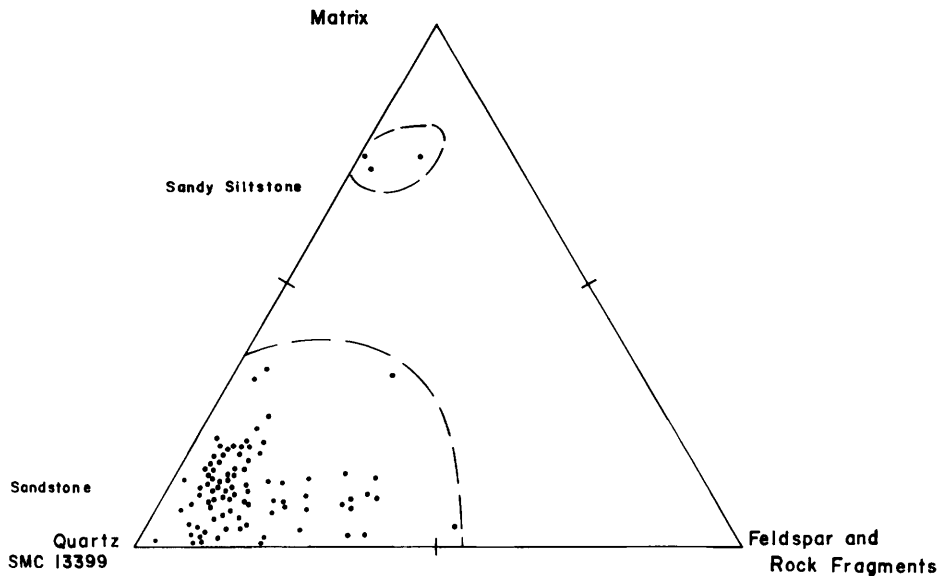


Figure 14a—Triangular diagram to show range in mineralogical composition of sandstone and siltstone in Mississagi Formation; Sudbury-Manitoulin Area; all positions 94 points.

Sudbury-Manitoulin Area

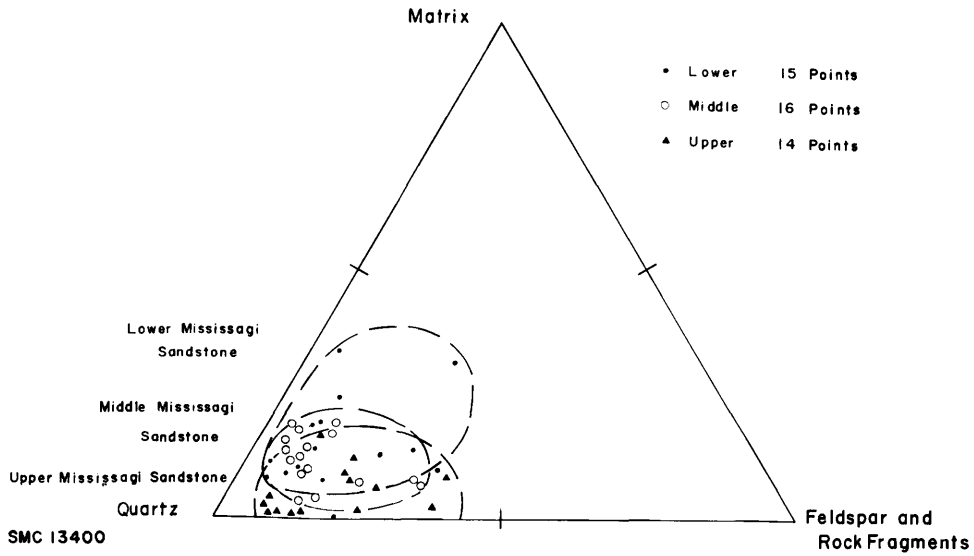


Figure 14b—Triangular diagram to show stratigraphic variation in mineralogical composition of sandstone in Mississagi Formation; Sudbury-Manitoulin Area. Lower Mississagi Formation, 15 points; Middle Mississagi Formation, 16 points; Upper Mississagi Formation, 14 points.

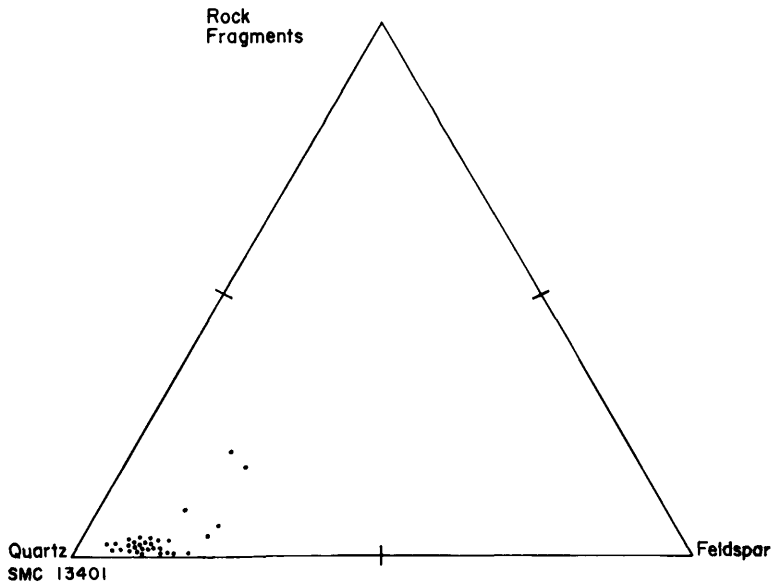


Figure 14c—Triangular diagram to show mineralogical composition of sandstones with recognizable rock fragments in Mississagi Formation; Sudbury-Manitoulin Area.

cent interstitial matrix consisting of phyllosilicate minerals and silt-size quartz and feldspar. Sandstones typical of the lower parts of the formation, and of the lower parts of sedimentary cycles throughout the formation, are fine- to medium-grained, poorly sorted greywacke, subgreywacke, and protoquartzite containing 40 to 85 percent (average 65 percent) quartz, 5 to 35 percent (average 10 percent) feldspar and rock fragments, and 10 to 35 percent (average 15 percent) matrix (Figure 14). Sandstone typical of the middle parts of cycles, and of the middle part of the formation in general, are poorly to moderately sorted, medium-grained feldspathic protoquartzite, subarkose, and subgreywacke containing 60 to 75 percent (average 70 percent) quartz, 5 to 30 percent (average 10 percent) feldspars and rock fragments, and 5 to 20 percent (average 12 percent) matrix. The medium- to coarse-grained, moderately well-sorted subarkose and arkose typical of the upper parts of individual cycles and of the upper part of the formation consist of approximately 70 percent quartz, 15 to 25 percent feldspars and rock fragments, and 5 to 10 percent matrix. Orthoquartzite is rare, and consists largely (95 percent) of quartz, probably both detrital grains and recrystallized authigenic cement, with minor amounts of muscovite and feldspar.

Potassic feldspar and plagioclase are present in Mississagi rocks and include twinned microcline, untwinned orthoclase, perthite, and twinned albite-oligoclase. The ratio of potassic feldspar to plagioclase is commonly in the range 1:1 to 2:1, and the proportion of potassic feldspar to plagioclase increases upward in general. The ratio of quartz to feldspars ranges from 10:1 to 2:1 and averages about 6:1.

Recognizable rock fragments are not abundant, generally constituting less than 5 percent of the rock, or are absent entirely. The rock fragments include granitic, felsic metavolcanic, and schistose metasedimentary varieties, and occur in about that order of abundance. Polygranular quartz fragments, which probably represent recrystallized detrital vein quartz as well as chert and quartzite, are present in amounts of up to 10 percent in some of the samples studied. Locally, siltstone and argillite fragments, ranging in size from microscopic to slabs a foot (0.3 m) or more in length, are abundant. These fragments were probably derived by fragmentation of silty interbeds within the sequence, and cannot be taken as evidence of a metasedimentary provenance in contrast to the predominantly felsic plutonic (quartz monzonite, granodiorite) provenance indicated by the other compositional criteria.

Muscovite is the chief phyllosilicate mineral, and minor amounts of biotite and chlorite are commonly also present. Minor amounts of recrystallized authigenic quartz cement are present in a few of the samples studied. Accessory minerals, including pyrite, iron-titanium oxides, sphene, carbonate, zircon, and tourmaline, are present in amounts of 0.5 to 1.0 percent. Pyrite, in the form of locally disseminated cubic crystals constitutes up to approximately 2 percent of the rock. Hematite is an important accessory in some beds, occurring as disseminations and grain coatings in amounts up to about 1 or 2 percent.

Siltstone, sandy siltstone, and laminated argillite of the Mississagi Formation are dark green to black, thin-bedded, commonly laminated or cross laminated, rocks consisting of abundant phyllosilicate minerals (muscovite, biotite, chlorite) and silt size quartz and feldspars. Sand to granule size quartz, feldspars, and rock fragments are present in the sandy varieties of these rocks in amounts up to 30 percent.

Several types of conglomeratic rock occur as thin, discontinuous lenses. Pebbly lenses a few inches thick consisting of small, less than ½ inch (1 cm) diameter pebbles of quartz and granite in a siltstone or mudstone matrix are common in Unit C of the sedimentary cycles. These appear to represent lag deposits formed by winnowing of the underlying sediment. Coarse arkose in the upper part of the formation is locally conglomeratic, containing scattered, small pebbles and granules of quartz, feldspars, and granite. The polymictic paraconglomerate lenses present are up to about 100 feet (30 m) thick and consist of 20 to 60 percent pebbles of quartz, granite, and mafic igneous rocks in a poorly sorted feldspathic greywacke or protoquartzite matrix. Also present are oligomictic quartz-pebble conglomerate units similar to those of the Matinenda Formation, except that the pebbles are smaller, less than 1 inch (2.5 cm) in diameter, and less abundant (20 to 50 percent), and pyrite and uranium-bearing minerals are rare or absent.

QUIRKE LAKE GROUP

Bruce Formation

The basal part of the Quirke Lake Group, the Bruce Formation, is a relatively thin, sheet-like body of polymictic paraconglomerate with minor amounts of intercalated quartz-feldspar sandstone, greywacke, siltstone, and calcareous siltstone. Within the map-area, the rocks of this formation form three main outcrop zones: a northern zone in the Porter and Vernon Synclines (see Map 2360, back pocket); a central zone which extends eastward from Harrow Township to Lake Panache where it splits, one part extending along the north shore of Lake Panache to Eden Township, the other part extending south of Lake Panache to Bevin Township; and a southern zone exposed about the McGregor Bay Anticline in the Bay of Islands-McGregor Bay area.

The contact between the Bruce Formation and the underlying Mississagi Formation is generally abrupt and regular with no evidence of erosion or of angular discordance between the underlying Mississagi sandstone and the Bruce conglomerate (Photo 16). However, there are exceptions to this generalization. At several localities in Foster Township, in the Louise-Eden area, in Vernon Township, and in the McGregor Bay area, the contact is gradational with interbedding of feldspathic sandstone and conglomerate over a stratigraphic interval that is 10 to 50 feet (3 to 15 m) thick. Ginn (1961) described the Mississagi-Bruce contact in Porter Township as being gradational from quartzite into conglomerate and marked by the appearance of pebbles accompanied by an increase in silt and clay content of the matrix material. In some places, as in southwestern Porter Township, the contact between the sandstone and overlying conglomerate is transitional through a boulder-free greywacke unit up to 70 feet (20 m) thick.

In contrast, evidence at other localities indicates that the Mississagi-Bruce contact represents an erosional disconformity. On the south shore of McGregor Island, the base of the Bruce conglomerate bevels across bedding in the underlying Mississagi sandstone. In Eden Township, near the Grenville Front Tectonic



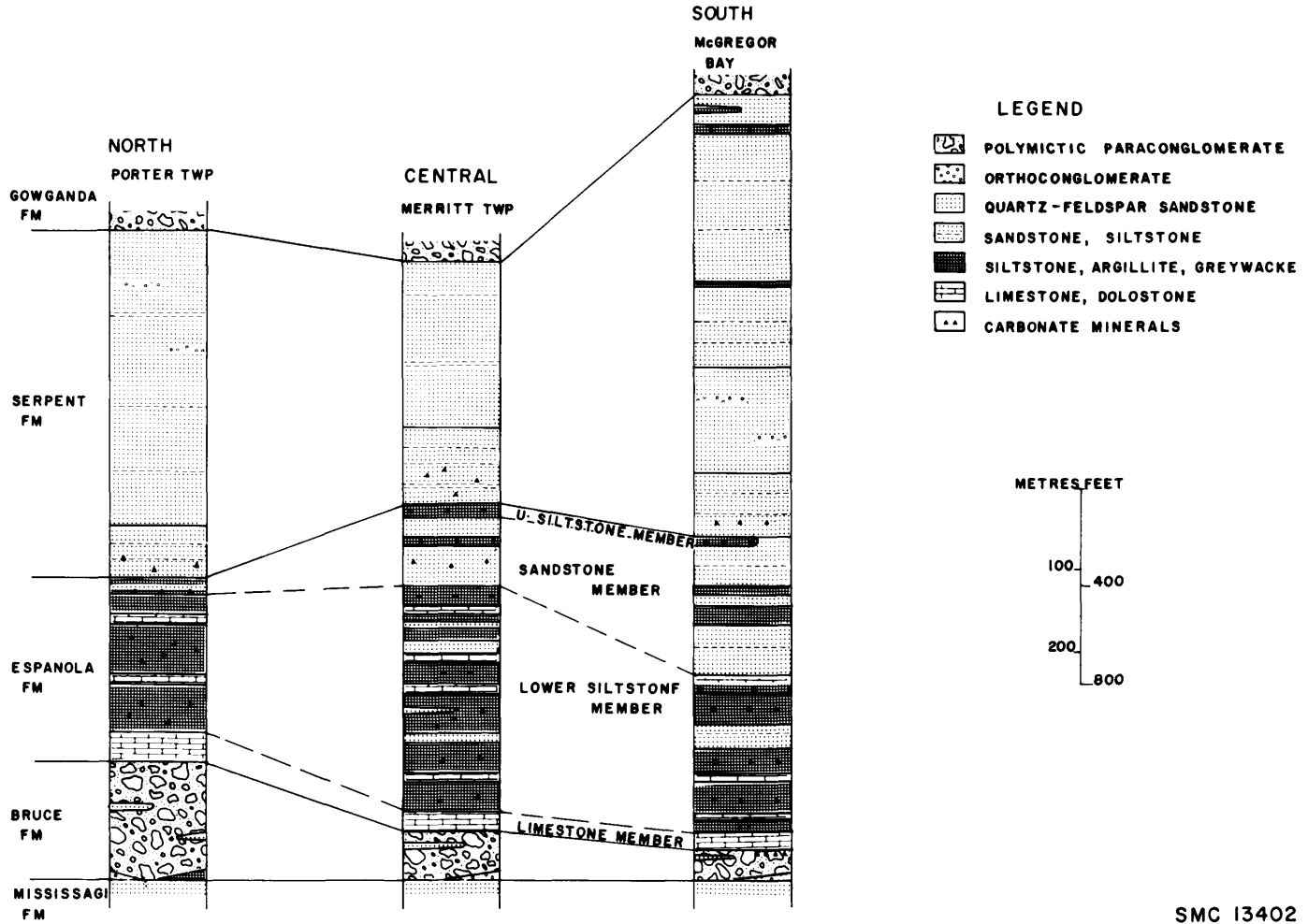
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Photo 16—Abrupt, non-erosional contact between sandstone of the Mississagi Formation (right) and conglomerate of the Bruce Formation (left), Merritt Township.

Zone, the contact is sharp and irregular with local relief of several feet, and large blocks of Mississagi-type sandstone are present in the lower part of the Bruce Formation. Even in areas where the contact is abrupt but regular and apparently conformable, as in Merritt Township, the lower part of the poorly sorted immature Bruce conglomerate contains angular, sharp-bordered fragments of Mississagi-type sandstone, lensoid, wisp-like bodies of sandstone with diffuse margins, and a high proportion of coarse, well-rounded quartz grains. The nature of the contact between the Mississagi Formation and the Bruce Formation varies, from being gradational to abrupt but conformable, to erosional and disconformable, and apparently bears no relationship to location within the map-area, to thickness of the Bruce Formation, or to regional structural elements.

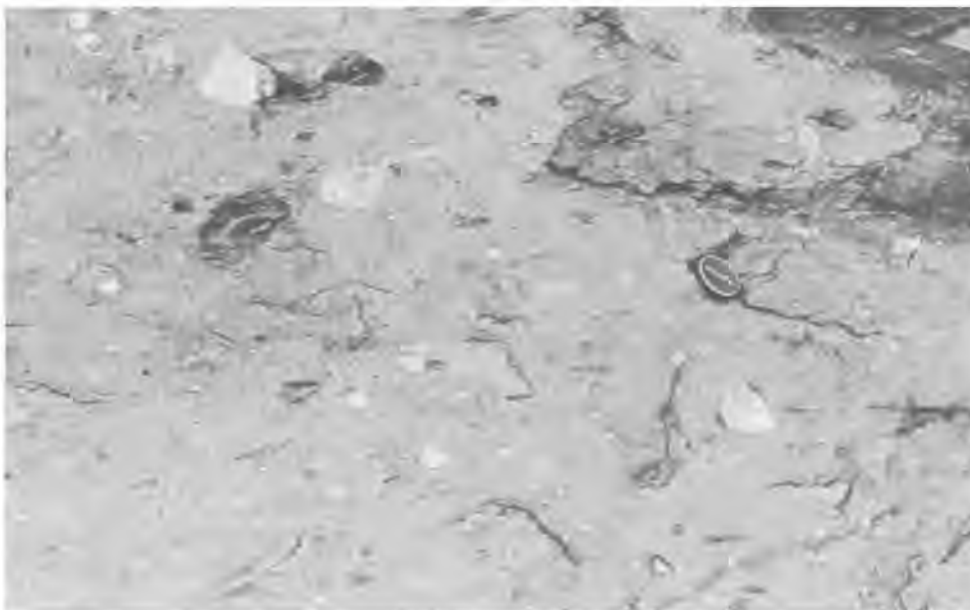
In the north, the Bruce Formation varies from approximately 200 to 1,300 feet (60 to 400 m) in thickness, and is on average about 500 feet (150 m) thick (Figure 15). It consists mainly (95 percent) of polymictic paraconglomerate with a greywacke matrix, but locally the basal unit consists of pebble-free greywacke, or of polymictic paraconglomerate with a moderately sorted subgreywacke-protoquartzite matrix, interbedded with feldspathic sandstone.

In the central zone, the thickness of the formation is up to about 1,500 feet (450 m), but averages only 200 to 300 feet (60 to 90 m). The formation apparently thins eastward toward the Grenville Front Tectonic Zone, and around Wavy Lake in Eden Township it is less than 50 feet (15 m) thick or missing entirely. In the thinner sections, polymictic paraconglomerate with greywacke ma-



SMC 13402

Figure 15—Generalized stratigraphy of the Quirke Lake Group, Sudbury-Manitoulin Area.



ODM9588

Photo 17—Polymictic paraconglomerate of the Bruce Formation, Merritt Township.

trix is abundant (95 percent) with only minor amounts of the following present: paraconglomerate and orthoconglomerate with protoquartzite matrix; and feldspathic sandstone and greywacke. In the thicker sections, appreciable amounts (15 to 20 percent) of feldspathic sandstone, siltstone, and greywacke are interbedded with the conglomeratic rocks.

In the south, the Bruce Formation is less than 200 feet (60 m) thick, is commonly only 20 to 50 feet (6 to 15 m) thick, and is locally missing entirely. The formation consists mainly of polymictic paraconglomerate with minor, local units of orthoconglomerate and feldspathic sandstone in the lower parts. In summary, the Bruce Formation exhibits a general trend of southward and eastward thinning.

The conglomeratic rocks of the Bruce Formation are characteristically massive, unbedded, and unsorted (Photo 17). Thick beds are poorly defined in certain areas by the following: variations in pebble size and sorting; variations in matrix composition; and by sandstone and siltstone interbeds and lenses. Ginn (1961) noted that in the lower part of the formation in Porter Township, pebbles appear to have been dropped into silty sandstone before consolidation of the latter. Casshyap (1967) found that the long axes of pebbles have a preferred, approximately north-south orientation in the Espanola-Whitefish Falls area.

Polymictic paraconglomerate forms most of the Bruce Formation, and is a dark grey, buff or rusty weathering rock composed of pebbles, cobbles, and boulders, mainly of felsic plutonic derivation in a silty sandstone matrix. Angular to subrounded rock fragments constitute 5 to 40 percent of the rock, and are generally present in amounts of about 15 percent by volume.

Polymictic orthoconglomerate, present in minor amounts in the lower part of the formation, contains up to 70 percent pebbles that are generally less than 1 inch (2.5 cm) in diameter, and are relatively well rounded and sorted. Granitic rock fragments are the most abundant, constituting 40 percent to 80 percent, and averaging approximately 60 percent of the clasts over ½ inch (1 cm) in diameter. Quartz and quartzite (1 to 25 percent; average 20 percent), mafic igneous (1 to 30 percent; average 15 percent), felsic volcanic (1 to 35 percent; average 5 percent), and pelitic metasedimentary (0 to 10 percent; average 2 percent) varieties are also present. Fragments range in maximum dimension from less than ½ inch (1 cm) to about 5 feet (1.5 m) and average about 1 inch (2.5 cm). Ninety percent or more of the fragments are less than 3 inches (8 cm) in diameter.

The paraconglomerate matrix is mainly poorly sorted, immature silty sandstone characterized by the presence of numerous quartz grains and granules 1 to 5 mm in diameter and by disseminated sulphide minerals, which upon weathering impart the typical buff or rusty weathered surface to the rock. The matrix consists of angular to rounded grains of quartz and chert (25 to 70 percent; average 45 percent), feldspars (5 to 20 percent; average 7 percent), pelitic rock fragments (0 to 10 percent; average 3 percent), and felsic igneous rock fragments (0 to 10 percent; average 2 percent) with abundant (20 to 70 percent; average 35 percent) interstitial muscovite, chlorite, biotite, and silt size quartz and feldspar (Figure 16). The size distribution of the conglomerate matrix constituents is polymodal with the principal mode in the fine-sand range (0.1 to 1.25 mm) and secondary modes in the coarse sand-granule range (0.5 to 5 mm) and in the clay-silt range. The coarser secondary mode is attributable to rounded quartz grains and small rock fragments, the finer secondary mode to silty interstitial material. The conglomerate matrix is mainly feldspathic greywacke, but lithic greywacke, quartz greywacke, subgreywacke, and protoquartzite also compose it. The ratio of potassic feldspar to plagioclase varies widely, but generally plagioclase is the most abundant feldspar. Lithic greywacke tends to have a relatively high plagioclase content, feldspathic greywacke may have either a high plagioclase or a high potassic feldspar content. Quartz greywacke, subgreywacke, and protoquartzite matrices commonly have high potassic feldspar contents relative to that of plagioclase. Accessory minerals commonly present in amounts of about 1 to 3 percent, include carbonate, zircon, tourmaline, epidote, sphene, and iron-titanium oxides. Sulphides, mainly pyrite and pyrrhotite with rare chalcopyrite are generally present in amounts of 1 to 5 percent. Carbonate minerals present in the upper part of the formation in amounts of 1 to 5 percent, consist mainly of dolomite with lesser calcite.

Chemical analyses of typical Bruce conglomerate matrices given in Table 7 show that these rocks have K_2O/Na_2O , CaO/Na_2O , and Al_2O_3/Na_2O ratios of about 0.9, 0.3, and 4 respectively. Comparison of these with the ratios given for conglomeratic rocks of the Ramsay Lake and Gowganda Formations (Tables 6 and 8) shows that the Bruce conglomerate is intermediate in chemical maturity between these two formations.

The sandstone of the Bruce Formation is mainly poorly to moderately sorted, medium-grained feldspathic protoquartzite and subgreywacke similar to rocks of the Mississagi Formation and consists of approximately 55 to 75 percent quartz, 5 to 35 percent feldspars and minor rock fragments, and 10 to 30 percent matrix. The greywacke is compositionally and texturally similar to the paracon-

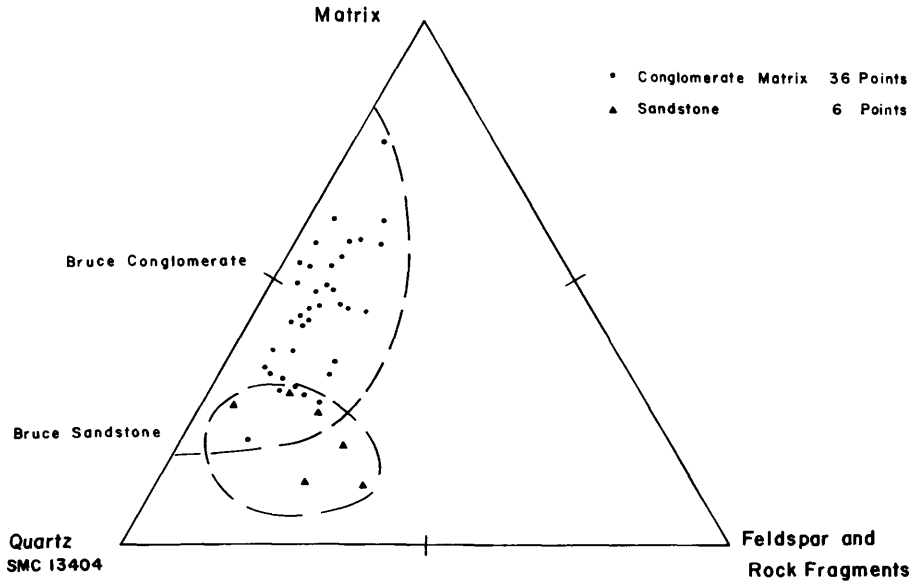


Figure 16a—Triangular diagram to show mineralogical compositions of sandstone and conglomerate in the Bruce Formation; Sudbury-Manitoulin Area. Conglomerate matrix, 36 points. Sandstone, 6 points.

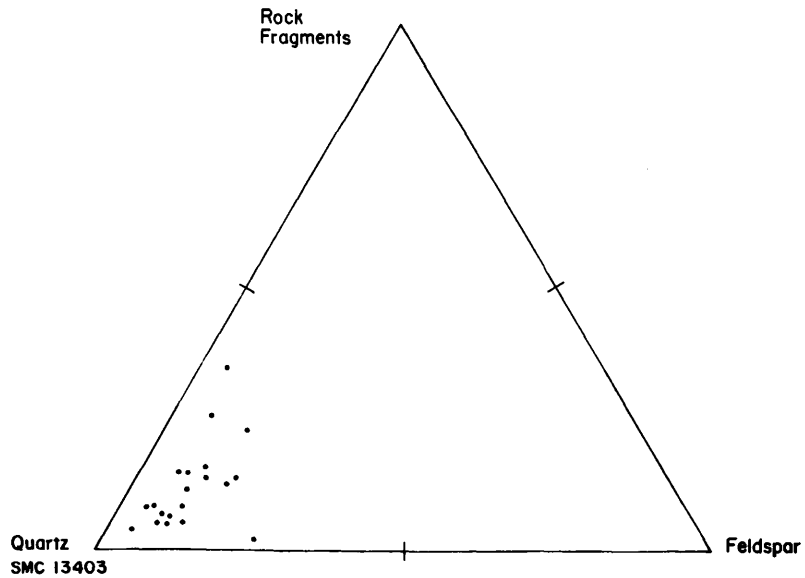


Figure 16b—Triangular diagram to show mineralogical compositions of conglomerate matrices with recognisable rock fragments in the Bruce Formation; Sudbury-Manitoulin Area.

TABLE 7 | **CHEMICAL ANALYSES OF ROCKS OF THE QUIRKE LAKE GROUP, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.**

Major Components in Weight Percent																	
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻	CO ₂	TiO ₂	MnO	P ₂ O ₅	S	Total	S.G.
(1)	4.37	0.76	0.36	0.70	0.59	51.00	0.04	0.30	-	0.41	40.00	0.05	0.32	0.22	0.06	99.42	2.72
(2)	26.15	2.71	1.60	2.48	3.91	31.56	0.84	0.80	0.66	0.01	28.25	0.11	0.22	0.06	0.05	99.41	2.79
(3)	45.50	12.50	5.82	12.55	4.65	2.13	0.57	2.34	5.53	0.70	2.22	3.65	0.17	0.15	0.02	98.74	2.68
(4)	59.30	15.60	1.09	3.98	6.80	2.42	1.70	4.92	1.11	0.05	0.82	0.53	0.03	0.12	0.27	98.74	-
(5)	73.50	9.58	-	0.55	0.56	5.35	4.10	0.80	0.18	0.06	4.40	0.14	0.08	0.03	0.02	99.35	2.64
(6)	73.50	11.92	1.39	1.88	2.18	0.20	3.50	3.12	1.48	-	-	0.46	-	0.11	-	99.74	-
(7)	70.55	12.10	0.88	3.64	2.02	1.64	2.84	2.29	2.20	-	0.72	0.56	-	0.14	-	99.58	-

Notes

- (1) Limestone (marble), Espanola Formation, McGregor Bay.
 (2) Silty limestone, Espanola Formation, Foster Township.
 (3) Calcareous siltstone, Espanola Formation, Foster Township.
 (4) Calcareous siltstone, Espanola Formation, (scapolitic hornfels), Merritt Township.
 (5) Calcareous sandstone, Espanola Formation, Mongowin Township.
 (6) Paraconglomerate matrix, Bruce Formation.
 (7) Paraconglomerate matrix, Bruce Formation.

Abbreviations

- Not detected
 S.G. Specific Gravity



ODM9589

Photo 18—Contact between crudely stratified paraconglomerate of the Bruce Formation (right) and thin-bedded silty limestone of the Espanola Formation (left), McGregor Bay.

glomerate matrix, and siltstone and calcareous siltstone lenses are comparable to rocks of the overlying Espanola Formation.

Espanola Formation

Rocks of the Espanola Formation comprise well-bedded metamorphosed siltstone, sandstone, limestone, and dolostone, and are characterized by the prevalence of carbonate minerals. The formation represents one of the oldest, extensive carbonate deposits of sedimentary origin in the geological record, and is the only carbonate-bearing unit of note in the Huronian succession.

The Espanola Formation is exposed in the northern, central, and southern parts of the map-area where it is in generally abrupt, but conformable contact with the underlying Bruce Formation (Photo 18) and in gradational contact with the overlying Serpent Formation. Disseminated carbonate minerals are commonly present in the upper part of the Bruce conglomerate. Locally, as in the area north of Lake Panache and along the northern shore of McGregor Bay, there is interstratification of Bruce-type conglomerate and Espanola-type calcareous rocks over a narrow stratigraphic interval. The contact with the overlying Serpent Formation is commonly gradational over a stratigraphic interval several hundred feet wide wherein the proportion of sandstone increases relative to the proportions of siltstone and carbonate minerals which decrease upward. At many localities in the south, a thin unit of calcareous siltstone and limestone

within this transition zone serves as a convenient marker horizon to separate the two formations.

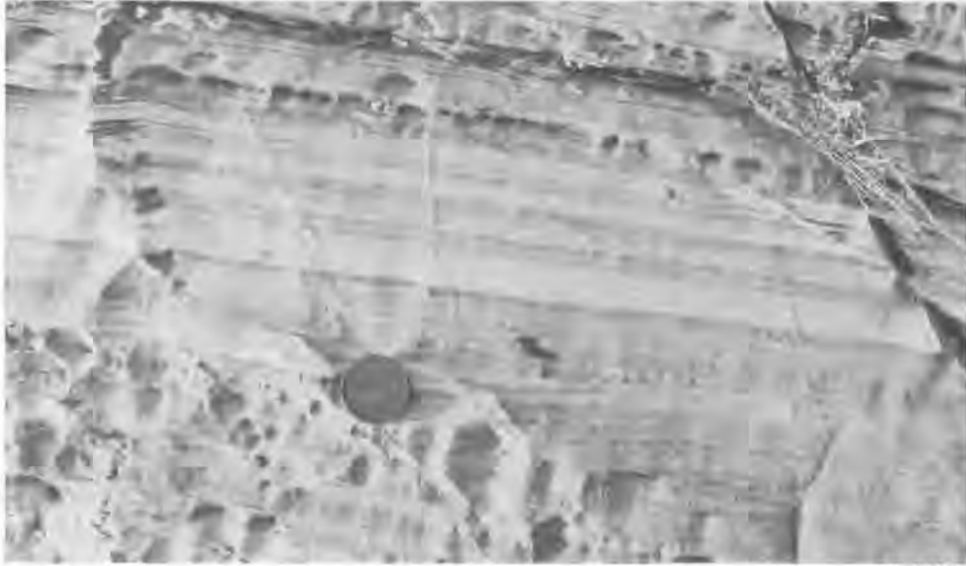
The Espanola Formation is divisible into several conformable intergradational lithological members including in ascending order: a unit of limestone, calcareous siltstone, and dolostone, herein termed the Limestone Member; a thick unit consisting of mainly siltstone, the Lower Siltstone Member; a thick unit of sandstone, the Sandstone Member; and a thin discontinuous calcareous siltstone-limestone unit, the Upper Siltstone Member (see Figure 15). The first two members correspond generally to the "Bruce Limestone" and "Espanola Greywacke" units of Collins (1925). In the south, a thin, poorly defined unit of calcareous siltstone, limestone, and dolostone is locally distinguishable at the top of the Lower Siltstone Member, and this may correspond to Collins' "Espanola Limestone" (Young 1973).

The thick Sandstone Member included here with the Espanola Formation could also be assigned to the Serpent Formation. It has features in common with the Serpent Formation, such as the prevalence of crossbedded sandstone rich in quartz and feldspar. This member, nevertheless, also contains appreciable amounts of carbonate minerals and siltstone, and displays ball-and-pillow structures, features typical of the Espanola Formation.

The Espanola Formation generally thickens southward, from about 500 to 800 feet (150 to 240 m) in the north to 1,000 to possibly 2,000 feet (300 to 600 m) in the south. Within the central belt, the formation apparently thins eastward from an average thickness of 1,200 feet (360 m) in the west to about 600 feet (180 m) adjacent to the Grenville Front Tectonic Zone in Eden Township. In general, where the formation is thin, the Sandstone Member is thin or absent, the Limestone Member is thicker than the other members and contains a higher proportion of "pure" limestone, and the siltstone units are finer grained on the average (Figure 15).

In the north in Vernon and Porter Townships, the formation is about 700 feet (200 m) thick, and includes a lower limestone unit 200 feet (60 m) thick, a lower siltstone unit 400 feet (120 m) thick, and an upper, thin 100-foot (30 m) thick sequence of interbedded sandstone and siltstone which represents the transition into the overlying Serpent Formation. The Limestone Member is composed of white to light grey "pure" limestone beds approximately 1 to 4 inches (2.5 to 10 cm) thick with numerous thin ¼- to 1-inch (0.6 to 2.5 cm) contorted interbeds of black fine-grained siltstone. Some rusty weathering dolostone beds are present in the upper part of the Limestone Member, and the siltstones of the succeeding member are fine grained and thin bedded, being generally less than ½ inch (1.3 cm) thick.

In the central and southern parts of the map-area, the Limestone Member is generally less than 100 feet (30 m) thick, and consists mainly of silty limestone and calcareous siltstone (70 percent) with lesser amounts of limestone (20 percent) and minor dolostone and fine-grained greywacke (10 percent). The amount of siltstone increases upward in the member. These rocks are thin-bedded (generally less than 1 inch (2.5 cm) thick) and commonly display rhythmic alternations of light-coloured, carbonate-rich and dark-coloured silt-rich laminae, or thin beds about 0.4 inch to 1 inch (10 mm to 2.5 cm) thick (Photo 19). Some ball-and-pillow structures and slump folds are present. In southeastern McGregor Bay area, a bed of sedimentary breccia consists of angular dolostone and dolomi-



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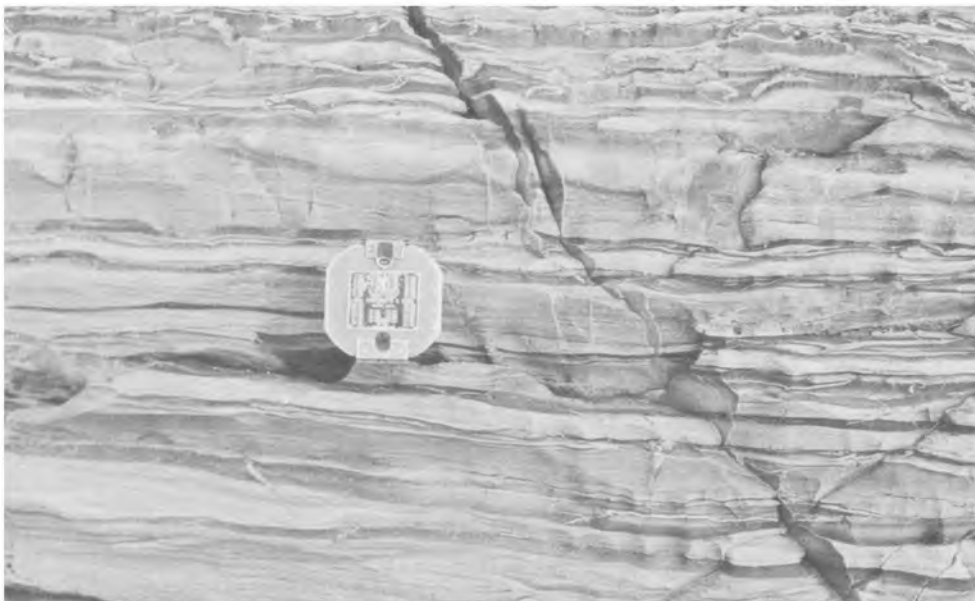
Photo 19—Silty limestone of the Espanola Formation with parallel laminations, McGregor Bay.

tic siltstone chips arranged in an imbricate fashion. In the Lake Panache area, a basal unit up to 200 feet (60 m) thick consists of thin-bedded, black, non-calcareous argillite. In Foster Township, some thin interbeds of greenish, laminated, chert-like siltstone are commonly disrupted to form a breccia consisting of angular chips and blocks of greenish “chert” in a dark grey calcareous siltstone matrix.

The Lower Siltstone Member ranges from 400 to 800 feet (120 to 240 m) in thickness, averages 700 feet (200 m) in thickness, and consists of calcareous and non-calcareous siltstone, argillite, and fine-grained greywacke (70 percent) with interbeds of limestone, and quartz-feldspar sandstone (30 percent), especially in the upper parts of the unit. Bedding ranges in thickness from less than 1 inch to about 1 foot (2.5 to 30 cm), and is commonly less than 2 inches (5 cm). Sedimentary structures are particularly abundant, and include graded beds, parallel laminations, ripples, and ripple-drift cross-lamination present in Bouma-type cycles. Spheroidal, concretion-like structures, small lensoid sand bodies with internal cross-lamination which represent starved ripples, ball-and-pillow and flame structures, sandstone and siltstone injections, some of which resemble desiccation cracks, clastic dikes, slumped and brecciated beds, and slump folds are prevalent (Photos 20 and 21).

The Sandstone Member varies in thickness from about 300 to 700 feet (90 to 200 m), and averages 500 feet (150 m) thick in the central area; and is 500 to 1,000 feet (150 to 300 m) thick and averages 800 feet (250 m) in thickness in the south. It consists mainly (75 percent) of medium-bedded calcareous and non-calcareous white to pinkish weathering quartz-feldspar sandstone with interbedded siltstone and calcareous siltstone (25 percent). Planar and trough crossbeds are

Sudbury-Manitoulin Area



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Photo 20—Silty limestone and calcareous siltstone of the Espanola Formation with ripple cross-lamination and clastic dikelets (pseudo-mudcracks), Bay of Islands.



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Photo 21—Calcareous siltstone and silty limestone of the Espanola Formation displaying climbing ripples and "starved" ripples, McGregor Bay.

common in sandstone, as are ripples and laminations in siltstone. Large-scale tabular crossbeds and ball-and-pillow structures occur in the upper parts of this member. Fining-upward sedimentary cycles in this unit have been described by Young (1973). These are 5 to 15 feet (1.5 to 4.5 m) thick, have an erosional base, and consist of lower thick units of crossbedded sandstone overlain successively by planar bedded sandstone, cross-laminated and rippled siltstone, and argillite.

The Upper Siltstone Member, which is up to 50 feet (15 m) thick and consists mainly of thin-bedded (less than 1 to 6 inches; 2.5 to 15 cm) calcareous siltstone with lesser amounts of silty limestone, dolostone, and quartz-feldspar sandstone. Laminated bedding, cross-laminations, ball-and-pillow structures, and clastic dikes occur in this member.

The white to grey metamorphosed limestone, dolostone, and silty sandy limestone and dolostone of the Espanola Formation consist of calcite and dolomite (70 to 90 percent; average 75 percent) with variable amounts of sand size quartz and feldspar (0 to 30 percent; average 20 percent), silty clastic material and phyllosilicate minerals of metamorphic origin (0 to 20 percent; average 5 percent). The mineralogical and chemical composition of rocks of the Espanola Formation are shown in Figure 17. The texture is a metamorphic one consisting of a mosaic of recrystallized carbonate and phyllosilicate minerals with "floating" corroded clastic grains of quartz and feldspar. Large metamorphic porphyroblasts of mica, chlorite, amphibole, scapolite, garnet, and idocrase are common. Accessory minerals include epidote, clinozoisite, sulphide, iron-titanium oxide, zircon, and apatite. The limestone and dolostone of the Limestone Member are mainly fine grained, with detrital clastic material of silt size (less than 0.05 mm) whereas those rocks in the middle and upper parts of the formation generally contain appreciable amounts of fine-grained sand size material, mainly quartz and sodic plagioclase. Calcite is the dominant carbonate mineral in carbonate-rich rocks throughout the formation, except for some dolomite-rich units in the upper parts of the Limestone, Lower Siltstone, and Upper Siltstone Members. Young (1973) has shown that dolomite from the Espanola Formation contains 4 to 9 molar percent siderite in solid solution; this accounts for its rusty weathering nature. He has also shown that the calcite is essentially free of magnesia and iron.

Siltstone and fine-grained greywacke, although characteristic of the siltstone members occur throughout the formation. They are dark grey to black, fine-grained (less than 0.1 mm), poorly sorted rocks composed of phyllosilicate minerals, angular to subrounded grains of quartz and feldspar, and variable amounts (0 to 60 percent) of carbonate minerals. The ratio of calcite to dolomite is variable, but in general calcite is dominant except in the upper parts of the Limestone and Lower Siltstone Members. Modal analyses, plotted in terms of the components carbonate, sand-size quartz and feldspar, and silt-size material and phyllosilicate minerals (Figure 17), show that the siltstone and greywacke consist of variable proportions of these components, and that they fall into two groups, one having less than 10 percent carbonate minerals, the other about 30 percent carbonate. The ratio of potassic feldspar to plagioclase is variable (0.5 to 15) but in general, plagioclase is dominant. Rock fragments, mainly siltstone and chert, are present in the sandy rocks in amounts of up to 10 percent but generally constitute less than 3 percent. Minor amounts of zircon, apatite, tourmaline, iron-titanium oxides, and sulphide minerals are present.

Sudbury-Manitoulin Area

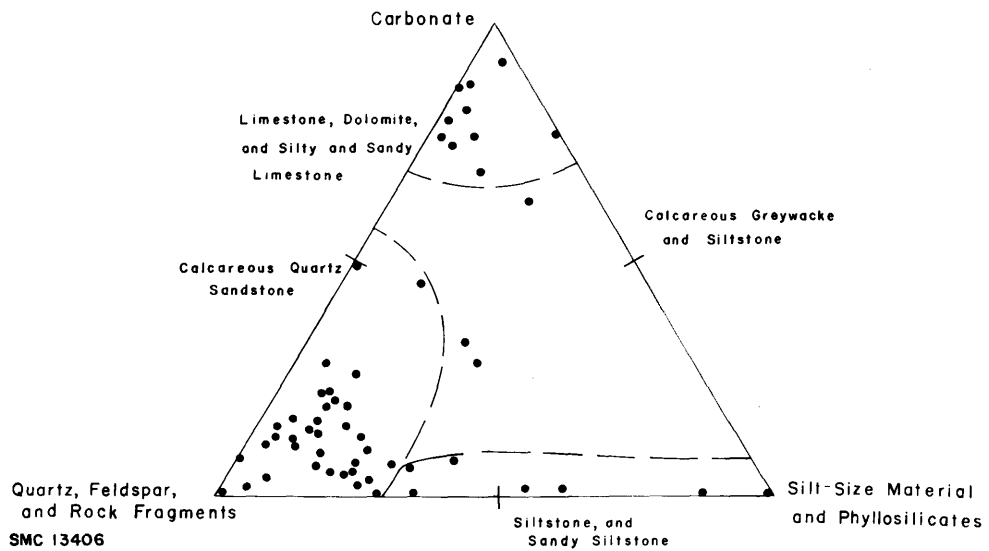


Figure 17a—Triangular diagram to show mineralogical compositions of rocks of the Espanola Formation; Sudbury-Manitoulin Area. All positions 55 points.

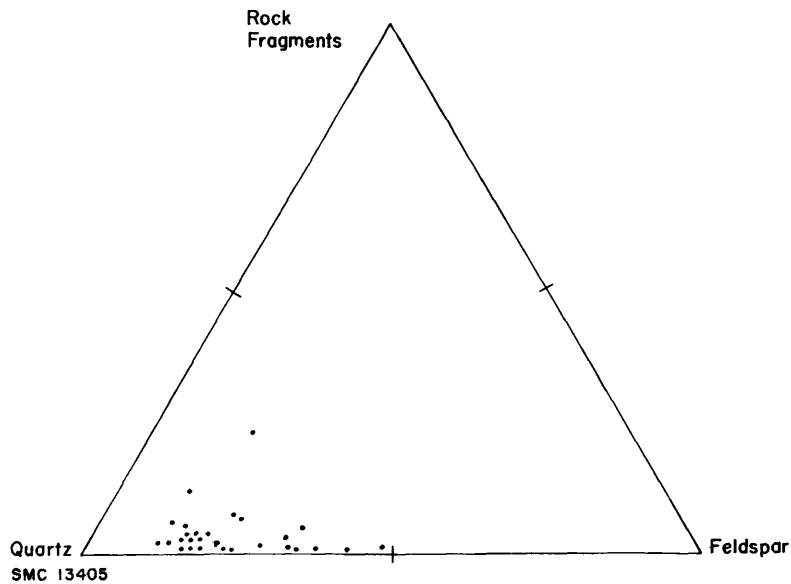


Figure 17b—Triangular diagram to show mineralogical compositions of sandstone of the Espanola Formation with recognisable rock fragments, Sudbury-Manitoulin Area.

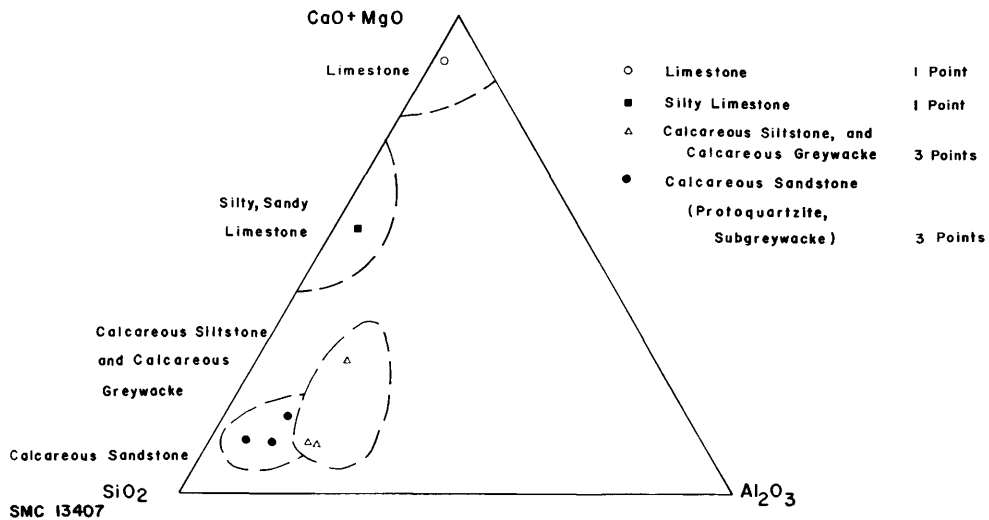


Figure 17c— $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-CaO}$ diagram to show chemical composition of analyzed rocks of the Espanola Formation; Sudbury-Manitoulin Area.

Quartz-feldspar sandstone, mainly present in the upper part of the formation, is a grey to pink-weathering, poorly to moderately sorted rock consisting of fine- to coarse-grained, angular to rounded grains of quartz, feldspar, and rock fragments (60 to 90 percent; average 70 percent) in a matrix of silty material and phyllosilicates (1 to 30 percent; average 15 percent), and carbonate (0 to 50 percent; average 15 percent). The carbonate minerals, both calcite and dolomite, occur as interstitial cement and as disseminated patches and euhedral crystals. Rusty weathering dolomite rhombs are present in the upper part of the Sandstone Member. Feldspar, commonly present in amounts of 10 to 15 percent includes potassic feldspar and plagioclase, the latter being the dominant species. Rock fragments, present in amounts up to 10 percent, but generally constituting less than 2 percent, include siltstone and granitoid varieties. Most of the sandstone is fine to medium grained (0.1 to 0.5 mm), and has a unimodal size distribution. However, in the upper part of the formation, sandstone beds show a distinct bimodal grain size distribution consisting of well-rounded quartz grains and granules (1 to 10 mm) in a poorly to moderately sorted, fine- to medium-grained sandstone matrix.

Chemical analyses of the main rock types are given in Table 7, and plotted in Figure 17c. $\text{CaO} + \text{MgO} - \text{SiO}_2 - \text{Al}_2\text{O}_3$ plots give an indication of the relative proportions of carbonate, sand, and silt in each of the analyzed rocks (Figure 17c). The analyzed limestone and sandstone specimens have relatively high CaO/MgO ratios (85, 8, 9), indicative of the prevalence of calcite over dolomite. Calcareous siltstone has a relatively low CaO/MgO ratio (0.3, 0.5), possibly indicating the prevalence of dolomite, or of other magnesium-rich minerals such as chlorite. The $\text{FeO}/\text{Fe}_2\text{O}_3$ ratio of the pelitic rocks averages about three.



ODM9593

Photo 22—Sandstone clastic dike cutting thinly bedded siltstone and sandstone of the Espanola Formation, Bay of Islands.

Clastic intrusions, which are remobilized bodies of sedimentary rock emplaced as dikes, sills, and irregular masses, are abundant throughout the Espanola Formation (Photo 22). Some are lithologically similar to rocks of the Espanola Formation, consisting of coarse, calcareous siltstone or fine sandstone, and can be traced into the beds from which they originated. Other clastic intrusions are similar to rocks of the underlying Bruce Formation, consisting of polymictic paraconglomerate, and still others consist of feldspathic sandstone similar to that of the overlying Serpent Formation. Elongate minerals are commonly preferentially oriented parallel to the dike walls, and some of the conglomeratic dikes display pebble concentrations in their central parts. The dike walls are generally sharp and the wall-rocks undisturbed, although locally the country rocks are offset by dikes. These features indicate that the dikes were emplaced by forceful injection and laminar flow of water-soaked unconsolidated sediment into consolidated or semi-consolidated pelitic and calcareous sediments along fractures and faults. In the Espanola-McGregor Bay area, the dikes show north-south and east-west preferred orientations, and several cut the axes of minor folds. Some small clastic dikelets follow cleavage planes. These features suggest

emplacement at an early tectonic stage before complete lithification. Carbonate and pelitic rocks would probably lithify relatively early because of diagenetic processes, and would fracture in response to earth movements, allowing ingress of highly mobile, water-soaked sandy sediments.

Desiccation cracks in the Espanola Formation, implying conditions of shallow water deposition with periodic subaerial exposure, have been reported by numerous workers. However, as Young (1973) has suggested, most if not all are injection structures, formed by injections of sediment in a manner analogous to clastic dike formation rather than by infilling of desiccation cracks from above.

Serpent Formation

Rocks of the Serpent Formation, mainly feldspathic sandstone with subordinate amounts of siltstone, and minor calcareous and conglomeratic rocks, conformably and gradationally overlie the Espanola Formation in the northern, central, and southern parts of the map-area. The thickness of the Serpent Formation is highly variable, possibly caused by erosion preceding or accompanying deposition of the overlying Gowganda Formation. The formation is up to 2,000 feet (600 m) thick in Porter Township and thins northward to a thickness of 500 feet (150 m) and less in Vernon Township. The thickness of the formation is generally in the range of 600 to 2,400 feet (180 to 620 m) in the central and southern area, but locally as in the Bay of Islands area, is as little as 100 feet (30 m) and, in Curtin and Roosevelt Townships, is in excess of 5,000 feet (1500 m) (Figure 15).

The formation is divisible into two parts: a lower part approximately 200 feet (60 m) thick consisting of thin-bedded, average 1 foot (0.3 m) thick, poorly sorted, fine- to medium-grained silty feldspathic sandstone with appreciable amounts (15 percent) of siltstone and silty sandstone interbeds and partings, and minor (up to 10 percent) disseminated carbonate minerals; and an upper part, consisting of fine to very coarse grained, moderately sorted quartz-feldspar sandstone with minor silty partings. Several thin units of calcareous siltstone and silty limestone, and beds of conglomerate occur in the upper part of the formation in the southern part of the map-area. Within the formation as a whole, there is a general upward increase in bedding thickness, and a decrease in the amount of silty material, although the carbonate-bearing silty units near the top would represent a reversal of this general trend. The carbonate-bearing and conglomeratic units are present only in the south where the sandstone is coarser grained on the average; less fine-grained "porcellaneous" sandstone outcrops in the south than in the north.

The sequence in Porter Township (Figure 15) consists of a lower unit (200 feet; 60 m thick) of fine- to medium-grained silty feldspathic sandstone, some beds of which contain disseminated carbonate minerals (mainly dolomite), with siltstone interbeds and partings, some of which are also carbonate-bearing. This lower unit is overlain by a thick (700 feet; 200 m thick) sequence of medium-grained, medium- to thick-bedded (1 to 4 feet; 0.3 to 1.2 m), crossbedded feldspathic sandstone with minor silty partings. The upper part of the formation consists of fine-grained, white or pale grey feldspathic sandstone with a



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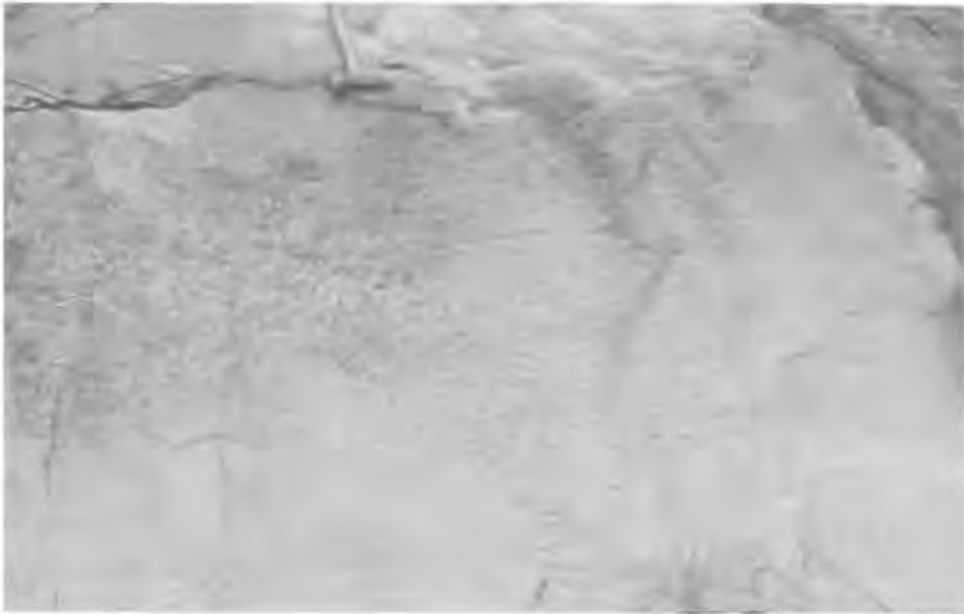
Photo 23—Large-scale tabular crossbed sets in sandstone of the Serpent Formation, Truman Township.

“porcellaneous” weathering surface with lenses of medium to very coarse grained sandstone and of silty sandstone. Bedding, which ranges in thickness from a few inches to about 4 feet (1.2 m) is characteristically coarsely laminated. Crossbeds and ripples are present locally.

The Serpent Formation in the central and southern parts of the map-area comprises a lower unit, 200 feet (60 m) in thickness which is similar to that in Porter Township. These rocks are succeeded by a number of cyclically repeated thick-bedded and thin-bedded feldspathic sandstone units and by carbonate-bearing and conglomeratic members near the top. The thick-bedded units consist of medium- to coarse-grained, commonly conglomeratic feldspathic sandstone with minor (5 percent) amounts of siltstone and silty sandstone partings. Bedding ranges in thickness from approximately 2 to 20 feet (0.6 to 6 m) and averages 4 feet (1.2 m). Planar and trough crossbedding is characteristic, and some beds that are up to 5 feet (1.5 m) thick, actually represent large-scale tabular crossbed sets (Photo 23). Coarse parallel laminations, cross-laminations, and graded laminations are present. Many beds contain scattered granules and pebbles up to 1 inch (2.5 cm) in diameter of granite, quartz, gabbro, and chert, and larger (up to 6 inches; 15 cm) angular fragments of greenish argillite.

Excellent examples of lag pebble concentrations on the upper surface of thick beds and tabular crossbeds are exposed on the south shore of Walker Lake in Truman Township (Photo 24).

The relatively thin-bedded, (average 1 foot (0.3 m) thick) sequences consist of medium-grained feldspathic sandstone with 10 to 15 percent siltstone and



ODM9595

Photo 24—Lag-pebble concentrations on the surface of a crossbed foreset, Serpent Formation, Truman Township.

silty sandstone partings and interbeds. The thin-bedded sequences are typically laminated, and the silty interbeds display parallel laminations, cross-laminations and ripples.

The carbonate-bearing units in the upper part of the formation are approximately 10 to 50 feet (3 to 15 m) thick, and are laterally persistent for at least several miles (5 km). These units consist of thinly bedded, 1 inch to 6 inches (2.5 to 16 cm) thick calcareous siltstone, silty limestone, calcareous sandstone, and pink feldspathic sandstone. Laminated bedding, cross-laminations, ripples, starved ripples, clastic dikes, and concretionary structures are present.

The thin (1 to 3 feet ; 0.3 to 1 m) orthoconglomerate and paraconglomerate beds near the top of the formation in the McGregor Bay area consist of rounded pebbles, which are generally about 1 inch (2.5 cm) in diameter, and consist of granite, gabbro, quartzite, and quartz, set in a greywacke or feldspathic sandstone (protoquartzite and subgreywacke) matrix.

Sandstone in the Serpent Formation is notably feldspathic, containing on the average approximately 30 percent feldspar. The mineralogical composition of rocks of the Serpent Formation is shown in Figure 18. The sandstone in the lower part of the formation is mainly poorly sorted, fine-grained to medium-grained (0.1 to 0.5 mm) immature to submature silty feldspathic sandstone. The sandstone consists of angular to subrounded grains of quartz (50 to 70 percent; average 55 percent), feldspars and rock fragments (10 to 40 percent; average 25 percent), and silty interstitial matrix (5 to 30 percent; average 20 percent), micas and silt-size quartz. Sandstone in the remainder of the formation is mainly me-

Sudbury-Manitoulin Area

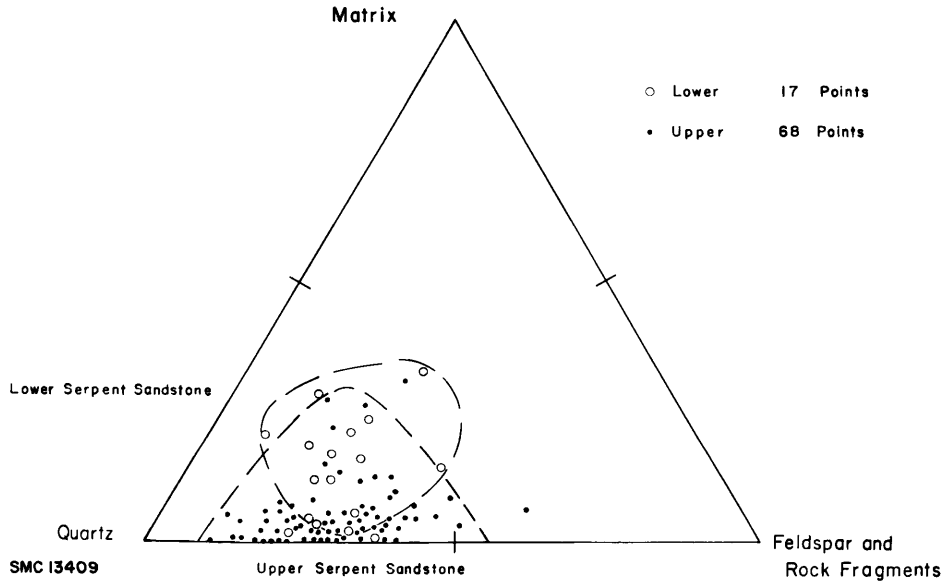


Figure 18a—Triangular diagram to show stratigraphic variations in mineralogical compositions of sandstones from the Serpent Formation; Sudbury-Manitoulin Area.

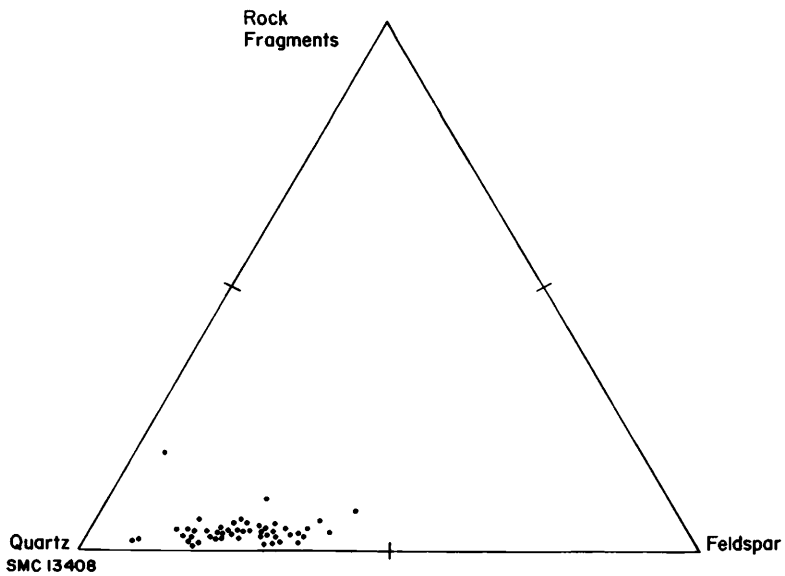


Figure 18b—Triangular diagram to show variation in mineralogical composition of sandstones with recognisable rock fragments from the Serpent Formation; Sudbury-Manitoulin Area.

dium to coarse or very coarse grained (0.3 to 2 mm or more; average 0.5 mm), submature arkose and subarkose consisting of subangular to rounded grains of quartz (45 to 90 percent; average 60 percent), feldspars and rock fragments (10 to 50 percent; average 35 percent), and minor interstitial matrix (0 to 30 percent; average 5 percent). Most sandstone has a unimodal sand size distribution, although some of the coarse units have a second mode in the coarse sand to granule range (1 to 5 mm). Potassic feldspar and sodic plagioclase are both present; plagioclase is the dominant feldspar in the lower part, and potassic feldspar is the dominant feldspar in the remainder of the formation. Rock fragments, mainly granitic, vein quartz and chert, generally constitute less than 5 percent where present. Angular siltstone and argillite chips, probably derived from the breakup of pelitic interbeds, are locally abundant. Accessory minerals, including zircon, tourmaline, iron oxides, and sulphide minerals are rare. Carbonate cement, mainly dolomite, is present in amounts of 5 to 10 percent in some of the lower sandstone beds.








The calcareous siltstone, silty limestone, and fine-grained sandstone in the upper part of the formation are similar to their counterparts in the Espanola Formation; the conglomerate beds find their counterparts in the overlying Gowganda Formation.

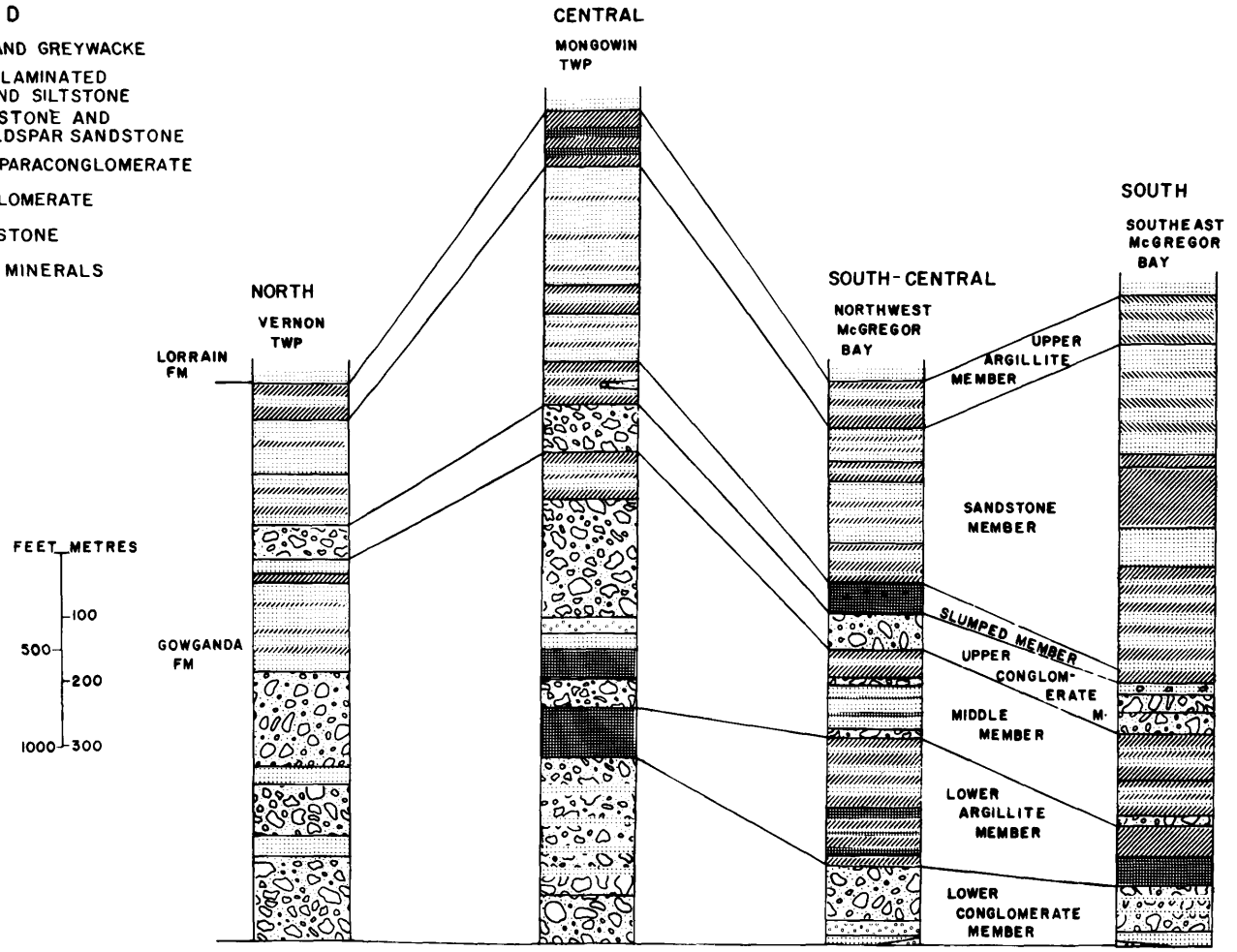
COBALT GROUP

Gowganda Formation

Rocks of the Gowganda Formation occur in the following areas: in a restricted area in Vernon Township in the northern part of the map-area; in a broad belt extending eastward from Harrow Township to Sale Township and northward into Bevin and Eden Townships in the central part of the area, and about the McGregor Bay Anticline in the south of the area. The formation can be divided into two approximately equal parts, a lower unit of cyclically repeated conglomeratic and pelitic units, and an upper unit of interbedded sandstone and siltstone that forms several coarsening-upward sedimentary cycles. Within the present map-area, at least, each of these units is of sufficient thickness and continuity to warrant formational status. Lindsey (1967) has suggested the name "La Cloche Formation" for the upper unit in the McGregor Bay area.

In Vernon Township in the north, the Gowganda Formation conformably overlies sandstone of the Serpent Formation, and nonconformably overlies the Early Precambrian granitic basement. The Gowganda-basement contact is unconformable with coarse-grained, unsorted feldspathic grit and coarse rubbly conglomerate consisting of abundant (70 percent), large, up to 6 feet (1.8 m) in maximum dimension, angular blocks of quartz monzonite in a sandy mudstone matrix that rests on weathered, disrupted quartz monzonite. The remainder of the formation, which is about 2,800 feet (850 m) thick, consists of polymictic paraconglomerate (50 percent) with sandstone and orthoconglomerate units passing upward into sandstone (30 percent) and siltstone (20 percent) with minor conglomerate (Figure 19).

- LEGEND**
-  SILTSTONE AND GREYWACKE
 -  REGULARLY LAMINATED ARGILLITE AND SILTSTONE
 -  SILTY SANDSTONE AND QUARTZ-FELDSPAR SANDSTONE
 -  POLYMIC TIC PARACONGLOMERATE
 -  ORTHOCONGLOMERATE
 -  PEBBLY MUDSTONE
 -  CARBONATE MINERALS



SMC 13410

Figure 19—Generalized stratigraphy of the Gowganda Formation in the Sudbury-Manitoulin Area.



ODM9596

Photo 25—Interbedded conglomerate and sandstone of the Gowganda Formation (right) conformably and gradationally overlying Serpent Formation sandstone (left), McGregor Bay.

In the central and southern parts of the map-area where the Gowganda Formation overlies the Serpent Formation, the basal contact for the most part is abrupt and regular, or only slightly wavy, and conformable. The basal Gowganda paraconglomerate is commonly rich in quartz and feldspar; lenses of feldspathic sandstone and orthoconglomerate are present. Local interbedding of conglomerate and sandstone occurs in a transitional contact zone up to 100 feet (30 m) thick between the Serpent and Gowganda Formations (Photo 25). However, at numerous other localities, as in southern Merritt Township and in the Bay of Islands, the base of the Gowganda conglomerate bevels across the bedding in the underlying Serpent sandstones (Photo 26) and fills channels which cut downward into the sandstone for as much as 30 feet (9 m). Large angular blocks of Serpent-type sandstone as much as 5 feet (1.5 m) in maximum dimension are present in the basal Gowganda conglomerate. Dike-like projections of conglomerate project into sandstone, and contorted masses of sandstone caught up in the basal Gowganda conglomerate, are commonly present, suggesting that there has been large-scale slumping of conglomerate into unconsolidated or semi-consolidated sand. In summary, the contact between the Gowganda and Serpent Formations varies from conformable and gradational through conformable and abrupt, to an erosional disconformity.

In Eden Township, near the Grenville Front Tectonic Zone, the Gowganda Formation is approximately 600 to 1,800 feet (180 to 500 m) thick and consists mainly of siltstone, fine-grained greywacke, and quartz-feldspar sandstone with only minor (5 percent) polymictic paraconglomerate. Throughout the remainder of the central part of the map-area, the formation is approximately 3,000 to



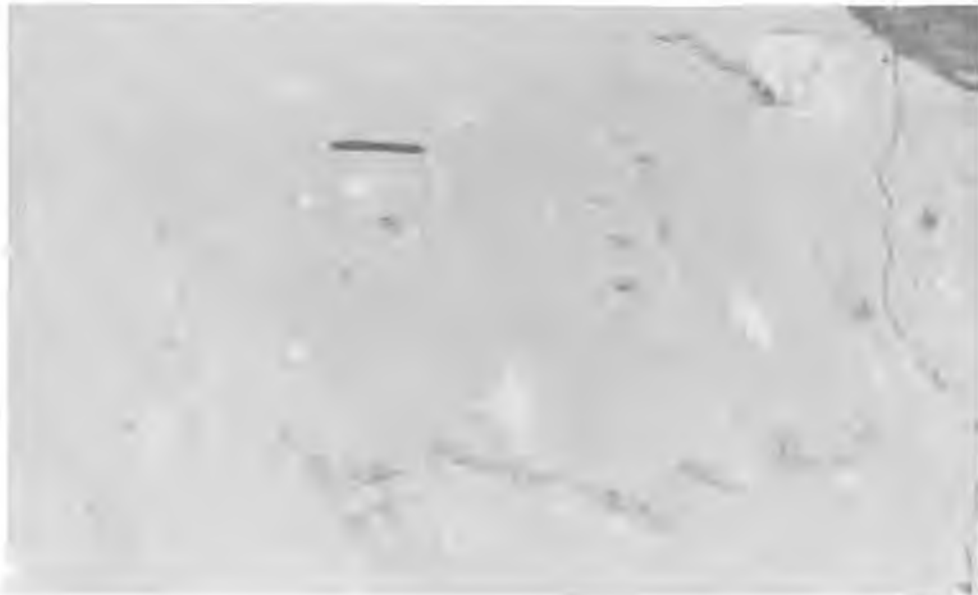
ODM9597

Photo 26—Abrupt, transgressive contact between the basal conglomerate of the Gowganda Formation (above) and sandstone of the Serpent Formation (below), Merritt Township.

5,500 feet (900 to 1680 m) thick, averages 4,000 feet (1200 m) in thickness, and consists of approximately 40 percent conglomerate. In the southern part of the area, the formation is approximately 2,800 to 3,800 feet (850 to 1160 m) thick, averages 3,000 feet (900 m), and contains approximately 15 to 25 percent conglomeratic rocks (Figure 19).

Although erosional disconformities locally truncate some units, and other units are lensoid and consequently not everywhere present, the formation can be divided into the following lithostratigraphic members in the central and southern areas (as shown in Figure 19):

(1) Lower Conglomerate Member: Up to 1,000 feet (300 m) thick in the central area where it consists mainly of massive or crudely stratified polymictic paraconglomerate with a greywacke or siltstone matrix (Photo 27). Locally, lenses and irregular bodies of sandstone, and partly sorted orthoconglomerate and paraconglomerate units are present, some of which display bedding and crossbedding. The member thins southeastward to approximately 300 to 400 feet (90 to 120 m) in thickness in McGregor Bay where it consists of a lower sequence (100 feet; 30 m thick) of relatively well-bedded orthoconglomerate, paraconglomerate, and feldspathic sandstone (Photo 27) overlain by massive polymictic paraconglomerate. In McGregor Bay bedding in the lower part of the member ranges from about 6 inches to 5 feet (15.2 cm to 1.5 m) in thickness. Some conglomeratic units are well sorted, others poorly so, and some graded sequences do occur. Grading takes the form of an upward decrease in pebble size in conglomerate



ODM9596

Photo 27—Massive polymictic paraconglomerate of the Gowganda Formation, Mongowin Formation.

beds, and continuous variations from orthoconglomerate through pebbly sandstone to sandstone.

(2) *Lower Argillite Member*: Two hundred to 800 feet (60 to 240 m) thick, and composed of laminated argillite and siltstone with interbedded siltstone and sandstone in the upper parts of thicker sections. Units of regularly laminated argillite-siltstone alternate with units of irregularly laminated siltstone and sandstone. The regularly laminated sequences consist of thin, laterally persistent, rhythmically alternating grey siltstone laminae or beds 1 mm to 2 cm thick and black mudstone laminae $\frac{1}{2}$ to 2 mm thick (Photo 28). The irregularly laminated facies consists of thin-bedded ($\frac{1}{2}$ - to 2-inch; 1.3 to 5 cm) thick siltstone layers and fine-grained greywacke with lensoid bodies of siltstone and sandstone which represent starved ripples (Photo 29). Graded beds, parallel laminations, ripples, and ripple-drift cross-laminations are commonly present in Bouma-type cycles. The rocks of the upper part of this member display contorted laminations, slumped beds, and ball-and-pillow structures.

(3) *Middle Member*: A heterogeneous sequence of conglomerate, siltstone, and sandstone, which, in the central area, is approximately 1,000 feet (300 m) thick, and consists mainly of polymictic paraconglomerate with lenses of orthoconglomerate, siltstone, and feldspathic sandstone. In the south of the map-area, this member is approximately 500 feet (150 m) thick, and consists mainly of siltstone and sandstone with minor thin conglomerate units. The conglomeratic rocks include polymictic paraconglomerate with a massive greywacke or laminated siltstone matrix, and partly sorted polymictic orthoconglomerate. Most of



ODM9599

Photo 28—Regularly laminated argillite-siltstone facies of the Gowganda Formation, Bay of Islands.

the siltstone units consist of irregularly laminated siltstone and fine-grained sandstone, although minor regularly laminated sections are present. Load casts, flames, ball-and-pillow structures, contorted bedding, and scour-and-fill features are common, especially at the bases of conglomerate units. Graded, laminated, cross-laminated sequences, ripples and starved ripples are prevalent in siltstone. Dropstones, pebbles which disrupt bedding laminations in pebbly siltstone and apparently have been dropped into unconsolidated fine-grained sediment, are present (Photo 30).

(4) *Upper Conglomerate Member*: Commonly 200 to 300 feet (60 to 90 m) thick but locally absent, it consists of polymictic paraconglomerate with lenses of orthoconglomerate and feldspathic sandstone. The conglomeratic rocks have massive greywacke, bedded protoquartzite-subgreywacke, and laminated siltstone matrices.

(5) *Slumped Member*: Three hundred and fifty to 600 feet (105 to 180 m) thick, it consists of argillite and siltstone passing gradationally upward into interbedded feldspathic sandstone and siltstone. The lower part of this member is characterized by the presence of contorted laminations and minor amounts (up to 10 percent) of carbonate minerals in some beds.

(6) *Sandstone Member*: One thousand to 2,000 feet (300 to 600 m) thick composed of interbedded feldspathic sandstone and siltstone which form several, commonly three or four, upward-coarsening sedimentary cycles 100 to 500 feet



ODM9600

Photo 29—Irregularly laminated "streaky" facies of the Gowganda Formation, Bay of Islands. The light coloured silt-sand lenses represent "starved" ripples.

(30 to 150 m) thick. Each cycle consists of a lower unit of siltstone with minor interbedded sandstone, a middle unit in which siltstone and sandstone are present in approximately equal proportions, and an upper unit consisting mainly of feldspathic sandstone. Bedding in the lower portions is typically thin, 1 to 6 inches (2.5 to 15 cm) thick, irregular and lensoid, or wavy. Parallel laminations, cross-laminations, convolute laminations, mud-chips, and ball-and-pillow structures are present. Beds in the upper sandstone are generally 1 to 2 feet (0.3 to 0.6 m) thick; planar and festoon crossbeds and ball-and-pillow structures are characteristic in them (Photo 31). Some thin lenses of polymictic orthoconglomerate are present in the upper part of this member in Mongowin Township.

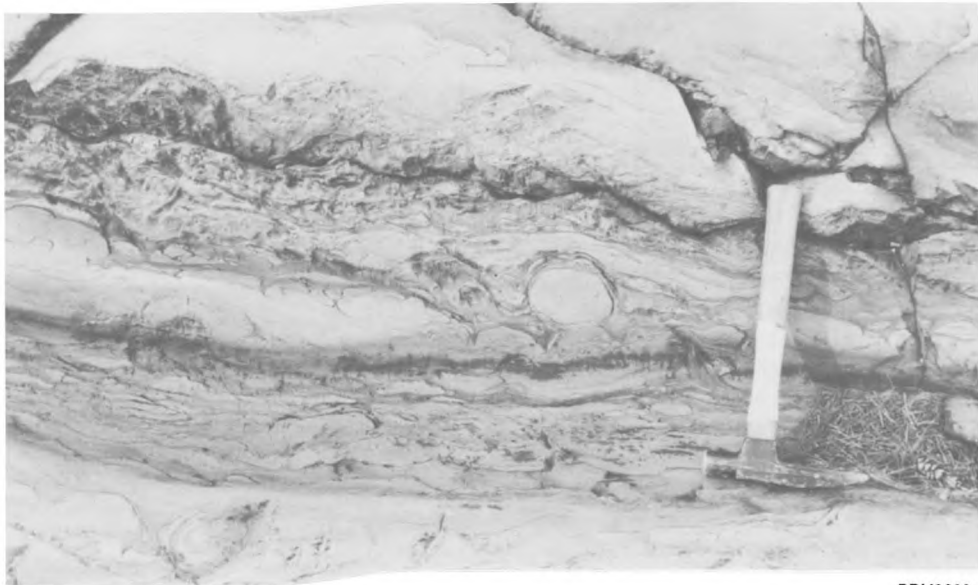
(7) *Upper Argillite Member*: A coarsening-upward sequence some 200 to 450 feet (60 to 137 m) thick composed of argillite and siltstone with feldspathic sandstone which increases in amount upward represents the gradational contact zone with the overlying Lorrain Formation. Structures such as ripples, cross-laminations, regularly and irregularly laminated bedding, and ball-and-pillow structures are particularly well developed (Photo 32).

Sudbury-Manitoulin Area



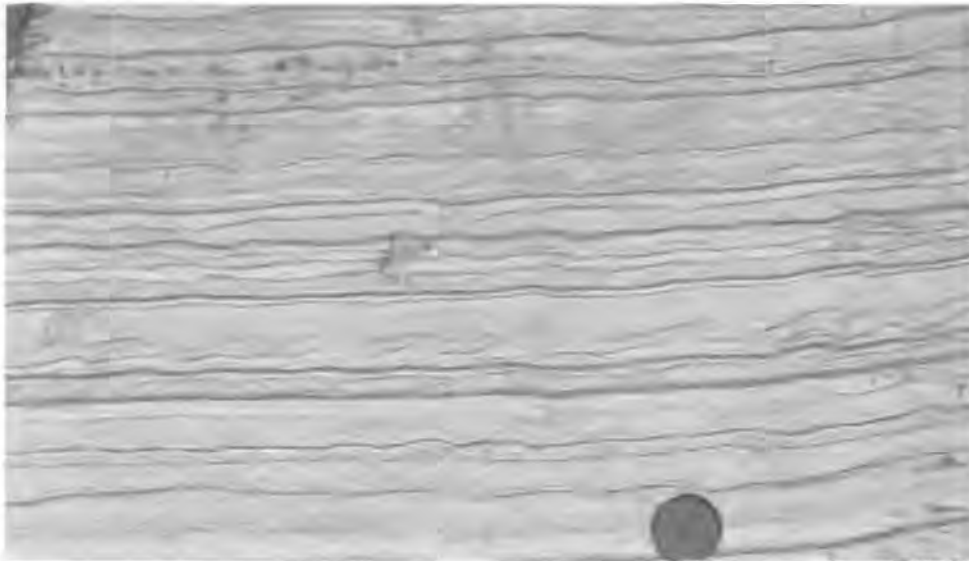
ODM9601

Photo 30—"Dropstone" in the Gowganda Formation, McGregor Bay. The large granitic clast (centre) interrupts and disrupts thinly laminated bedding in the enclosing siltstone.



ODM9602

Photo 31—Ball-and-pillow structures in sandstone and siltstone of the Gowganda Formation, McGregor Bay.



ODM9603

Photo 32—Ripple cross-laminated siltstone and fine sandstone of the upper part of the Gowganda Formation, McGregor Bay.

Polymictic paraconglomerate, comprising pebbly sandstone, and pebbly siltstone is the dominant type of conglomerate in the lower half of the Gowganda Formation. It is a poorly sorted rock consisting of mainly plutonic rock clasts in a massive silty sandstone (greywacke) or laminated sandy siltstone matrix. Angular to rounded rock clasts range in maximum dimension from less than 1 inch (2.5 cm) to about 15 feet (5 m), average 2 to 3 inches (5 cm to 7.6 cm) and constitute 5 to 30 percent (average 15 percent) of the rock. These clasts are mainly of granitoid composition (80 percent) but felsic volcanic (5 percent), mafic igneous (10 percent) and metasedimentary (5 percent) varieties are also present. Generally, the rock fragments are unsorted, but locally the paraconglomerate is crudely sorted and displays relatively uniform pebble size and poorly developed bedding or lamination. Fabric studies by Casshyap (1967) in the Espanola-Whitefish area indicate that the long axes of rock fragments have a preferred, approximately north-south orientation. However, studies by Lindsey (1969) in the same area indicate that any primary pebble fabric is probably complicated by tectonic re-orientation.

The paraconglomerate matrix is mainly a massive, poorly sorted, silty feldspathic greywacke. The grain size distribution is commonly polymodal with the principal mode in the fine-sand range (0.1 to 0.2 mm) and minor modes in the clay and fine gravel (4 to 16 mm) grades. The matrix is composed of the following: angular to subrounded grains of quartz (25 to 50 percent; average 40 percent), feldspar and rock clasts (5 to 65 percent; average 15 percent), and interstitial micas, chlorite, and silty quartz and feldspar (35 to 80 percent; average 45 percent) (Figure 20). In some localities the matrix is a moderately sorted quartz

Sudbury-Manitoulin Area

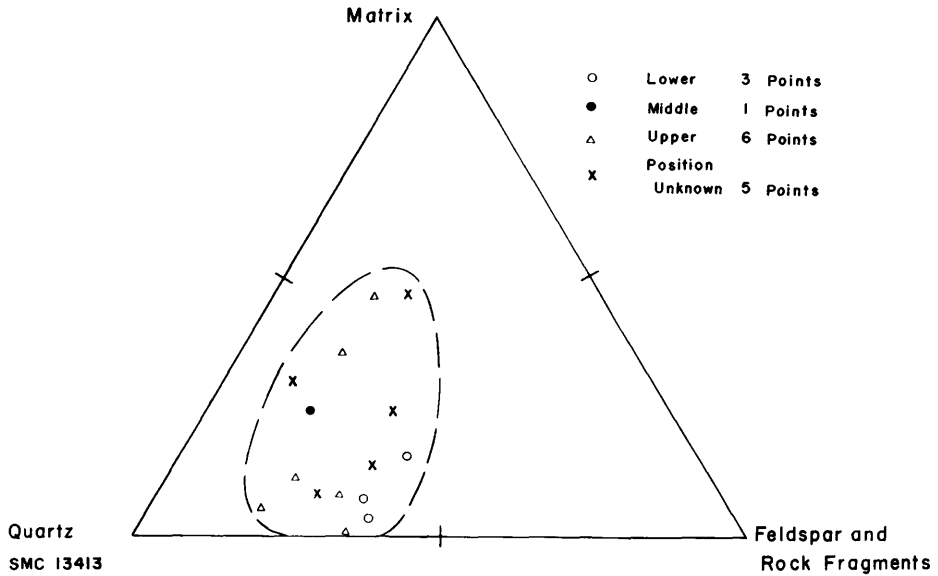


Figure 20a—Triangular diagram to show stratigraphic variation in mineralogical composition of sandstone, Gowganda Formation, Sudbury-Manitoulin Area.

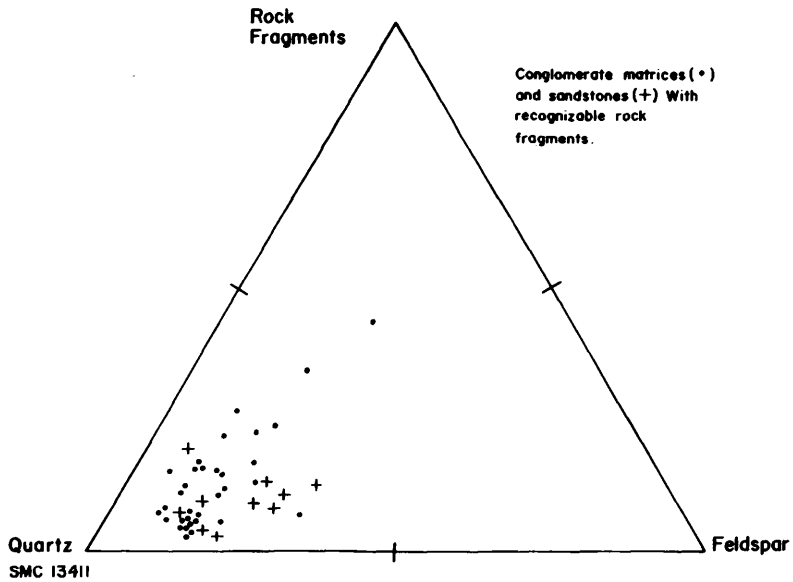


Figure 20b—Triangular diagram to show mineralogical composition of conglomerate matrices and sandstones with recognisable rock fragments; Sudbury-Manitoulin Area.

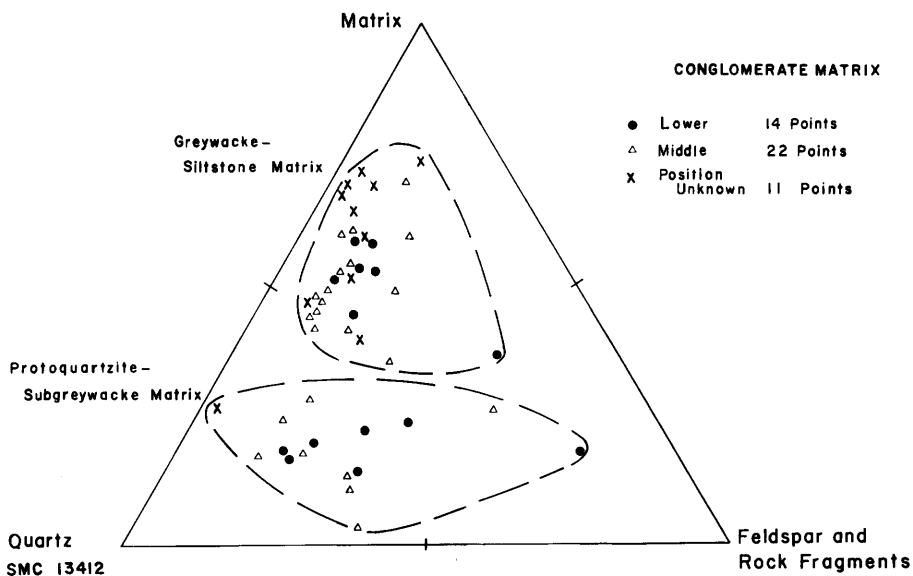


Figure 20c—Triangular diagram to show variation in mineralogical composition of conglomerate matrices, Gowganda Formation, Sudbury-Manitoulin Area.

wacke, subgreywacke, or protoquartzite with abundant rounded quartz grains and granules. The better sorted matrix consists of quartz (15 to 70 percent; average 65 percent), feldspars and rock fragments (15 to 65 percent; average 25 percent), and interstitial materials (10 to 30 percent; average 20 percent). Sand-size rock fragments, mainly granitic, mafic igneous, and metasedimentary types, are present in amounts up to 25 percent by volume of the rock, but commonly constitute less than 10 percent of the rock. The ratio of potassic feldspar to plagioclase is generally low (0.1 to 4) and commonly the two feldspars are present in about equal proportions. The mineralogical composition of rocks of the Gowganda Formation is shown in Figure 20.

Polymictic orthoconglomerate, which occurs mainly as lenses and beds in the middle of the formation and locally at the base, contains a high proportion of rock fragments (50 to 80 percent), and is generally better sorted than the paraconglomerate. The rock fragments ranging from less than 1 inch (2.5 cm) to about 2 feet (0.6 m) and averaging 1 inch (2.5 cm) in diameter, are relatively uniform in size in any one bed, and are generally subrounded to rounded. The fragments are mainly derived from granitic, vein quartz, mafic and felsic volcanic, and metasedimentary sources. The matrix is medium-grained quartz greywacke, subgreywacke, and protoquartzite, and is better sorted, has a lower proportion of silty material, and a higher quartz-feldspar ratio than the paraconglomerate greywacke matrix (Figure 20). Accessory minerals in the conglomerates include iron-titanium oxides, sulphide minerals, sphene, epidote, and zircon. Carbonate minerals (dolomite, calcite, ankerite) may be present in minor amounts (2 percent).

Sudbury-Manitoulin Area

Argillite, siltstone, and fine-grained silty sandstone (greywacke) occur throughout the formation as members, interbeds, and partings. Regularly laminated argillite and siltstone are common in the lower part of the formation and consist of parallel, persistent, varve-like, alternating light and dark coloured laminae or thin beds ranging in thickness from less than 1 to about 10 mm. These rocks are not typical varved sediments consisting of continuous couplets of graded silt and clay laminae, but rather the silt and clay are segregated into distinct layers. The grain size of the silty laminae averages 0.03 mm and ranges up to fine sand. The grain size of the dark laminae averages less than 0.01 mm.

The irregularly laminated siltstone, silty sandstone, and mudstone facies consists of wavy, irregular, lensoid, light silty or sandy and dark muddy laminae, or thin beds ranging in thickness from about 1 to 50 mm. In addition, numerous stratabound lenses of cross-laminated silty sandstone and siltstone approximately $\frac{1}{2}$ inch to 2 inches (1 to 5 cm) thick and 3 to 12 inches (8 to 30 cm) long represent starved ripples.

These silty rocks consist of variable proportions of muscovite, biotite, chlorite, epidote, and angular silt to fine sand size grains of quartz and feldspar. Phyllosilicate minerals are dominant in the dark muddy laminae, silt or fine sand size quartz and feldspars are dominant in the light layers. Accessory minerals include iron - titanium oxides, sphene, and sulphide minerals. In the Lower Argillite Member, magnetite is present in amounts of about 5 percent, making this unit magnetically responsive. Carbonate minerals, both dolomite and calcite, are present in amounts of about 10 percent in some siltstone beds near the top of the lower half of the formation.

Quartz-feldspar sandstone is present throughout the formation, and constitutes the dominant lithology in the upper half. The rock is poorly to moderately sorted, fine- to medium-grained (0.1 to 0.35 mm; average 0.3 mm), and ranges in composition from feldspathic greywacke to arkose. These rocks consist of angular to subrounded grains of quartz (30 to 70 percent; average 55 percent), feldspars and rock fragments (10 to 40 percent; average 25 percent), and interstitial matrix (1 to 50 percent; average 20 percent) (Figure 20). The ratio of potassic feldspar to plagioclase varies from 0.2 to 4. In general, plagioclase is equal to or more abundant than potassic feldspar. Rock fragments, mainly chert and siltstone with minor granitic and mafic igneous types are locally present in amounts up to 15 percent but generally constitute less than 5 percent.

Chemical analyses of rocks of the Gowganda Formation, given in Table 8, show that the silty rocks are depleted in SiO_2 and CaO , and enriched in Al_2O_3 , total iron, and MgO relative to both the conglomerate matrix and to average Archean Shield composition of northwestern Ontario (Shaw *et al.* 1967). The conglomerate matrices are chemically similar to the average shield composition, but do show relative enrichment in total iron and MgO , and depletion in CaO . The $\text{Al}_2\text{O}_3/\text{NaO}$ ratio of the silty rocks analyzed averages about 6 and of the conglomerate matrices about 4. The $\text{CaO}/\text{Na}_2\text{O}$ ratio averages 0.4 and 0.35 respectively, and the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios average about 2.5. The $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios range from 1 to 2 and average about 1.5.

TABLE 8

CHEMICAL ANALYSES OF ROCKS OF THE COBALT GROUP, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

	Major Components in Weight Percent																Total	S.G.
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻	CO ₂	TiO ₂	MnO	P ₂ O ₅	S			
(1)	51.20	21.90	2.40	2.76	5.92	0.40	5.14	2.63	3.93	0.23	0.06	0.95	0.07	0.14	0.01	97.74	N.D.	
(2)	60.40	19.40	3.42	4.94	2.70	0.65	2.33	3.01	3.47	0.18	0.20	0.73	0.11	0.14	0.01	101.69	N.D.	
(3)	59.10	16.50	4.69	5.31	3.21	1.55	2.91	2.98	2.63	0.15	0.25	0.82	0.13	0.15	0.04	100.42	2.80	
(4)	57.76	17.82	2.87	4.96	4.16	1.22	3.15	3.36	3.19		-	0.75	0.00	0.23	-	99.47	N.D.	
(5)	65.14	14.80	3.68	3.69	3.56	1.50	4.39	1.72	2.73		-	0.60	-	0.16	-	101.97	N.D.	
(6)	66.30	15.37	1.26	2.85	2.05	3.97	3.87	2.25	0.87		-	0.47	0.07	0.13	-	99.46	N.D.	
(7)	87.80	7.48	0.55	0.28	0.37	0.33	0.09	2.16	0.48	0.07	0.35	0.05	0.01	0.01	0.01	100.04	2.75	
(8)	95.96	2.73	0.35	-	-	-	0.26	0.21	-	0.11	-	0.03	-	0.01	-	99.66	2.72	
(9)	68.60	16.90	2.79	0.83	2.42	0.10	0.40	5.56	1.51	0.16	0.05	0.63	0.01	0.06	0.02	100.04	2.73	

Notes

- (1) Laminated siltstone-argillite, Gowganda Formation, McGregor Bay.
- (2) Laminated siltstone-argillite, Gowganda Formation, McGregor Bay.
- (3) Laminated siltstone-argillite, Gowganda Formation, Mongowin Township.
- (4) Laminated argillite, Gowganda Formation, average of 9 (Young 1969).
- (5) Paraconglomerate matrix, Gowganda Formation, average of 16 (Young 1969).
- (6) Average Archean Shield of N.W. Ontario (Shaw *et al.* 1967).
- (7) Feldspathic sandstone, lower Lorrain Formation, McGregor Bay.
- (8) Fine-grained orthoquartzite, upper Lorrain Formation, Curtin Township.
- (9) Siltstone, Gordon Lake Formation, Curtin Township.

Abbreviations

- S.G. Specific Gravity
 N.D. Not determined
 - Not detected

Lorrain Formation

The Lorrain Formation is a remarkably thick (5,000 to 8,000 feet; 1500 to 2500 m) sequence of quartz-rich sandstone that is exposed in the northern and southern parts of the map-area. In the north, the Lorrain Formation is exposed in a restricted area in Vernon Township where it conformably overlies the Gowganda Formation and is apparently in fault contact with Early Precambrian granitic basement rocks. In the south, the formation is extensively exposed in a belt extending eastward from Harrow Township to Goschen and Carlyle Townships where it abuts against the Grenville Front Felsic Plutons and then swings southwest to McGregor, Frazer, and Badgeley Points in Lake Huron. Isolated exposures correlated with the Lorrain Formation are located on Heywood, Great Cloche, and Manitoulin Islands, and in Bevin and Eden Townships in the north-eastern part of the area. Bodies of sandstone lithologically similar to rocks of the Lorrain Formation form part of the paragneiss sequence in the Grenville Province.

The contact between the Lorrain and Gowganda Formations is conformable and transitional through a stratigraphic interval some 50 to 100 feet (15 to 30 m) thick that marks the progressive incoming of feldspathic sandstone at the expense of siltstone. This contact is placed arbitrarily where the proportion of sandstone is greater than that of siltstone, a level which corresponds closely to the appearance of relatively thick-bedded (2 to 4 feet (0.6 to 1.2 m) thick), cross-bedded feldspathic sandstone. The rocks of this transition zone are also characterized by slumped, brecciated bedding and ball-and-pillow structures.







In the north, where its preserved thickness is probably less than 1,200 feet (360 m) thick, the formation consists of a lower unit 400 feet (120 m) thick of thin-bedded to thick-bedded 1 to 4 feet (0.3 to 1.2 m) thick, medium- to coarse-grained feldspathic sandstone, a pebbly sandstone unit 500 feet (150 m) thick with small ½ inch (1.3 cm) diameter scattered quartz pebbles, quartz-pebble conglomerate lenses, and an upper sequence of medium-grained white sandstone.

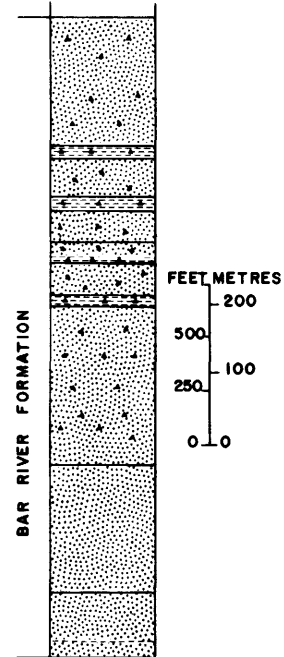
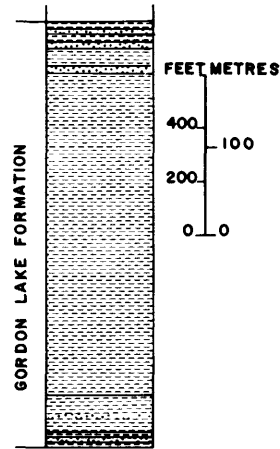
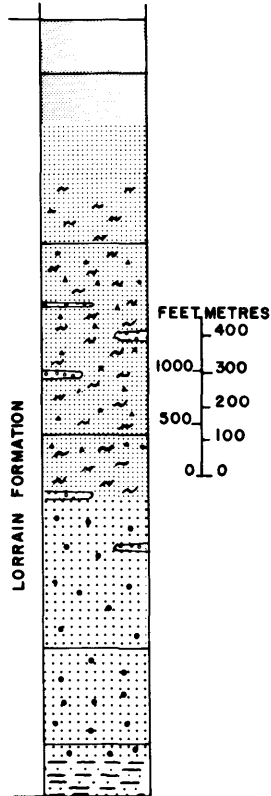
In Eden and Bevin Townships near the Grenville Front Tectonic Zone where it is intruded by the Chief Lake Batholith, the formation has a preserved thickness of some 1,000 to 5,000 feet (300 to 1500 m). A basal unit of feldspathic sandstone and siltstone grades into a sequence of pink and green feldspathic sandstone beds 1 to 6 feet (0.3 to 1.8 m) thick. The upper part of the formation, which exists mainly as isolated xenoliths in the batholith, consists of fine- to medium-grained white and mottled red orthoquartzite. Xenoliths composed of thin-bedded siltstone and silty sandstone north of Wavy Lake may be correlated with the Gordon Lake Formation. Metamorphism and metasomatism of the Lorrain sandstone in this area has resulted in incipient gneissic layering.

In the main area of outcrop in the south, the Lorrain Formation can be divided into a number of conformable, intergradational lithostratigraphic members as follows (as shown in Figure 21):

(1) Silty Sandstone Member: 200 to 500 feet (60 to 150 m) of pink and grey, fine- to medium-grained feldspathic sandstone with silt and silty sandstone interbeds and partings. The proportion of feldspathic sandstone increases upward from about 50 percent in the lower part to 70 percent in the upper part of the member. Average bedding thickness, ranging from a few inches to about 3 feet (1 m)

LEGEND - LORRAIN FM

-  FINE-GRAINED ORTHOQUARTZITE
-  MEDIUM-GRAINED MICACEOUS ALUMINOUS SANDSTONE
-  MEDIUM-GRAINED HEMATITIC SANDSTONE
-  MEDIUM-TO COARSE-GRAINED FELDSPATHIC SANDSTONE
-  FELDSPATHIC SILTY SANDSTONE AND SILTSTONE
-  CONGLOMERATE



LEGEND - GORDON LAKE & BAR RIVER FORMATIONS





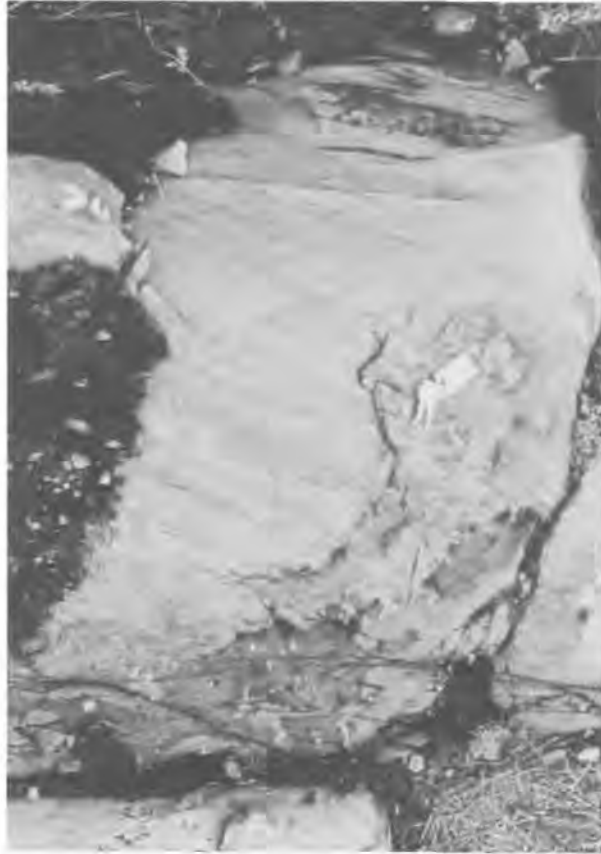
-  ORTHOQUARTZITE
-  HEMATITIC ORTHOQUARTZITE AND MICACEOUS SANDSTONE
-  SILTSTONE AND SILTY SANDSTONE
-  HEMATITIC SILTSTONE AND SANDSTONE

Figure 21—Generalized stratigraphy of the Lorrain, Gordon Lake, and Bar River Formations; Sudbury-Manitoulin Area.



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Photo 33—Coarse feldspathic sandstone of the lower part of the Lorrain Formation with graded cross-stratification, Curtin Township.

increases upward. The average grain size of the sandstone also increases upward. Laminated bedding, slump breccias, ball-and-pillow structures, ripples, cross-laminations, and parallel laminations are present.

(2) Feldspathic Sandstone Member: Five hundred to 1,200 feet (150 to 360 m) of medium to very coarse grained feldspathic sandstone with approximately 30 percent silty sandstone partings and interbeds in the lower part, and only minor amounts of such rocks in the upper half. Bedding thickness increases upward from approximately 1 to 10 feet (0.3 to 3 m) and an average of 3 feet (1 m) in the lower part to a maximum of about 15 feet (5 m) and an average of 5 feet (1.5 m) in the upper part. Similarly, the average grain size increases upward from medium to coarse grained. Very coarse grained units with scattered small pebbles and granules of quartz, feldspar and granitic rocks are common. There are cyclic repetitions of thick-bedded 5 to 10 feet (1.5 to 3 m) and medium-bedded 1 to 3 feet (0.3 to 1 m) sections. Planar and festoon crossbeds are common, and graded crossbeds are present (Photo 33). Specular hematite grains accentuate some bed-

ding and crossbed surfaces. Coarse, less than 1- to 3-inch (2.5 to 8 cm) thick parallel laminations, some of which are graded, are present. The rocks of this member pass gradationally upward into green micaceous sandstone of the overlying member through a stratigraphic interval some 20 feet (6 m) thick of interbedded pink arkose and green, micaceous arkose.

(3) *Green Micaceous Sandstone Member*: Six hundred feet to 2,000 feet (180 to 600 m) of medium- to coarse-grained micaceous feldspathic sandstone and feldspar-free green micaceous sandstone. The green feldspathic sandstone is generally coarse, contains small scattered pebbles and granules of quartz, feldspar and granitic rock fragments, and there are a few thin ½- to 3-inch (1 to 8 cm) thick lenses of quartz-pebble conglomerate. Bedding thickness decreases upward from 2 to 10 feet (0.6 to 3 m) in the lower part to 6 inches (15 cm) to 10 feet (3 m) in the upper part. Planar, festoon, and graded crossbeds are present. The green colour of the sandstone is due to the presence of pale green ferri-muscovite and to minor amounts of bright green chrome mica. In the upper part of this member, feldspar is absent although altered feldspar pseudomorphs are locally discernible. The contact with the overlying Hematitic Sandstone Member is gradational over a stratigraphic interval of about 20 feet (6 m) marked by the incoming of hematite in the form of streaks, grain coatings, and hematitic sandstone interbeds.

(4) *Hematitic Sandstone Member*: Up to 1,800 feet (550 m) in thickness of medium-grained, buff weathering, micaceous sandstone characterized by the presence of minor amounts of hematite and of clay minerals or their metamorphic equivalents. Thin, (average 3-inch (8 cm) thick) conglomerate lenses, composed of small, up to 1-inch (2.5 cm) diameter rounded quartz and minor red jasperoid pebbles are relatively abundant. Large-scale festoon crossbeds, with foreset surfaces commonly marked by specular hematite concentrations, are characteristic (Photo 34). Hematite occurs as (1 to 10 mm) rounded spots, as irregular streaks, and as concentrations along joints, foliations, and bedding and crossbedding surfaces. The contact with the overlying White Sandstone Member is gradational over a stratigraphic interval some 50 feet (15 m) thick with gradual loss of hematite.

(5) *White Aluminous Sandstone Member*: One thousand to 2,500 feet (300 to 750 m) of medium-grained white sandstone characterized by the presence of clay minerals (kaolinite) and the equivalent metamorphic minerals pyrophyllite, kyanite, and andalusite (Photo 35). Bedding thickness decreases from 6 inches to 6 feet (0.1 to 2 m) in the lower part to 4 inches to 3 feet (0.1 to 1 m) in the upper part. Average grain size decreases also. A few beds display festoon crossbeds, and there are buff-coloured bedding plane partings rich in aluminous minerals. The contact with the overlying orthoquartzite member is difficult to define, as it involves only a loss of few percent micaceous and aluminosilicate minerals. Distinction of the two units is of economic importance, however, because only the uppermost unit is of sufficient purity for use as smelter-flux or in glass manufacture.

(6) *Upper Orthoquartzite Member* : Three hundred to 500 feet (90 to 150 m) of fine-grained, white and mottled red sandstone consisting almost totally of quartz. Bedding thickness in the lower part ranges from about 4 inches (10 cm) to 2 feet (0.6 m) and averages about 6 inches (15 cm) in the upper parts. Festoon crossbeds are present locally, and ripples are common near the top of the formation.

Sudbury-Manitoulin Area



ODM9605

Photo 34— Thick-bedded hematitic sandstone of the Lorrain Formation, Curtin Township. Festoon crossbed foresets are marked by specular hematite concentrations.



ODM9606

Photo 35— Medium-bedded white aluminous orthoquartzite of the Lorrain Formation, Curtin Township.

The feldspathic sandstone of the lower part of the formation (Silty Sandstone and Feldspathic Sandstone Members) is composed of poorly to moderately sorted arkose, feldspathic quartzite, protoquartzite, and subgreywacke. The grain size of these rocks ranges from fine to medium (0.01 to 0.3 mm) in the lower member, and from medium to coarse and very coarse (average size 0.5 to 1 mm) in the second member. The mineralogical composition of the rocks of the Lorrain Formation is shown in Figure 22. These rocks consist of angular to subrounded grains of quartz (30 to 75 percent; average 60 percent) and feldspars and rock fragments (5 to 45 percent; average 20 percent) in a micaceous silty matrix (average 20 percent), (Figure 22). Rock fragments, including granite, siltstone, chert, and quartzite are generally present in amounts of less than 5 percent, although locally they are more abundant as in the feldspathic sandstone member where granules and small pebbles of granite, feldspar, and quartz are common. Potassic and plagioclase feldspars are present, the ratio ranging from 0.2 to 10, and averaging 1 or 2. Accessory minerals include iron-titanium oxides, zircon, tourmaline, and apatite.

A chemical analysis of a typical feldspathic sandstone is given in Table 8.

The sandstone of the Green Micaceous Sandstone Member is a medium- to coarse-grained, poorly to moderately sorted rock consisting of subangular to subrounded grains of quartz (60 to 85 percent; average 65 percent), and feldspars and rock fragments (0 to 20 percent; average 10 to 15 percent), in a micaceous matrix (5 to 30 percent; average 15 percent). Rock fragments, if present, generally constitute less than 5 percent of the rock. Feldspars are present in amounts of 5 percent to 15 percent in the lower parts of the member and the potassic/feldspar/plagioclase ratio averages 5 to 10.

Sandstone of the Hematitic Sandstone and White Aluminous Sandstone Members is a fine- to medium-grained (0.2 to 0.3 mm), well-sorted rock consisting of rounded grains of quartz (70 to 95 percent) in a micaceous matrix (0 to 30 percent). Rock fragments are generally absent, and where present are mainly chert and quartzite. Minor amounts (1 to 2 percent) of hematite are present in the hematitic sandstone, and detrital heavy minerals, mainly zircon, are rare.

The sandstone of the Upper Orthoquartzite Member is a fine-grained (0.1 mm or less), well-sorted, orthoquartzite consisting mainly of rounded quartz grains and authigenic quartz cement (generally over 95 percent) with very minor amounts of hematite and mica. A chemical analysis given in Table 8, analysis 8, shows that orthoquartzite consists mainly of silica and contains only minor amounts of other oxides.

Conglomerate lenses concentrated in the middle part of the the formation consist of 30 percent to 70 percent rounded quartz, chert, and jasperoid pebbles averaging about ½ inch (1 to 2 cm) in diameter in a micaceous sandstone matrix.

In summary, sandstone of the Lorrain Formation displays a general upward decrease in bedding thickness and grain size. Sandstone of the lower half of the formation is immature to submature; that of the upper half is mature to supermature. Feldspar is abundant in the lower half of the formation but is absent in the upper half where its place is taken by phyllosilicate and aluminosilicate minerals. Hematite appears in relative abundance at about the same stratigraphic level. In the south, there is apparently little lateral variation in thickness or lithology of the formation, although locally the Hematitic Sandstone Member cannot be distinguished. The northern section in Vernon Township, although

Sudbury-Manitoulin Area

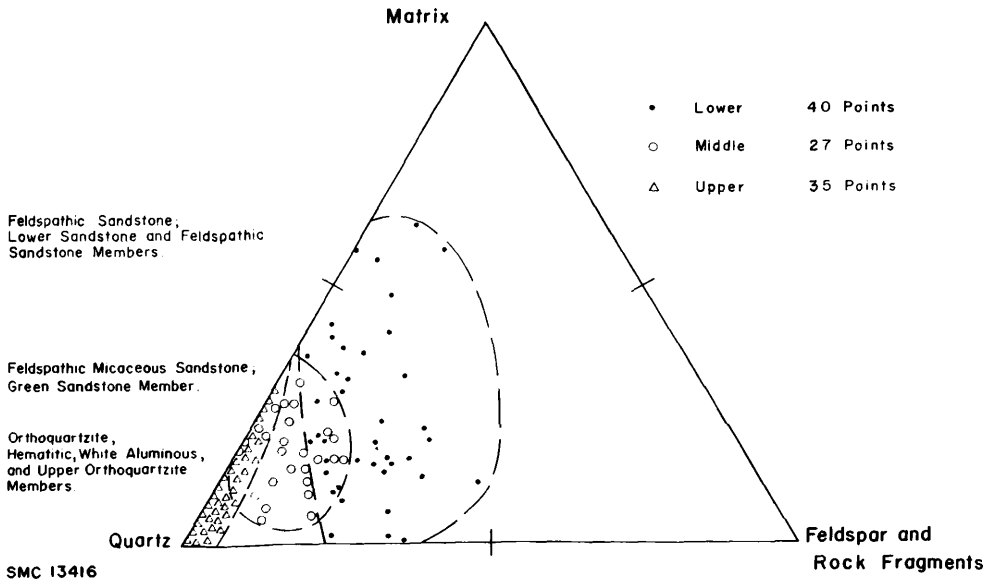


Figure 22a—Triangular diagram to show stratigraphic variation in mineralogical composition of sandstone from the Lorrain Formation; Sudbury-Manitoulin Area. Member 1-Silty Sandstone Member; Member 2-Feldspathic Sandstone Member; Member 3-Green Micaceous Sandstone Member; Member 4-Hematitic Sandstone Member; Member 5-White Aluminous Sandstone Member; Member 6-Upper Orthoquartzite Member.

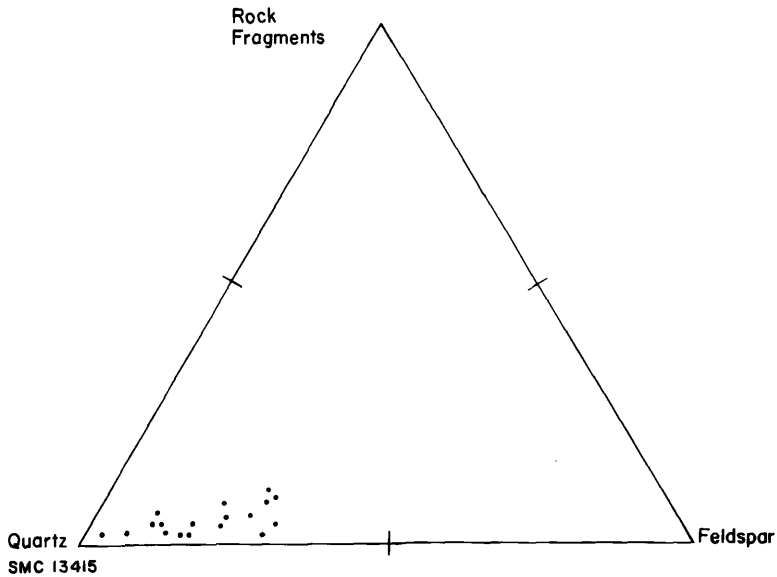


Figure 22b—Triangular diagram to show composition of sandstone with recognisable rock fragments, Lorrain Formation; Sudbury-Manitoulin Area.

only partly preserved and in an area of complex structure and poor exposure, is apparently somewhat different from the southern section. The lower two members, the Feldspathic and Green Micaceous Sandstone Members are thinner than their southern counterparts, and the Green Micaceous Sandstone Member in the north contains appreciably more conglomeratic material.

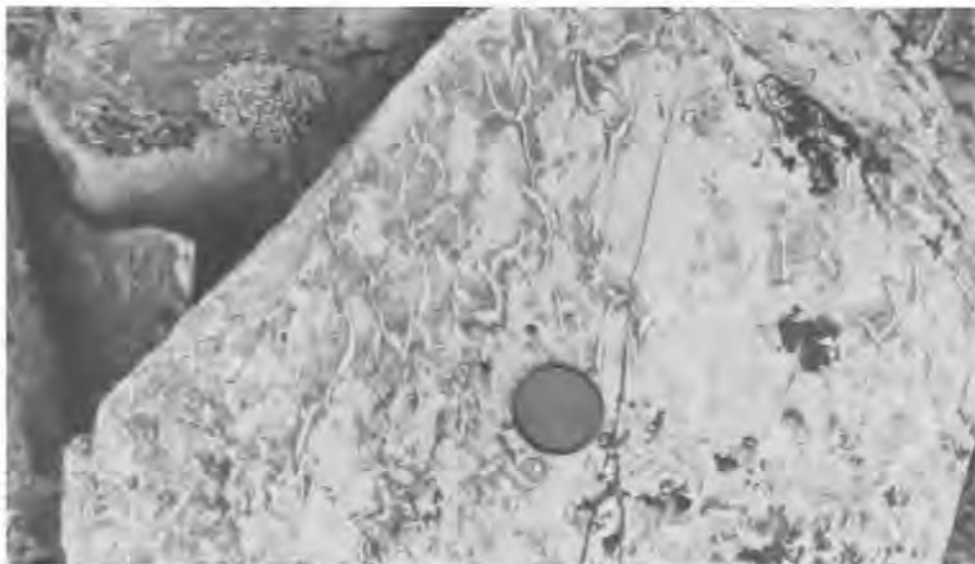
Gordon Lake Formation

Rocks of the Gordon Lake Formation, some 1,800 to 2,000 feet (540 to 600 m) of green, grey, pink, black, and buff siltstone and fine-grained sandstone, are exposed in the southern part of the map-area in the axial zone of the La Cloche Syncline, in a zone extending westward from Killarney Township to the western end of Bay Finn, and as shoreline and island exposures in Killarney Bay, on Badgeley Island, and on Heywood Island. These rocks were previously assigned to the Gowganda and Espanola Formations by Quirke and Collins (1930), but the present mapping has demonstrated (Card 1976b) that they lie in normal stratigraphic order above the Lorrain Formation, and are consequently correlative with the "Banded Cherty Quartzite" of Collins (1925), formally named the Gordon Lake Formation by Frarey (1967).

The formation can be divided into three intergradational units as follows (see Figure 21):

(1) A lower upward-fining sequence of interbedded sandstone and siltstone some 200 to 300 feet (60 to 90 m) thick, the lower 30 feet (9 m) of which represents the conformable transitional contact zone with the underlying Lorrain Formation. Bedding thickness in this unit ranges from about 1 to 10 inches (2.5 to 25.4 cm) and averages 2 inches (5 cm) and generally decreases upward. Similarly, the amount of siltstone increases upward to form approximately 50 percent of the rock at the expense of sandstone, and fine-grained white and reddish orthoquartzite beds are present in the lower part. Ripples are common.

(2) A middle sequence some 1,000 to 2,000 feet (300 to 600 m) thick of thin-bedded, ½- to 6-inch, average 1 inch thick (1 to 15 cm; 2.5 cm average), siltstone (70 percent) and fine-grained grey silty sandstone (30 percent). A great variety of sedimentary structures are present, including cross-laminations, ripples, graded beds, laminated beds, lensoid beds, ("starved ripples"), and ball-and-pillow and flame structures. Clastic dikelets are particularly abundant, and many are seen to follow cleavages. Desiccation cracks have been reported from this formation, but most of the structures seen by the writer which resemble desiccation cracks are small clastic dikelets which outline roughly polygonal areas on bedding surfaces (Photo 36). The dikelets commonly crosscut each other and extend through several beds, features not consistent with a desiccation crack origin. They probably represent the filling of sub-aqueous shrinkage or syneresis cracks with mobile clastic material from above or below, rather than infilling of subaerial mudcracks from above. Sedimentary breccia beds, consisting of small, less than 1 inch (2.5 cm) in diameter angular to rounded chips of very fine grained, chert-like siltstone in a siltstone or silty sandstone matrix, are prevalent, and were possibly also formed by a subaqueous shrinkage process. Toward the top of the sequence, units of thicker bedded, up to 1 foot (0.3 m) thick siltstone, silty sandstone, and



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Photo 36—Clastic dikelets (pseudo-mudcracks) exposed on the bedding surface of interbedded siltstone and sandstone of the Gordon Lake Formation, Narrow Bay.

white orthoquartzite appear. The amount of sandstone increases upward into the overlying unit.

(3) An upper, upward-coarsening sequence of sandstone and siltstone 100 to 300 feet (30 to 90 m) thick representing the transitional contact zone with the overlying Bar River Formation is present. The proportion of sandstone increases upward from about 40 percent in the lower part to 90 percent at the top, and the proportion of orthoquartzite relative to silty sandstone shows a parallel increase. The base of the Bar River Formation was arbitrarily placed at the base of a relatively thick-bedded (1 to 3 feet; 0.3 to 1 m) white and reddish orthoquartzite unit above which only minor (10 percent) amounts of silty interbeds and partings are present.

The grey, pink, buff and green silty sandstone of the Gordon Lake Formation is a fine-grained (0.05 to 0.2 mm), poorly sorted rock composed of subangular grains of quartz (55 to 75 percent; average 70 percent) and minor feldspars and rock fragments (average 5 percent), in an abundant silty matrix (20 to 45 percent; average 25 percent) of micas, chlorite, and quartz (see Figure 21). Accessory minerals include tourmaline, sphene, leucoxene, and iron-titanium oxides. Carbonate cement is present in some beds in amounts up to 5 percent. Some units contain up to 3 percent magnetite making the formation magnetically responsive. Rock fragments present are mainly fine-grained cherty siltstone and argillite, probably derived from the fragmentation of silty or muddy interbeds. Potassic feldspar and plagioclase are present, with the potassic feldspar predominating.

Orthoquartzite present in the lower and upper parts of the formation is essentially similar to that of the adjacent Lorrain and Bar River Formations, al-

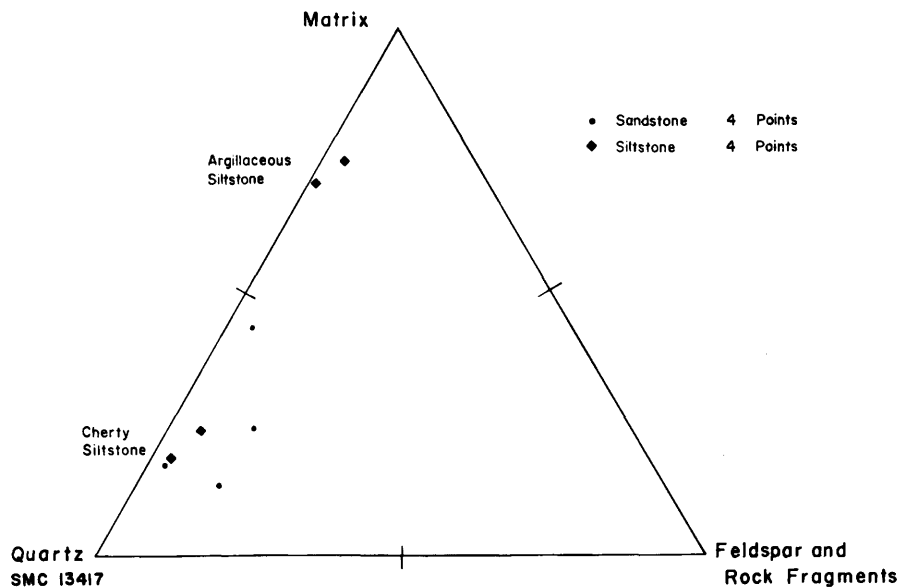


Figure 23—Triangular diagram to show mineralogical composition of siltstone in the Gordon Lake Formation.

though they commonly contain more silty material.

Siltstone in the Gordon Lake Formation represents variable mixtures of silt-, clay-, and fine sand-size material. Two main types are present (Figure 23):

(a) *Argillaceous Siltstone*

A poorly sorted rock consisting of silt with variable proportions of clay and fine sand. Those examined microscopically consist of silt- to fine sand-size quartz (20 to 25 percent) and feldspar and rock fragments (0 to 5 percent) with abundant (70 to 80 percent) phyllosilicates and minor (2 percent) carbonate cement.

(b) *Cherty Siltstone*

Buff, green and black rocks composed of very fine silt-size, well-sorted, angular grains of quartz (65 to 70 percent) and minor feldspar (5 percent) with appreciable phyllosilicates (20 to 25 percent).

A chemical analysis of a laminated, argillaceous siltstone is given in Table 8, sample 9. Megascopically this rock is similar to laminated argillite of the Gowganda and McKim Formations, but chemically the Gordon Lake sample is poorer in Al_2O_3 , total iron, CaO, Na_2O , and K_2O . The ratios $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$, $\text{CaO}/\text{Na}_2\text{O}$, $\text{K}_2\text{O}/\text{Na}_2\text{O}$, and $\text{FeO}/\text{Fe}_2\text{O}_3$ for the Gordon Lake sample are 40, 0.25, 14 and 0.3 respectively. In comparison, these ratios average 6, 0.4, 2.5 and 1.5 for Gowganda siltstone samples, and 17, 0.8, 2 and 2.5 for the McKim samples. The upward transition in the Huronian sequence from ferrous iron-rich to ferric iron-rich argillaceous rocks, generally corresponding to the appearance of hematite in the sandstone, demonstrates that the generally high $\text{FeO}/\text{Fe}_2\text{O}_3$ ra-

Sudbury-Manitoulin Area

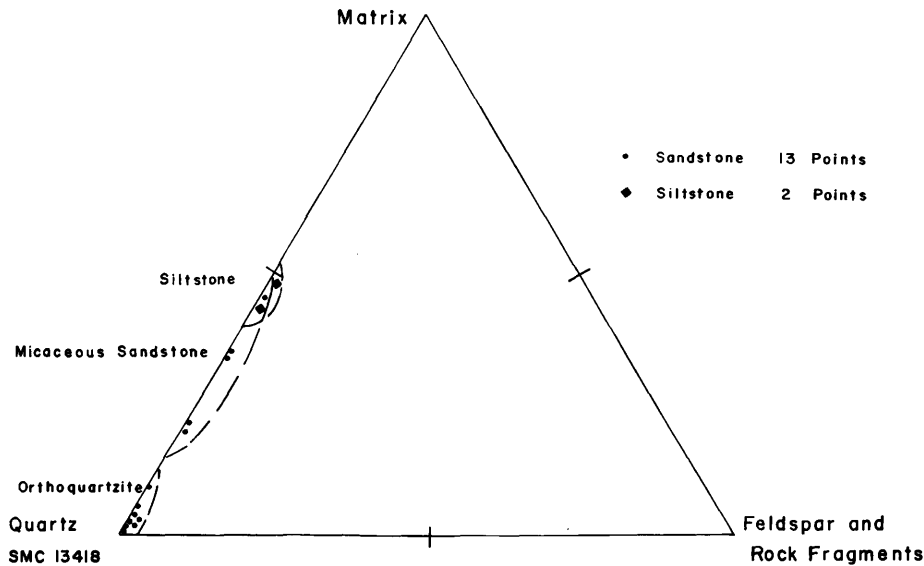


Figure 24—Triangular diagram to show mineralogical composition of rocks in the Bar River Formation, Sudbury-Manitoulin Area.

tio of the rocks in the lower part of the sequence is an original characteristic, and was not caused by reduction of iron during regional metamorphism.

Bar River Formation

The Bar River Formation, a sequence of white orthoquartzite and hematite-bearing sandstone and siltstone at least 3,000 feet (900 m) thick at the top of the Huronian Supergroup, is exposed in the southern part of the map-area. The main outcrop area extends west from Carlyle Township to Frazer Point, and there are numerous exposures on the islands of Killarney Bay and the North Channel, and at Sheguiandah on Manitoulin Island. These rocks were previously correlated with the Lorrain and Mississagi Formations in the Killarney area (Quirke and Collins 1930), but as they lie in normal stratigraphic order above the Gordon Lake Formation they correspond to Collins' (1925) "Upper White Quartzite" which Frarey (1967) formally named the Bar River Formation.

The formation can be divided into several conformable intergradational units as follows (Figure 24):

- (1) A lower sequence some 300 feet (90 m) thick of white and reddish orthoquartzite with minor (10 percent) silty partings and interbeds near the base. The beds are about 1 to 3 feet (0.3 to 1 m) thick and are commonly coarsely laminated (1 to 5 cm thick).
- (2) Some 600 feet (180 m) of white orthoquartzite with very minor disse-



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Photo 37—Ripples in fine-grained orthoquartzite of the Bar River Formation, Frazer Point.

minated hematite and hematitic siltstone chips in some beds. Bedding thickness ranges from 1 to 4 feet (0.3 to 1.2 m) and averages 2 feet (0.6 m) in the lower part, and 2 inches to 1 foot (5 to 30 cm), and averages 6 inches (15 cm) in the upper part. Bedding planes and planar and festoon crossbedding surfaces are marked by hematite concentrations.

(3) Approximately 750 feet (230 m) of blue and reddish hematitic sandstone and white orthoquartzite. Bedding thickness ranges from 4 inches to 2 feet (10 cm to 0.6 m) and averages 6 inches (15 cm). Crossbeds, slump breccias, and asymmetric and symmetric ripples are present.

(4) Approximately 700 to 800 feet (210 to 240 m) of sandstone and siltstone which form several upward-coarsening cycles consist of a lower siltstone-sandstone portion 30 to 100 feet (9 to 30 m) thick and an upper sandstone portion 100 to 250 feet (30 to 75 m) thick. The lower part of each cycle typically consists of black, bluish, and reddish, thin-bedded, 1 to 6-inch (2.5 to 15 cm), average 2-inch (5 cm) thick layers of siltstone and fine-grained micaceous sandstone which are rich in hematite. Lenticular and laminated beds, ripples, cross-laminations, and ball-and-pillow structures are present (Photo 37). The upper parts of each cycle consist of white orthoquartzite, bluish and reddish hematitic orthoquartzite, and buff, grey, and reddish micaceous sandstone. Bedding thickness ranges from 2 inches to 2 feet (5 cm to 0.6 m) averages 6 inches (15 cm), and ripples are present.

(5) An upper unit approximately 600 feet (180 m) thick of cream, buff,

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and bluish orthoquartzite. Bedding thickness ranges from 6 inches (15 cm) to 3 feet (1 m), averages 1 foot (0.3 m) and parallel laminations, festoon crossbeds, and ripples are present.

Orthoquartzite of the Bar River Formation is similar to that of the upper part of the Lorrain Formation, consisting mainly of rounded, well-sorted, fine- to medium-sized (0.1 to 0.3 mm) grains of quartz (95 percent) with recrystallized silica cement and minor amounts of muscovite and accessory hematite, zircon, tourmaline, and monazite (Figure 24). Locally, as on Manitoulin Island, interbeds and shear zones contain minor amounts of talc, chlorite, and amphiboles. Chemical analyses of orthoquartzite from the Sheguiandah Quarry, Manitoulin Island, show that it contains more than 98 percent SiO₂ and only minor amounts of other oxides (Hewitt 1963, p.14).

The micaceous sandstones are moderately sorted and consist of fine- to medium-grained quartz (35 to 80 percent), very minor feldspar (0 to 0.5 percent) and micaceous minerals (30 to 35 percent), mainly muscovite with lesser amounts of chlorite and talc. Hematite is a common constituent in the upper part of the formation where it constitutes 5 to 10 percent of some iron-rich beds.

Siltstone of the Bar River Formation consists of subangular to subrounded silt-size grains of quartz and minor feldspar with abundant micaceous minerals (50 percent), including muscovite, chlorite, biotite, and hematite. These rocks are characteristically rich in hematite. Some beds contain 15 to 20 percent hematite, over 15 percent total iron as Fe₂O₃, and could consequently be classed as lean iron formation.

ORIGIN AND DEPOSITION OF THE HURONIAN SUPERGROUP

Problems connected with the origin of the Huronian Supergroup are centered on the paleogeography and tectonic nature of the depositional basin, and the provenance and mode of deposition of the sediments. A glacial origin for the conglomeratic rocks of the Gowganda Formation has long been in vogue (Coleman 1905b) and several recent workers (Casshyap 1969; Young 1970) have assigned a major role to glaciation in the evolution of most of the sequence. The Huronian sandstone units have been regarded by some (McDowell 1957; Frarey and Roscoe 1970) as largely of fluvial or fluvial-deltaic origin, by others (Pettijohn 1970; Palonen 1973) as dominantly shallow marine deposits. The Huronian may also bear evidence of climatic changes (Chandler *et al.* 1969) and of evolution of the atmosphere from anoxygenic to oxygenic (Roscoe 1969).

Nature of the Depositional Basin

The Huronian Supergroup is a southward thickening sequence of Middle Precambrian clastic sedimentary rocks with local basal volcanic accumulations, which overlaps northward onto a basement of Early Precambrian granitic rocks. The sequence would appear to represent an ensialic clastic wedge deposited on the southern flank of the Superior Province craton.

The origin, original shape, and extent of the Huronian depositional area are matters of conjecture. It has been suggested that the Huronian was deposited on a stable piedmont plane, a tectonically segmented platform or exogeosyncline developed on the perimeter of an Early Precambrian protocontinental segment (Frarey and Roscoe 1970); in a marginal paraliageosyncline in which subsidence was tectonically controlled (Young 1971); in the miogeosynclinal portion of an Alpine-type geosyncline (Dietz and Holden 1966); and in a simple primitive trough similar to other Proterozoic orogens and to the Appalachian geosyncline in its early stages (Church 1971).

The southward extensions of the Precambrian are covered by Paleozoic strata and the waters of Lake Huron. Interpretations of the covered Precambrian terrane by Nwachukwu *et al.* (1965), Card (1976b), and Van Schmus, Card and Harrower (1975), mainly on the basis of aeromagnetic data, indicate that the Grenville Front extends southwestward along the eastern shore of Manitoulin Island and that Huronian rocks form part of the Precambrian basement beneath the northern half of Manitoulin Island. The southern half of the island and adjacent Lake Huron are apparently underlain by gneissic, felsic and mafic (metavolcanic ?) igneous rocks. If the rocks that bound the Huronian sequence on the south as well as on the north of the area are of Early Precambrian age, the Huronian basin was an elongate (generally east-west) graben-style trough.

The pronounced circular aeromagnetic anomalies over Manitoulin Island are probably attributable to zoned, magnetic intrusions similar to the Croker Island Complex (Card 1965). Drilling by Union Carbide Exploration Limited (Resident Geologist's Files, Ontario Ministry of Natural Resources, Sudbury) along the north shore of Manitoulin Island has confirmed the presence of Precambrian felsic plutonic rocks similar to those exposed in the Croker Island Complex. Radiometric age determinations by rubidium-strontium and zircon methods of the Union Carbide core show that these rocks are about 1500 m.y. old, or approximately the same age as the Croker Island Complex (Van Schmus, Card, and Harrower 1975).

The southeastward extension of the Middle Precambrian supracrustal rocks are obscured by high rank metamorphism and deformation of the Grenville Province. However, recent work by Lumbers (1975) has shown that much of the terrane in the northwestern part of the Grenville Province consists of clastic metasediments which are probably similar in age to the Huronian Supergroup.

The original northward extent of Huronian supracrustal cover rocks cannot be defined precisely, but radiometric age studies by Van Schmus (1965) indicate that the Superior Province rocks north to about Latitude 47° North have been affected, in the form of "metamorphic overprinting" and lowering of apparent radiometric age, by Middle Precambrian orogenic events. This may approximately define the northward limit of crustal instability, downwarp, and deposition of Middle Precambrian sedimentary rocks.

The Huronian Supergroup thickens southward to a maximum total cumulative thickness of some 35,000 to 40,000 feet (10 700 to 12 200 m). On a regional scale, and even within the present map-area, the paleolimits of successively younger formations occur progressively further northward. Consequently, some of the thickening is caused by the presence of a more complete succession of the Huronian strata progressively southward.

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Much of the thickening occurs relatively abruptly across zones now marked by major faults, indicating that there was tectonic control of deposition. For example, in the Sudbury-Manitoulin map-area, the McKim Formation is less than 10 feet (3 m) to possibly 2,000 feet (600 m) thick in areas north of the Hunter Lake Fault and approximately 5,000 to 6,000 feet (1500 to 1800 m) thick south of this structure. Similarly, the Mississagi Formation is 2,000 to 3,000 feet (600 to 900 m) thick in areas to the north of the Murray Fault, and 5,000 to 10,000 feet (1500 to 3000 m) thick in areas to the south.

The southward thickening of the Huronian Supergroup is neither simple nor uniform. Sandstone units such as the Mississagi and Serpent Formations show rapid thickening accompanied by the incoming of an increased proportion of silty material in the form of interbeds and members. The rate of thickening of individual formations is difficult to estimate because of the structural complexity, but as an example, in the central part of the area, the Mississagi Formation thickens from west to east along strike at a rate of about 250 feet per mile (50 m/km). Pelitic units such as the McKim Formation display even greater rates of thickness change. Other units, especially conglomeratic formations such as the Bruce Formation, thin southward. Rapid thickness and facies changes within the lower part of the Huronian sequence, for example in the Sudbury area, probably reflect local factors such as a more deeply subsided depositional base. The location of volcanic accumulations and associated mafic (layered Gabbro-Anorthosite) and felsic (Creighton) Plutons, is probably related to deeply penetrating faults in these areas. Near the Grenville Front Tectonic Zone, some formations, notably the Mississagi and Pecors Formations, apparently thicken greatly, whereas others, such as the Espanola, Serpent, and Gowganda Formations thin rapidly. This suggests that in its early stages, the Grenville Front Tectonic Zone represented a paleogeographic hinge line.

The Huronian basin does not fit the conventional geosynclinal model of a miogeosyncline-eugeosyncline couple, proposed for many Phanerozoic orogens, and, in contrast was relatively stable tectonically. There are some similarities between the Huronian sequence and Phanerozoic miogeosynclinal sequences in terms of thickness, and some units, notably the McKim and Pecors Formations, are similar to the flysch facies of Alpine-type geosynclines. However, much of the Huronian consists of shelf-type sandstone; the post-orogenic molasse facies of Phanerozoic geosynclines is absent. The Huronian basin apparently received all its fill from the adjacent craton; no evidence exists for derivation of sediments from "rising orogenic welts", within a mobile belt. Consequently, the Huronian does not display the depositional polarity typical of many Phanerozoic geosynclines.

The Huronian sequence was deposited on a basement of Early Precambrian rocks in a basin or on a shelf which was initiated by faulting and was mildly tectonically active throughout its history. Sedimentation was controlled to some extent by volcanic accumulations and basement and source area topography, all of which were ultimately controlled by tectonics, mainly vertical fault movements. Similarly, thickness variations were controlled in large part by tectonically mobile basement blocks. The Huronian volcanic rocks probably represent fissure eruptions controlled by deeply penetrating, early marginal faults.

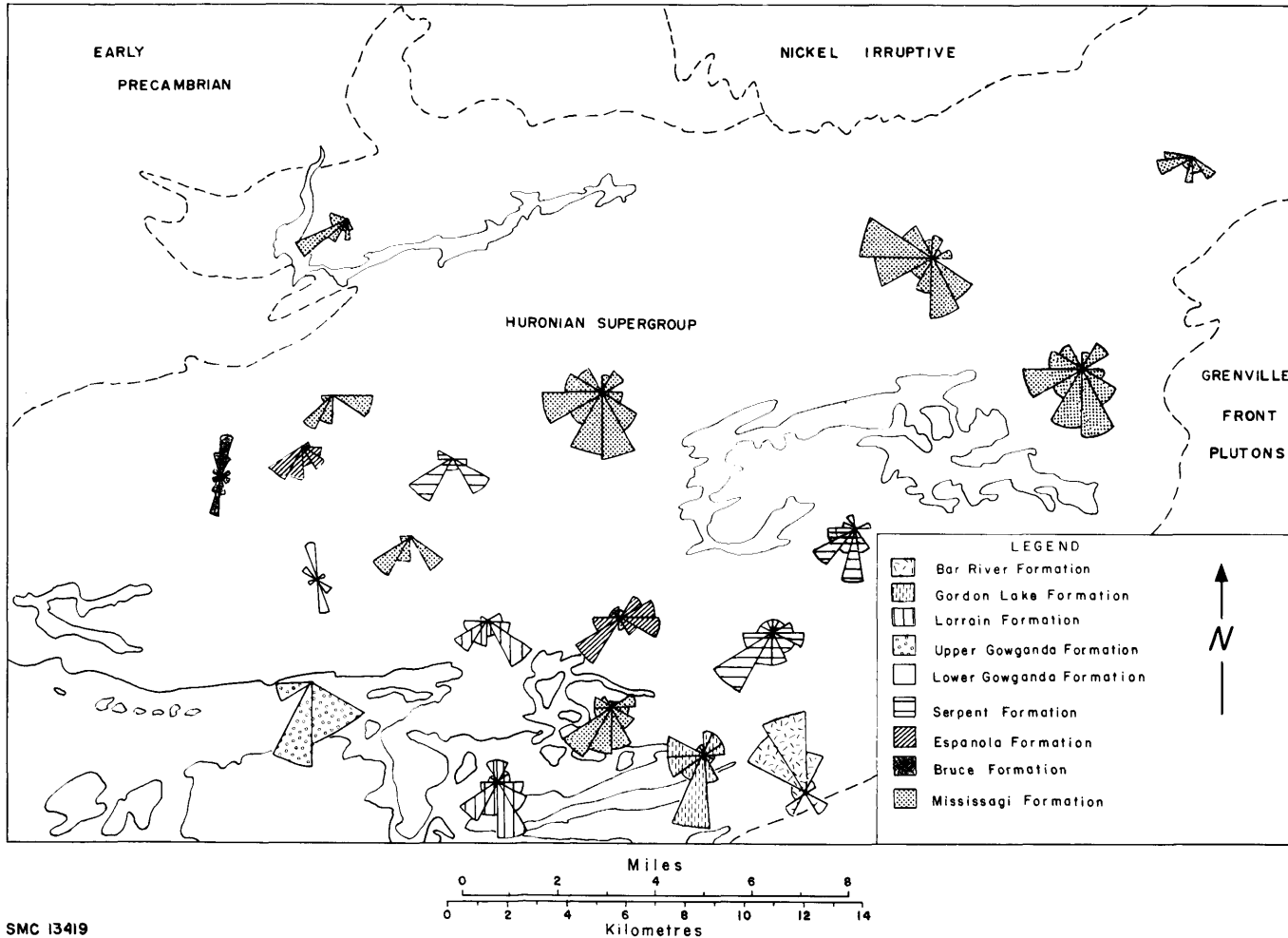
Paleocurrents and Provenance

The available paleocurrent data, based on the measurement of the attitudes of crossbedding, asymmetric ripples, and long axes of pebbles, are summarized in Figure 25, and indicate that the Huronian sediments were deposited by generally south-flowing currents. These data, along with the southward thickening trend suggest that the paleoslope had a general southward or southeastward inclination, and that it remained relatively constant throughout the deposition of the entire sequence.

Paleocurrent patterns in most of the Huronian formations are distinctly polymodal (commonly bimodal). Polymodal distribution of crossbed azimuths has been noted by several workers, notably Casshyap (1968), and Young (1966), who attributed it to sample bias, the preferential measurement of "end-member" crossbed classes to the exclusion of intermediate classes in steeply dipping strata. However, studies by Palonen (1971) and Card (1976b) have shown that the polymodal patterns are probably real. In the Mississagi Formation there are definite polymodal patterns in crossbed azimuth distribution relative to position within a single sedimentary cycle, and plots of trough and planar crossbeds from some individual beds produce a bimodal distribution pattern. Orientation of ripple marks, which should not be subject to sample bias, yield similar, and more complicated, paleocurrent patterns for the Lorrain and Bar River Formations. Many of the Huronian sandstone formations display two major modes, one indicating south- or southeast-flowing currents, another west or southwest currents (Figure 25). Although the formations have been affected to an unknown degree by deformation, the crossbed azimuths can probably be interpreted as the result of interaction of south-flowing depositional currents with east-west longshore currents in a turbulent, shallow water environment.

On a regional scale, Huronian conglomerate units display a preferred north-south orientation of long axes of pebbles and this has been interpreted as the direction of flow of the depositional medium (Lindsey 1969; Casshyap 1968). However, at many localities within the map-area, pebbles have a preferred east-west orientation parallel to the tectonic fabric and display features such as faulting, internal strain, and granulation which demonstrate that their orientation is of tectonic origin.

The composition of the bulk of Huronian sedimentary rocks indicates clearly that they were derived from felsic plutonic rocks. Quartz, feldspars, and granitic rock fragments are by far the dominant components, and the relative abundance of plagioclase indicates that the source rocks were mainly quartz monzonite-granodiorite in composition. In addition, there are relatively minor amounts of chert, schist, gabbro, and mafic and felsic volcanic fragments in these rocks, indicating subsidiary sources of such material existed. Siltstone and argillite fragments which are locally abundant were probably derived from within the sequence. Volcanic fragments, a notable component in some units in the lower part of the succession, were probably derived from the Huronian volcanic accumulations. On the basis of their petrography, the Huronian sedimentary rocks were derived from a terrane consisting largely of felsic plutonic rocks of general quartz monzonite-granodiorite composition, with lesser amounts of mafic intrusive, mafic and felsic volcanic and metasedimentary materials. Such a terrane



SMC 13419

Figure 25—Generalized paleocurrent patterns of the Huronian Supergroup, Sudbury-Manitoulin Area.

exists in the Early Precambrian Superior Province to the north, and together with the paleocurrent data, would indicate that this is the logical source area for the Huronian sedimentary rocks.

The rocks of the lower part of the Huronian sequence are immature, have relatively low quartz/feldspar and potassic feldspar/plagioclase ratios, and the feldspars are generally fresh. These features indicate that weathering of the source rocks was mainly mechanical, that there was negligible chemical weathering, and that deposition was rapid. This could be attributed to rigorous climatic conditions, lack of land plant cover, or both. In contrast, rocks of the upper part of the sequence are mature, and feldspar is practically absent, its place being taken by clay minerals, now converted to metamorphic aluminosilicates. This suggests appreciable chemical weathering, possibly connected with a major climatic change (Chandler *et al.* 1969).

The amount of Early Precambrian rocks eroded to form the Huronian sediments must have been great. Frarey and Roscoe (1970) estimated that the total volume of rocks eroded exceeded 1,000 cubic miles (2250 km³) per mile strike length of the Huronian fold belt. According to this figure, formation of the Huronian sequence along the North Shore of Lake Huron alone would necessitate erosion of that part of the present Superior Province bounded by Latitudes 47°N to 50°N and Longitudes 80°W to 86°W to a depth of about 4 miles (6.5 km).

Environment of Deposition

A great part of the Huronian Supergroup displays cyclical repetitions of conglomerate, shaley rocks, and quartz-feldspar sandstone units, indicating a cyclically repeated sedimentation process. Within the sequence as a whole, a general upward increase in maturity occurs implying more prolonged weathering of the source materials and increased sorting in the depositional environment.

Sandstones in the Matinenda Formation, the lower parts of the Mississagi, Serpent, and Lorrain Formations, and the upper parts of the Gowganda Formation are generally immature, poorly sorted rocks. These rocks were apparently deposited rapidly in a turbulent environment, but were little winnowed or reworked. Sandstone in the upper parts of the Mississagi, Serpent, Lorrain and Bar River Formations are submature to mature rocks, and were probably deposited in a turbulent environment where winnowing was moderate to strong. The fine detritus winnowed out was either deposited locally, in the form of argillaceous intercalations and interbeds, or was carried further down the paleoslope. Sandstones of all these formations are characterized by relatively thick, laterally persistent beds and abundant crossbedding.

Various workers have proposed a variety of depositional environments for the Huronian sandstone units. McDowell (1957) and Frarey and Roscoe (1970) suggested that most are fluvial or fluvial-deltaic deposits. Casshyap (1971) concluded that the Mississagi and Serpent Formations represent fluvial-deltaic deposits, the Gowganda sandstones prograding deltaic deposits, and the Lorrain deltaic, marine, and beach deposits. Palonen (1971) concluded, on the basis of upward-coarsening cycles and polymodal paleocurrent patterns, that the Mississagi Formation was deposited in a marine tidal flat-littoral environment as part

of a major regressive marine cycle. Such upward-coarsening cycles and paleocurrent patterns are also present in other sandstone formations, notably the Serpent and Gowganda Formations. These sequences were probably deposited in a prograding deltaic regime. Card (1976b) concluded that the mature sands of the Lorrain and Bar River Formations were deposited in a near-shore, coastal shelf environment during cyclically repeated marine transgressions and regressions.

Greywacke and pelitic rocks of the McKim, Pecors, Espanola, Gowganda, and Gordon Lake Formations are mainly poorly sorted, immature rocks with features such as thin laminated bedding indicating deposition in relatively deep water below wave base. These rocks also display features indicating deposition by turbidity currents such as graded beds, ripple-drift cross-lamination, and Bouma divisions. Breccias, slump folds, clastic dikes, and ball-and-pillow structures are prevalent, suggesting that faulting and earthquake activity played a role in their deposition. If structures previously interpreted as subaerial desiccation cracks are actually clastic dikelets or subaqueous shrinkage crack fillings, these rocks may have been deposited entirely in relatively deep water and were not subjected to periodic exposure in a tidal mud-flat environment. Within the McKim Formation there is a westward decrease in bedding thickness and in completeness of development of Bouma layering, indicating a westward transition from a proximal (near source) facies to a more distal facies. Young (1973) concluded that the carbonate-bearing Espanola Formation was deposited as diachronous migrating facies involving marine transgression and regression with deposition of limestone and dolostone in a shallow marine environment, siltstone in deeper water by turbidity currents, and sandstone in a prograding fluvial regime.

The conglomeratic rocks of the Ramsay Lake, Bruce, and Gowganda Formations are mainly poorly sorted, immature pebbly sandstones with a disrupted fabric. These units have great lateral extent relative to their thickness, and are generally massive although bedding is developed commonly enough to indicate that they were deposited in water. Rock fragments, some of which are 10 feet (3 m) or more in diameter, are mainly of plutonic igneous derivation and must have been transported over long distances. "Dropstones" are relatively large rock fragments which have been dropped into fine-grained, commonly bedded sediments and which disrupt this bedding, and have been reported from all these formations. The immaturity of the conglomerates indicates rapid erosion and deposition, probably under rigorous climatic conditions, and their textural characteristics imply transport by a high density medium.

The conglomeratic units also display some differences. The matrix of the Ramsay Lake conglomerate is better sorted than that of the Bruce and Gowganda Formations. The Ramsay Lake and Bruce conglomerates contain an appreciable amount of coarse, mature quartz sand, the Gowganda conglomerate does not except locally at the base of the formation. The Gowganda Formation is thicker than the Bruce and Ramsay Lake Formations and displays cyclical repetitions of conglomeratic units.

A glacial or marine glacial origin for the conglomeratic formations has been postulated by a number of workers (Coleman 1905b; Card 1976b; Casshyap 1969; Young 1970). Lindsey (1971) concluded that the Gowganda conglomerates

in the Whitefish Falls area represent the marine deposits of two major glacial events. A glacial origin could account for many of the characteristics of these rocks, such as the presence of dropstones which could represent ice-rafted fragments, the widespread occurrence, special texture and fabric of these rocks, and the evidence for long distance transport of large fragments in a high density medium. However, a glacial origin does not satisfactorily explain the differences noted between the various conglomerates, nor does it explain their association with rocks which display evidence of deposition by turbidity currents and of tectonic instability.

bris flows in a marine environment. Such deposits, described by Dzulynski *et al.* (1959), Walker (1970), and others are typically thick-bedded or massive, ungraded muddy sandstones with large, unsupported rock fragments, and are typically associated with turbidites. According to these authors, many such deposits are cleaner than "normal" turbidites, probably because of incorporation of relatively mature sands. Fisher (1971) described debris flows as high density fluids with large concentrations of coarse solids which flow in a laminar, rather than a turbulent fashion. Because of their flow characteristics, debris flows can override and be deposited on more easily eroded, fine-grained, unconsolidated sediment with little or no evidence of erosion. Rock fragments deposited from such flows may penetrate the bedding in the underlying undisturbed sediments, thus duplicating the features displayed by ice-rafted dropstones. Consequently, deposition by debris flows triggered by tectonic activity could account for the features displayed by the Huronian conglomerates, including the variations they display and their association with turbidites and rocks bearing evidence of large scale slumping.

Glaciation may have supplied coarse detritus to the basin initially, but a subsequent depositional mechanism such as turbidity currents and debris flows may have played a more important role.

The Huronian sediments have been regarded as the products of deposition in a stable platform environment, with continual northward marine transgression. According to this model, thickness and facies variations are ultimately attributable to variations in basement topography caused by differential erosion of basement granitic and volcanic rocks (Pienaar 1963).

Several workers have postulated that recurrent glaciation played a major role in the development of the sequence (Roscoe 1969; Casshyap 1969; Young 1970). According to this model, the conglomeratic rocks represent the direct deposits of several major continental-marine glacial episodes, the pelitic rocks are post-glacial transgressive marine deposits, and the sandstone regressive, prograding fluvial deposits following withdrawal of the glaciers. Glaciation may have played a part in the evolution of the sequence, but the thickness variations of the formations would indicate that the over-riding control was vertical tectonics.

Frarey and Roscoe (1970) and Pienaar (1963) have postulated that deficiency in iron in regolithic materials present locally at the base of the Huronian, and the general lack of ferric oxides (hematite) in the lower Huronian formations, in contrast to its relative abundance in the upper formations, records a major evolutionary change from anoxygenic to oxygenic atmospheric conditions. The presence of pyrite and uranium minerals of inferred detrital origin in the

lower part of the Huronian is also attributed to this lack of free oxygen. Others, notably Pettijohn (1970) have attributed the reduction and lack of iron to localized conditions in a marine depositional environment rather than to a general lack of atmospheric oxygen. In the Huronian sequence of the Sudbury-Manitoulin area a general upward increase in the ferric iron/ferrous iron ratio occurs which supports the concept of increasing oxygen availability with time. On the other hand, several units in the Mississagi Formation contain appreciable disseminated hematite, and Early Precambrian ferric iron-rich sedimentary rocks (hematite-bearing iron formations) are present in the Canadian Shield.

The Huronian sedimentary rocks, as Pettijohn (1970) has postulated, probably represent the deposits of a series of marine cycles. Evidence for such a model includes:

- (1) The general lack of fining-upward cycles characteristic of the fluvial deposits (the fining-upward cycles in the upper part of the Espanola Formation described by Young (1973) are an exception), and the presence of coarsening-upward cycles typical of a marine littoral-neritic environment in several formations.
- (2) The presence of polymodal paleocurrent patterns in several formations indicative of a variable current system in a marine littoral-neritic environment.
- (3) Characteristics of some of the sandstones, for example, those of the Lorrain and Bar River Formations, which are notably different in sorting, rounding, and composition from typical fluvial sands.
- (4) The presence of calcareous rocks in the Espanola Formation, and to a minor extent, in the Serpent and Gowganda Formations.
- (5) Evidence for a relatively deep-water, turbidite origin for several of the units, notably the McKim and Pecors Formations but also including parts of the Espanola, Gowganda, and Gordon Lake Formations.

According to the model proposed here, the Huronian Supergroup was deposited as a series of migrating, diachronous facies. Most of the sandstone units would represent regressive facies deposited in shallow turbulent waters, probably in fluvial-deltaic and shallow marine environments. Siltstone-greywacke units such as the McKim and Pecors Formations, generally represent transgressive facies deposited under relatively deep-water conditions by turbidity currents. However, some sandstone units, such as the Matinenda Formation and parts of the Lorrain Formation, may represent facies deposited during major marine transgressions, and some pelitic formations, notably the Espanola Formation, contain both transgressive and regressive facies. The conglomeratic units would represent rapid deposition of coarse clastics, possibly of glacial derivation, by extensive debris flows triggered by tectonic activity and sudden increase of the paleoslope, probably as a result of sporadic faulting in the basin and hinterland. The major sedimentary cycles displayed by the Huronian would represent a series of major regressive marine cycles which only periodically became emergent surfaces of accumulation. Some of the sedimentary rocks in the Matinenda Formation, in the upper parts of the Espanola and Serpent Formations, and possibly some units in the Lorrain Formation have characteristics of beach, dune, and fluvial sands.

Post-Huronian Metavolcanics (?)

On Pine, Sheep, and Badgeley Islands in Killarney Bay are several small bodies of mafic igneous rocks, interpreted to be mafic metavolcanics, which are too small to be shown at the present map-scale. These rocks are intruded and contact metamorphosed by the Killarney Pluton, and are isolated from the nearby Huronian rocks by granitic intrusions of this pluton. Judging from their location, the metavolcanics lie stratigraphically above the uppermost Huronian unit, the Bar River Formation, and measurement of poorly defined amygdaloidal zones indicated that their attitude is approximately the same as that of the underlying Huronian strata.

Both amygdaloidal and porphyritic mafic metavolcanics are present. The amygdaloidal varieties are fine-grained, dark green to black rocks composed of plagioclase, biotite, chlorite, epidote, quartz, iron-titanium oxides, and carbonate. The amygdules, which are up to 5 cm (2 inches) in maximum dimension, are commonly zoned and consist of quartz, chlorite, epidote, and carbonate. The porphyritic rocks are dark grey and consist of zoned, altered plagioclase (probably andesine-labradorite) phenocrysts about 1 mm long in a fine-grained matrix of plagioclase, quartz, biotite, epidote, muscovite, sphene, and iron-titanium oxides.

A chemical analysis of an amygdaloidal metavolcanic sample from Sheep Island (Table 9) shows that it is a calc-alkaline, high alumina, meta-andesite.

MIDDLE PRECAMBRIAN

CREIGHTON PLUTON

Two small felsic plutons, the Creighton and Murray Plutons, mainly quartz monzonite in composition, intrude metavolcanics and metasediments of the Elsie Mountain and Stobie Formations. The plutons are composite, high-level porphyritic intrusions, and apparently contain phases of diverse ages (Gibbins *et al.* 1972). Only the Creighton Pluton is exposed within the map-area; the Murray Pluton is exposed a short distance beyond the map-area to the northeast.

The Creighton Pluton, a metamorphosed porphyritic felsic intrusion consisting mainly of quartz monzonite is exposed in an area approximately 12 miles (19 km) long and 2 miles (3 km) wide in the northeastern part of the map-area, mainly in Graham, Waters, and Snider Townships. The pluton intrudes rocks of the Elsie Mountain and Stobie Formations and is intruded by the Nickel Irruptive and its associated dike, the Copper Cliff Offset, by metamorphosed mafic dikes and by late olivine diabase dikes of the Sudbury Swarm.

In addition to the Creighton Pluton, several dike-like bodies of quartz monzonite in Porter, Baldwin, and Shakespeare Townships intrude rocks of the Huronian Supergroup, but are too small to be shown at the present map-scale.

TABLE 9

CHEMICAL ANALYSIS AND NORM OF A POST-HURONIAN AMYGDALOIDAL META-ANDESITE (?), SHEEP ISLAND, KILLARNEY BAY, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSIS BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Chemical Analysis		Norm in weight percent		Trace Elements in ppm	
Major Components in Weight Percent					
SiO ₂	57.10	Quartz	9.40	Sb	10
Al ₂ O ₃	18.10	Orthoclase	22.11	As	10
Fe ₂ O ₃	3.84	Acmite	0.00	Ba	500
FeO	3.99	Enstatite	6.61	Cr	40
MgO	2.60	Ferrosilite	6.50	Co	11
CaO	4.80	Corundum	0.76	Cu	25
Na ₂ O	2.91	Ilmenite	1.75	Ga	15
K ₂ O	3.66	Magnetite	3.55	Pb	30
H ₂ O ⁺	0.26	Apatite	1.18	Li	40
H ₂ O ⁻	0.16	Pyrrhotite	0.03	Mn	1200
CO ₂	0.40	Albite	25.15	Mo	-
TiO ₂	0.90	Anorthite	23.99	Ni	30
P ₂ O ₅	0.05	Differentiation	56.69	Sc	30
S	0.01	Index		Sr	-
MnO	0.09	Colour Index	16.80	Sn	300
		Normative		Ti	-
Total	98.87	Plagioclase	47.34	V	200
		Composition		Y	30
Specific Gravity	2.78			Zn	100
				Zr	200

Abbreviation

- Present below limits

Age and Contact Relationships

The contacts of the Creighton Pluton, although commonly brecciated, are clearly transgressive with respect to stratification in the country rocks, and several granitic dikes and apophyses extend outward from the main contacts into the country rocks. Xenoliths or roof-pendants of metavolcanics and metasediments ranging from a few inches to 5 miles (8 km) in maximum dimension are scattered throughout the body. The contacts between the granite and the metavolcanics, where not brecciated, are sharp, and there is generally little evidence of contact metamorphic or metasomatic activity. Locally, porphyroblasts of potassic feldspar are present in the country rocks near granite contacts. Similarly, the country rock xenoliths, which are riddled with granitic dikes, show little evidence of contact metamorphism or assimilation, although they, like the granitic rocks, have been regionally metamorphosed.

The relative ages of the Creighton Pluton and the Sudbury Nickel Irruptive, and the nature of the contact between these two intrusions have been debated. Yates (1938), Burrows and Rickaby (1934), and others concluded that the Creighton Pluton is younger than the Sudbury Nickel Irruptive because granitic dikes intruding the Sudbury Nickel Irruptive are similar to parts of the Creighton Pluton. However, the Copper Cliff Offset, which is about the same age as the rest of the Sudbury Nickel Irruptive, clearly intrudes the Creighton Pluton. The contact between the Sudbury Nickel Irruptive and the Creighton Pluton is abrupt, the granitic rocks here are highly altered and locally impregnated with sulphide minerals, and a narrow marginal chill zone is displayed by the Sudbury Nickel Irruptive. Microscopic examination of several of the granitic dikes which cut the Sudbury Nickel Irruptive has shown that most are mineralogically and texturally similar to felsic segregations which occur throughout the norite, not to the granitic rocks of the Creighton Pluton (Card 1968a). Several, however, are similar and one dike can be traced in outcrop from the pluton into the Sudbury Nickel Irruptive (Thomson, J.E., personal communication 1959). The available evidence indicates that the bulk of the rocks composing the Creighton Pluton are of pre-Sudbury Nickel Irruptive age, although post-Sudbury Nickel Irruptive granitic dikes are present.

Fairbairn *et al.* (1969) have determined a Rb-Sr isochron age of about 2140 m.y. for the Creighton Pluton. Work by Gibbins *et al.* (1972) on the nearby Murray Pluton, which displays the same geological relationships as the Creighton Pluton, indicate that the Murray Pluton has a Rb-Sr isochron age of 2150 m.y. to 2230 m.y., and that granite dikes within the pluton and extending from the pluton into the Sudbury Nickel Irruptive have apparent radiometric ages of 1780 m.y. and 2050 m.y.

Structural Relationships

The Creighton Pluton is elongated parallel to the structural trends in the country rocks, and, like the country rocks, has been deformed and flattened. The pluton is also cut by numerous dike-like and irregular bodies of Sudbury Breccia which consist of rounded granitic rock fragments in a dark coloured granitic

Sudbury-Manitoulin Area

TABLE 10 | CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF ROCKS OF THE CREIGHTON PLUTON IN THE SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Major Components in Weight Percent			
	1	2	3
SiO ₂	75.90	78.30	70.34
Al ₂ O ₃	12.40	12.30	13.99
Fe ₂ O ₃	0.52	0.35	1.76
FeO	1.69	0.84	2.22
MgO	0.24	0.15	0.77
CaO	0.97	0.63	2.07
Na ₂ O	3.06	2.73	3.56
K ₂ O	5.30	5.28	4.53
H ₂ O ⁺	0.34	0.26	0.37
H ₂ O ⁻	0.19	0.20	0.14
CO ₂	-	-	-
TiO ₂	0.33	0.29	0.42
P ₂ O ₅	0.04	0.02	0.09
MnO	0.04	0.02	0.04
FeS ₂	0.11	0.37	0.26
Total	101.13	101.74	100.56
Specific Gravity	2.63	2.60	2.69

Trace Elements in ppm			
Ba	500	400	1000
Cr	10	10	10
Co	10	10	10
Cu	2	30	5
Ni	10	10	15
Pb	20	30	30
Sc	10	10	10
Sr	50	50	100
Sn	10	10	20
V	10	10	30
Y	30	20	30
Zr	150	100	150

Modal Analysis (Volume Percent)			
Quartz	32	32	30.5
Plagioclase	25	40	39.0
Perthitic	32	25	15.5
Microcline			
Biotite			
Muscovite	11	3	15.0
Chlorite			
Plagioclase Composition	An _{12±3}	Albite (saussuritized)	Albite (saussuritized)

Table 10 — continued

	Norms (Weight Percent)		
	1	2	3
Quartz	34.40	40.19	26.39
Corundum	-	0.98	-
Orthoclase	31.17	30.90	26.80
Albite	25.74	22.85	30.13
Anorthite	4.41	2.96	8.81
Diopside	0.03	-	0.41
Hedenbergite	0.08	-	0.31
Enstatite	0.58	0.37	1.73
Ferrosilite	1.94	0.12	1.48
Magnetite	0.75	0.50	2.55
Ilmenite	0.62	0.55	0.80
Apatite	0.09	0.05	0.21
Pyrrhotite	0.19	0.54	0.38
Differentiation Index	91.32	93.90	83.32
Colour Index	3.99	1.53	7.28

Notes

1. Pink equigranular granite, Denison Township.
2. Pink porphyritic quartz monzonite, Graham Township.
3. Grey porphyritic quartz monzonite, Graham Township.

Abbreviations

- Not detected

crush matrix. The granitic rocks show several foliations, including a local, marginal, flow-type foliation, imparted by preferred alignment of feldspar phenocrysts, which is parallel to contacts, a localized early, pre-breccia gneissic foliation, and a pervasive, post-breccia, cataclastic foliation which trends east-northeast parallel to the dominant foliation in the country rocks and the Sudbury Nickel Irruptive. The intrusive rocks also display several prominent joint sets and are offset by movements on the Creighton and other faults.

Petrography and Chemistry

The Creighton Pluton consists 90 percent of quartz monzonite with minor amounts of pink granite in the form of dikes and irregular bodies.

The quartz monzonite is a pink or grey, leucocratic rock, commonly with a porphyritic texture. It consists of large, up to 1 inch (2.5 cm), phenocrysts of sodic plagioclase, perthite, and microcline in a medium-grained (0.2 mm) groundmass of quartz, plagioclase, perthite, and minor biotite, chlorite, sericite, and epidote. The effects of metamorphism and deformation include saussuritization of plagioclase, chloritization of biotite, and cataclastic granulation and pre-

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ferred orientation of minerals. The pink and grey varieties are intergradational, and are texturally and mineralogically similar except that the grey quartz monzonite is generally more altered, and contains more biotite and chlorite and less potassic feldspar than the pink quartz monzonite. Near the contacts with mafic metavolcanics, the granitic rocks are littered with inclusions, and contain appreciable amounts of biotite and amphiboles.

The granite which intrudes the quartz monzonite is a pink, leucocratic, equigranular, medium- to coarse-grained (1 to 2 mm) rock composed of sodic plagioclase, perthitic microcline, quartz, biotite, and muscovite. The pegmatitic bodies are mineralogically similar. Modal and chemical analyses and normative mineral compositions of typical rocks of the Creighton Pluton are given in Table 10. Note that the granitic rocks are chemically similar to felsic volcanic rocks of the Copper Cliff Formation (see Figure 6).

Origin

The contact relationships and petrography of the Creighton Pluton indicate that it represents a porphyritic, magmatic intrusion discordantly emplaced at relatively high crustal levels by a block-stopping mechanism. There is no evidence at the present level of observation for assimilation of country rocks, although metasedimentary and metavolcanic xenoliths are prevalent.

The spatial relationship of the pluton to the Huronian metavolcanic sequence, the chemical similarity of the granitic rocks to felsic metavolcanics of the Copper Cliff Formation, and characteristics indicative of high level emplacement of the pluton, suggest that a genetic connection exists between the Creighton Pluton and the Huronian volcanic sequence. Possibly the Creighton Pluton represents the late-stage, epizonal magmatic intrusive phase of a prolonged extrusive-intrusive cycle.

The granitic rocks of the Creighton Pluton, like those of the Murray Pluton, have a high initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio, indicating appreciable contamination by crustal materials (Fairbairn *et al.* 1965; Gibbins *et al.* 1972).

NIPISSING DIABASE

Tholeiitic gabbro bodies of early Middle Precambrian age, collectively referred to as "Nipissing Diabase", occur throughout the eastern part of the Southern Province where they intrude rocks of the Huronian Supergroup. Some mafic intrusions in the southern part of the Superior Province and in the northwestern part of the Grenville Province are probably of the same age. Regionally metamorphosed mafic intrusions in the Sudbury area which have been referred to as "Sudbury Gabbro" are part of the Nipissing Diabase suite (Card and Pattison 1973).

Investigations by Van Schmus (1965) in the Blind River area, by Fairbairn *et al.* (1969) in the Gowganda area, and Lowdon *et al.* (1963) around Cobalt show that these intrusions have a Rb-Sr isochron age of about 2,160 m.y. Nipissing

Diabase Intrusions in the Sudbury area yield lower (commonly about $1,800 \pm 100$ m.y.), discordant, apparent radiometric ages, and this is probably caused by the effects of orogenic disturbance in this area (Fairbairn *et al.* 1969).

Forms and Structural Relationships

Nipissing Diabase Intrusions range in thickness from a few feet to several thousand feet. At Cobalt, the Nipissing Diabase Intrusion is a thick (1,000 feet; 300 m), undulating sheet exposed as a series of basin and arch structures (Thomson 1964). Paleomagnetic studies by Symons (1970) in the Cobalt Area indicate that these structures are dominantly primary, and that post-Nipissing deformation, possibly connected with major northwest faulting, has only accentuated the primary basin and arch structure. Symons also determined a pole position for the Nipissing Diabase at Cobalt of 91.9°E , 19.4°N . In the Maple Mountain area to the northeast, many intrusions have elliptical or circular outcrop patterns and display inward-dipping contacts and transgressive relationships toward the country-rock structural-stratigraphic trends. These probably represent cone-sheet intrusions (Lovell and Caine 1970; Card and Pattison 1973). Some intrusions in the present map-area may also represent cone-sheets, although deformation has obscured the diagnostic shape and contact relationships. Most intrusions of Nipissing Diabase in the map-area have the surface form of transgressive sill-like bodies, dikes, and incomplete rings. In the area extending eastward from the Baldwin Anticlinorium toward Sudbury, the area in which relatively late deformation is most pronounced, the Nipissing Diabase bodies have been folded along with the Huronian strata and are consequently generally conformable with the regional structure. However, to the north in the Vernon Syncline, and to the south in the McGregor Bay Anticline, intrusions of Nipissing Diabase display transgressive relationships toward early major fold structures. The Nipissing Diabase has, along with the Huronian rocks, been metamorphosed under conditions corresponding to the greenschist and lower amphibolite facies of regional metamorphism. Consequently, they were emplaced after initiation of early major folding, but prior to later deformation and regional metamorphism. Nipissing Diabase Intrusions are cut by Sudbury Breccia bodies, and are consequently older than this brecciation which is probably closely related in time and genesis to the Whitewater Group and the Sudbury Nickel Irruptive.

On a regional scale, the distribution of Nipissing Diabase Intrusions is related in part to major regional faults which probably acted as channelways allowing upward movement of magma (Lovell and Caine 1970; Card and Pattison 1973). On the more limited scale of the present map-area, many intrusions are spatially related to massive conglomeratic units such as the Ramsay Lake, Bruce, and Gowganda Formations, and to the contacts between massive conglomerate and sandstone formations and pelitic units. The massive sedimentary formations probably acted as stress barriers, blocking the upward movement of magma, but also their response to tectonic stress was such that they allowed lateral movement of magma.

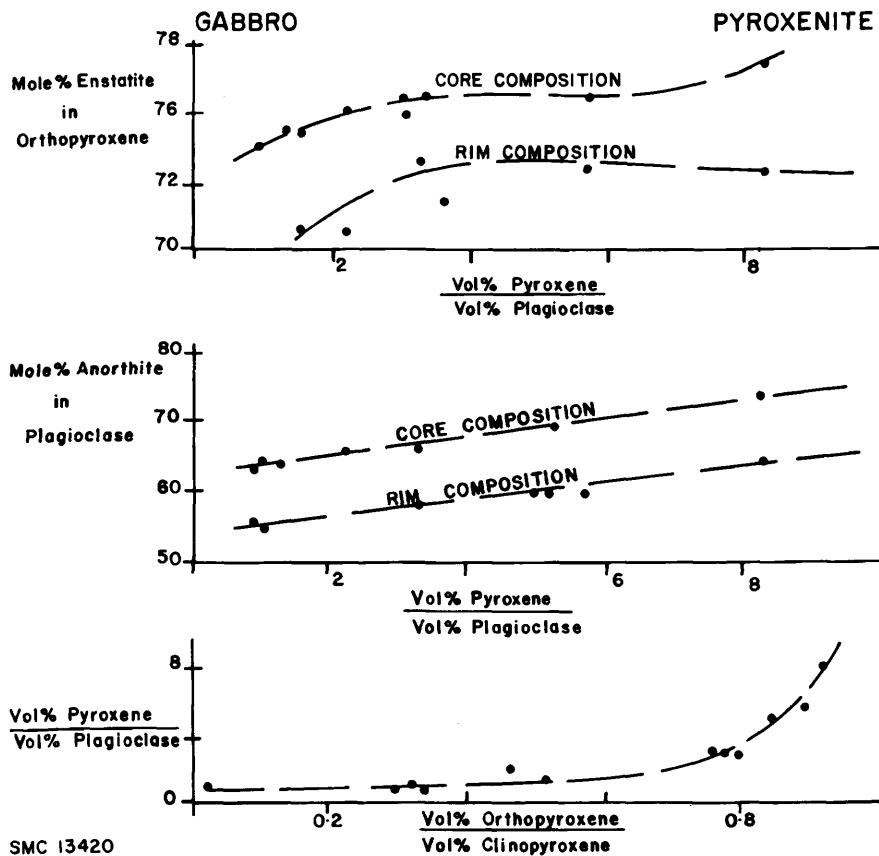
Petrography

In the Sudbury-Manitoulin map-area, the Nipissing Diabase Intrusions have been regionally metamorphosed and are now composed largely of amphibole-bearing metagabbro. However, remnants of unaltered gabbroic rocks are present in the central portions of many thick intrusions and these consist of pyroxene gabbro, hornblende gabbro, and feldspathic pyroxenite. In addition, there are relatively minor amounts of granophyric gabbro and granophyre in the upper parts of some intrusions.

Pyroxene gabbro and feldspathic pyroxenite are medium- to coarse-grained (average grain size 2 to 3 mm) grey, brown-weathering rocks consisting of variable proportions of calcic plagioclase, orthopyroxene, and clinopyroxene, with minor amounts of quartz, granophyre, amphiboles, micas, chlorite, apatite, carbonate, sphene, epidote, iron-titanium oxides, and sulphides (Table 11). Feldspathic pyroxenite consists of 80 to 90 percent of pyroxenes, and 10 to 20 percent calcic plagioclase; orthopyroxene and clinopyroxene are present in approximately equal proportions. In the gabbroic rocks, the pyroxene/plagioclase ratio varies from about 4:1 in mafic gabbros to about 1:2 in leucogabbros; most contain approximately equal proportions of pyroxenes and plagioclase. Similarly, the clinopyroxene/orthopyroxene ratio varies from about 1:1 to approximately 50:1 (Figure 26). In the more leucocratic gabbros, anhedral pyroxenes fill the interstices between euhedral plagioclase laths, whereas in rocks with more than 70 percent pyroxene, plagioclase is anhedral and interstitial to subhedral and euhedral pyroxenes. In the feldspathic pyroxenites, euhedral orthopyroxene crystals up to several centimetres in length poikilitically enclose small anhedral plagioclase and clinopyroxene grains.

The plagioclase, which displays carlsbad, albite, and pericline twinning, and normal and oscillatory zoning, ranges in composition from An_{75} in feldspathic pyroxenites to An_{65} in pyroxene gabbro. Rim compositions are about An_{55} to An_{60} (Figure 26). Similarly, orthopyroxene ranges in composition from $En_{80}Fs_{20}$ to $En_{74}Fs_{26}$ and is commonly zoned, with a rim composition ranging from $En_{70}Fs_{30}$ to $En_{60}Fs_{40}$. The augite displays well-developed twinning, and ranges in composition from $Wo_{41}En_{42}Fs_{17}$ to $Wo_{33}En_{56}Fs_{11}$. Orthopyroxene grains commonly display exsolution lamellae of diopsidic clinopyroxene parallel to the (100) crystallographic plane. Some orthopyroxenes contain clinopyroxene exsolution lamellae approximately parallel to the (101) plane, and these probably represent inverted pigeonite crystals in which clinopyroxene was exsolved parallel to the (001) plane of the original pigeonite. Augite commonly contains orthopyroxene exsolution lamellae parallel to the (100) plane, and, rarely, parallel to the (001) plane. The latter exsolution lamellae were interpreted as exsolved pigeonite which subsequently inverted to orthopyroxene (Hess 1960).

Iron-titanium oxides of the unaltered mafic rocks include ilmenite and titaniferous magnetite. Ilmenite typically occurs as exsolution lamellae in magnetite grains which form the host. The amount of ilmenite-magnetite generally increases with decreasing mafic mineral and increasing granophyre content. Sulphides, including pyrrhotite, chalcopyrite, and pentlandite, are present in minor amounts in the fresh gabbroic rocks, and like ilmenite-magnetite, increase with increasing granophyre content.



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Figure 26—Mineralogical and modal variation diagrams, Nipissing Diabase Intrusions, Sudbury-Manitoulin Area.

Granophyric gabbro, which forms diffuse irregular zones in some intrusions, commonly consists of 15 to 25 percent granophyric intergrowth of feldspar and quartz with saussuritized intermediate plagioclase (andesine), uralitic amphiboles (blue-green hornblende and actinolite), apatite, sulphides, and iron-titanium oxides. Granophyre, which forms fine to very coarse grained segregations and dikes, consists mainly of quartz-alkali-feldspar intergrowths and plagioclase with minor amounts of amphiboles, biotite, chlorite, epidote, sphene, carbonate, apatite, zircon, sulphides, and oxides (Table 11). Albitic plagioclase and microcline are present in pink-coloured granophyre, whereas a coarse-grained white variety contains only plagioclase.

Metamorphism of the Nipissing Diabase Intrusions involves uralization of pyroxenes and saussurization of plagioclase under elevated temperature-pressure conditions corresponding to the greenschist and lower amphibolite facies of

Sudbury-Manitoulin Area

TABLE 11 | CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Sample Number	Major Components							
	1	2	3	4	5	6	7	8
SiO ₂	50.61	49.97	54.00	60.70	71.60	73.00	68.20	48.60
Al ₂ O ₃	7.24	17.44	13.80	12.60	14.40	14.00	16.20	9.16
Fe ₂ O ₃	4.39	2.19	1.03	6.38	0.39	0.05	0.32	4.65
FeO	7.18	6.90	9.79	5.49	1.61	0.91	1.33	6.48
MgO	9.69	7.79	5.90	3.05	0.90	1.05	1.50	9.57
CaO	18.47	11.05	11.00	4.93	2.03	1.75	1.05	18.41
Na ₂ O	0.71	1.96	1.71	3.24	7.01	7.27	6.08	0.53
K ₂ O	0.24	0.48	0.49	1.18	0.45	0.36	1.45	0.20
H ₂ O ⁺	0.24	0.53	0.28	1.86	0.45	0.19	0.87	1.29
H ₂ O ⁻	-	0.22	0.12	0.30	0.21	0.22	0.09	-
CO ₂	0.05	0.39	0.10	0.11	0.44	0.55	0.12	0.07
TiO ₂	0.34	0.30	0.70	1.27	1.01	0.62	0.74	0.32
MnO	0.22	0.12	0.19	0.09	0.04	0.02	0.01	0.25
P ₂ O ₅	0.03	0.07	0.04	0.35	0.09	0.11	0.12	0.03
S	-	0.08	0.01	0.01	0.01	0.01	0.05	-
Cr ₂ O ₃	0.27	0.09	-	-	-	-	-	0.03
V ₂ O ₃	0.02	0.07	-	-	-	-	-	0.02
Total	99.70	99.65	99.16	101.56	100.64	100.11	98.13	99.61
Specific Gravity	N.D.	2.99	2.92	2.76	2.66	2.65	2.65	N.D.

Trace Elements							
Ag			1	1	1	1	1
As			-	-	5	60	-
Ba			100	-	-	-	150
Be			-	2	1	1	2
Co			50	20	5	10	5
Cr			600	-	-	20	-
Cu			80	15	20	10	15
Ga			20	30	30	30	30
Li			-	20	20	20	20
Mn			2000	600	300	150	100
Mo			5	10	-	-	10
Ni			200	5	5	10	5
Pb			10	10	10	10	10
Sb			-	10	-	-	-
Sc			80	30	30	20	20
Sn			5	5	5	5	5
Sr			150	100	20	20	100
Ti			4000	8000	5000	3000	3000
V			300	20	200	20	30
Y			20	30	20	20	20
Zn			90	30	40	20	10
Zr			100	300	50	50	60

NIPISSING DIABASE INTRUSIONS IN THE SUDBURY-MANITOULIN AREA. CHEMICAL

in Weight Percent									
9	10	11	12	13	14	15	16	17	18
48.34	54.20	54.60	52.40	49.40	50.30	51.90	50.89	53.80	53.00
18.03	11.40	14.60	15.10	14.60	14.40	14.00	14.60	13.70	14.40
1.28	1.70	1.22	6.07	6.01	3.24	1.91	1.52	0.76	3.82
8.15	9.10	7.43	7.50	4.20	5.14	8.40	8.08	8.08	9.41
8.45	8.40	6.30	4.50	9.05	9.87	6.80	8.38	8.08	4.50
9.83	11.30	11.70	8.73	9.77	11.70	10.90	9.94	11.60	9.40
2.08	1.50	2.16	2.09	2.47	1.18	2.18	1.65	1.52	2.18
0.60	0.47	0.54	0.88	0.82	0.80	0.70	0.55	0.60	0.91
1.52	0.81	0.82	1.73	1.87	1.18	0.95	1.76	0.45	1.03
0.23	0.06	0.23	0.15	0.11	0.20	0.24	0.28	0.06	0.04
0.33	0.28	0.16	0.25	0.50	0.23	0.11	0.27	0.20	0.28
0.28	0.71	0.58	0.98	0.59	0.45	0.63	0.19	0.63	1.08
0.14	0.19	0.16	0.17	0.15	0.16	0.19	0.14	0.17	0.17
0.07	0.05	0.04	0.09	0.07	0.05	0.04	0.03	0.01	0.02
0.09	0.03	0.03	0.08	0.04	0.05	0.09	0.08	0.02	0.06
0.03	-	-	-	-	-	-	0.05	-	-
0.04	-	-	-	-	-	-	0.09	-	-
99.49	100.20	100.57	100.72	99.65	98.95	99.04	98.50	99.68	100.30
2.96	2.97	2.97	2.94	2.93	2.91	2.99	2.98	3.02	3.02

in ppm

1	1	1	1	1	1	1	-	-
-	30	-	10	-	5	-	-	-
100	-	100	-	-	-	-	150	200
-	-	-	-	-	-	-	-	-
50	20	-	30	30	30	40	40	40
1000	150	20	200	600	50	200	40	40
90	80	90	90	40	160	70	190	190
20	10	20	10	10	10	15	20	20
-	20	30	40	20	20	-	-	-
2000	1200	1200	800	1000	1200	-	-	-
5	5	10	10	10	5	-	-	-
200	100	70	100	150	100	170	100	100
10	10	10	10	10	10	10	10	10
-	-	6	-	-	-	-	-	-
80	50	50	50	50	50	30	30	30
5	5	5	5	5	5	-	-	-
150	100	200	100	100	100	250	150	150
4000	3000	6000	3000	2000	4000	-	-	-
300	150	150	150	200	200	150	150	150
20	20	20	20	20	20	20	20	20
80	60	70	60	40	80	70	110	110
100	50	60	60	60	60	30	20	20

Table 11 continued next page

Sudbury-Manitoulin Area

Table 11 – continued

Sample Number	Modal Analyses							
	1	2	3	4	5	6	7	8
Plagioclase	10.7	52.4	50.0		32.5	63.0		15.0
Pyroxene	-	-	47.8		-	-		-
Orthopyroxene	42.8	6.8	-		-	-		-
Clinopyroxene	46.4	31.9	-		-	-		-
Amphibole	x	-	x		6.5	8.0		-
Hornblende	-	-	-		-	-		-
Actinolite	-	5.0	-		-	-		83.0
Granophyre	-	x	1.2		61.0	26.3		x
Quartz	x	x	-		-	-		x
Biotite	x	3.7	x		x	-		1.0
Chlorite	-	-	-		x	2.1		-
Muscovite	-	-	-		-	-		-
Talc	-	-	-		-	-		-
Epidote	-	-	-		x	-		x
Carbonate	-	x	-		-	x		-
Sphene	-	x	-		-	x		-
Apatite	-	x	-		x	x		-
Iron-titanium	x	1.2	x		0.1	x		1.0
Oxides	-	-	-		-	-		-
Sulphides	-	x	-		-	-		-
Plagioclase Composition	An75+3	An68+3	An65+5		An30+5	An35+5		Albite

	Norms							
Apatite	0.07	0.17	0.09	0.82	0.21	0.26	0.29	0.07
Pyrrhotite	0.00	0.22	0.03	0.03	0.03	0.03	0.14	0.00
Ilmenite	0.65	0.58	1.35	2.43	1.93	1.19	1.45	0.62
Orthoclase	1.43	2.89	2.94	7.03	2.67	2.15	8.84	1.21
Albite	6.06	16.87	14.67	27.61	59.59	62.04	53.02	4.57
Anorthite	16.00	38.02	28.92	16.47	6.53	4.55	4.56	22.43
Corundum	0.00	0.00	0.00	0.00	0.00	0.00	3.10	0.00
Acmite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnetite	6.41	3.23	1.51	9.32	0.57	0.73	0.48	6.87
Hematite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wollastonite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enstatite	3.12	15.29	9.78	6.00	1.45	1.57	3.85	4.03
Ferrosilite	1.22	8.08	10.89	2.25	0.64	0.36	0.79	1.35
Quartz	3.70	0.65	8.19	23.34	23.97	25.02	23.49	2.45
Diopside	45.77	9.59	11.03	3.55	1.74	2.31	0.00	43.64
Forsterite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hedenbergite	15.56	4.42	10.66	1.16	0.68	0.48	0.00	12.77
Colour Index	72.74	41.19	45.17	24.70	7.00	5.96	6.57	69.28
Normative Plagioclase Composition	71.33	67.99	65.02	35.99	9.36	6.46	7.50	82.24
Differentiation Index	11.19	20.40	25.79	57.98	86.23	89.21	85.34	8.22

(Volume Percent)

9	10	11	12	13	14	15	16	17	18
49.2	38.8	22.1	27.0		48.8			53.8	29.8
-	-	-	-		21.3			-	-
-	-	-	-		-			7.9	-
-	-	-	-		-			29.7	-
-	-	-	-		27.7			x	56.9
x	x	69.2	58.0		-			-	-
44.9	54.8	-	-		-			-	-
3.8	2.0	-	11.0		-			3.6	7.2
		x			1.1				
0.5	x	0.9	2.0		1.0			3.8	1.5
-	x	3.0						-	-
-	-	2.8	x		-			-	-
x	-	-	-		-			-	-
x	x	0.2	-		x			-	-
-	x	-	-		-			-	-
x	-	x	x		-			x	4.6
x	-	-	x		-			x	
1.6	0.8	1.8	1.0		x			1.2	
-	-	-	-		-			-	-
x	-	x	x		x			-	-
An70+5 partly to albite	Albite	An5	An35		An60			An60+5	An42+5

(Weight Percent)

0.17	0.12	0.09	0.21	0.17	0.12	0.10	0.07	0.02	0.05
0.25	0.08	0.08	0.22	0.11	0.14	0.25	0.23	0.06	0.17
0.55	1.36	1.11	1.89	1.15	0.88	1.23	0.38	1.21	2.07
3.65	2.81	3.22	5.28	4.99	4.86	4.24	3.39	3.59	5.44
18.09	12.81	18.40	17.94	21.51	10.26	18.88	14.54	12.99	18.65
39.15	23.21	28.74	29.65	27.10	32.50	26.97	32.09	29.09	27.11
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.91	2.49	1.78	8.93	8.97	4.83	2.84	2.30	1.11	5.60
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.27	13.28	9.05	8.04	15.63	17.12	10.89	17.09	13.39	7.43
7.14	9.12	6.84	5.11	1.31	4.26	8.23	10.81	8.92	8.23
0.00	7.69	6.58	11.55	1.53	3.68	3.34	3.57	5.94	8.73
5.49	16.91	14.55	7.19	16.33	17.55	13.90	10.02	14.98	8.41
5.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.03	10.12	9.58	3.98	1.19	3.80	9.15	5.53	8.70	8.12
38.69	53.28	42.90	35.14	44.58	48.43	46.22	46.12	48.30	39.90
67.11	63.06	59.55	60.90	54.29	74.91	57.38	67.53	67.80	57.80
21.74	23.31	29.06	34.77	28.04	18.80	27.59	21.49	-	-

Table 11 continued next page

Sudbury-Manitoulin Area

Table 11 – continued

Notes

1. Feldspathic pyroxenite, Drury Township.
2. Two-pyroxene gabbro, Mongowin Township.
3. Two-pyroxene gabbro, McGregor Bay area.
4. Granophyric gabbro, McGregor Bay.
5. Granophyre, McGregor Bay area.
6. Granophyre, McGregor Bay area.
7. Granophyre, McGregor Bay area.
8. Actinolite amphibolite, Drury Township. Metamorphic equivalent of feldspathic pyroxenite, analysis 1.
9. Metagabbro, Mongowin Township. Metamorphic equivalent of two-pyroxene gabbro, analysis 2.
10. Metagabbro, McGregor Bay area. Metamorphic equivalent of two-pyroxene gabbro, analysis 3.

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11. Metagabbro, McGregor Bay area. Metamorphosed under greenschist facies conditions.
 12. Metagabbro, McGregor Bay area. Metamorphosed under lower almandine amphibolite facies conditions.
 13. Metagabbro, McGregor Bay area.
 14. Metagabbro, McGregor Bay area.
 15. Metagabbro, McGregor Bay area.
 16. Metagabbro, Mongowin Township.
 17. Pyroxene gabbro, Shakespeare Township.
 18. Hornblende metagabbro, Shakespeare Township.

Abbreviations

- N.D. Not determined
- Not detected
x Trace amounts

regional metamorphism. The contacts between altered and unaltered gabbroic rocks are commonly sharp, microscopically as well as in outcrop, but areas of dominantly unaltered gabbro are crisscrossed by alteration veinlets. The metamorphosed gabbroic rocks consist mainly of amphiboles and sodic plagioclase, with variable amounts of quartz, biotite, chlorite, talc, epidote, sphene, muscovite, carbonate, garnet, oxides, and sulphide minerals (Table 11).

The ilmenite-magnetite intergrowths of the original pyroxene gabbros are replaced by magnetite-leucoxene aggregates in the altered rocks. This change in the oxide mineral assemblage can be correlated in a general way with variations in magnetic response; fresh gabbro intrusions are magnetically unresponsive or produce weak negative anomalies in contrast to metagabbros which generally give weak positive anomalies.

Nipissing Diabase gabbroic rocks which have been metamorphosed under low to intermediate greenschist facies conditions, consist of albitic plagioclase and actinolite, or actinolite and blue-green hornblende. Gabbro, metamorphosed under upper greenschist to lower amphibolite facies, consists essentially of intermediate plagioclase (oligoclase-andesine) and blue-green hornblende (Card 1964).

Petrology

The Nipissing Diabase Intrusions are similar in chemistry and mineralogy to many other suites of magmatic mafic intrusions which occur throughout the world and the geological column (Hess 1960). Their initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.706 (Fairbairn *et al.* 1969) is consistent with derivation from an upper heterogeneous part of the mantle or from the lower crust. The norite of the Sudbury Nickel Irruptive, which is similar to the Nipissing Diabase in chemistry and petrology, though not age, also has a $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.706, (Gibbins *et al.* 1972) indicating a similar source for these intrusions. Deep penetrating faults probably formed channelways for periodic upward movement of magma.

The Nipissing Diabase has a tholeiitic composition, containing normative, and commonly modal quartz. The chemical-mineralogical variations noted in these bodies can probably be accounted for by magmatic differentiation, mainly gravity settling of early formed pyroxenes and plagioclase. Increase in total pyroxene content is mainly due to increase in the amount of orthopyroxene present, and the enstatite content of the orthopyroxene increases with total pyroxene content. This fact, and their textural characteristics, indicate that the pyroxene-rich rocks were formed by gravity settling of early formed orthopyroxene. Similarly, the anorthite content of plagioclase is highest in the more mafic rocks, and these calcic plagioclases display oscillatory zoning, which is probably attributable to growth in a convecting magma. Gravity settling of early formed pyroxene and plagioclase led to depletion of the residual magma in MgO and CaO and to its enrichment of iron, Na_2O , and K_2O and concentrations of various trace elements also vary systematically from one rock type to another. Chemical variation diagrams (Figure 27) show that differentiation was essentially continuous and resulted finally in production of small amounts of residual magma rich in alkalis, silica, and volatiles which formed the granophyre.

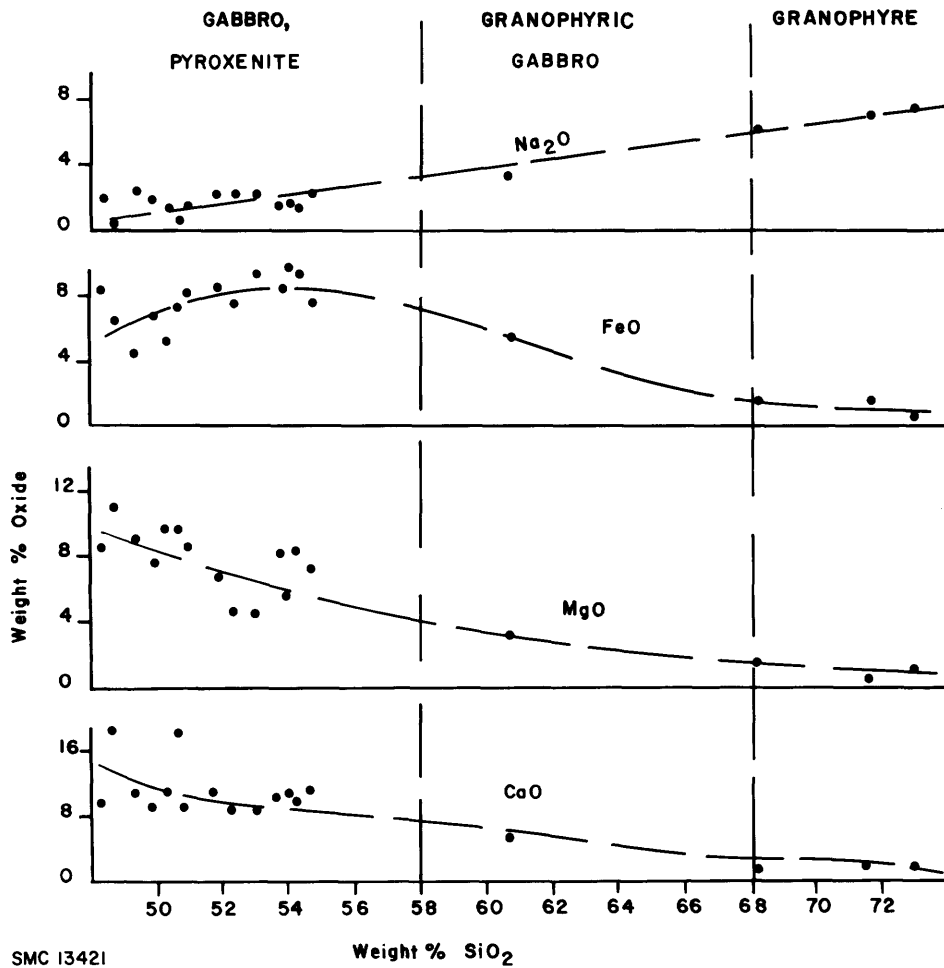


Figure 27a—Major oxides versus silica variation diagrams for Nipissing Diabase Intrusions, Sudbury-Manitoulin Area.

Sudbury-Manitoulin Area

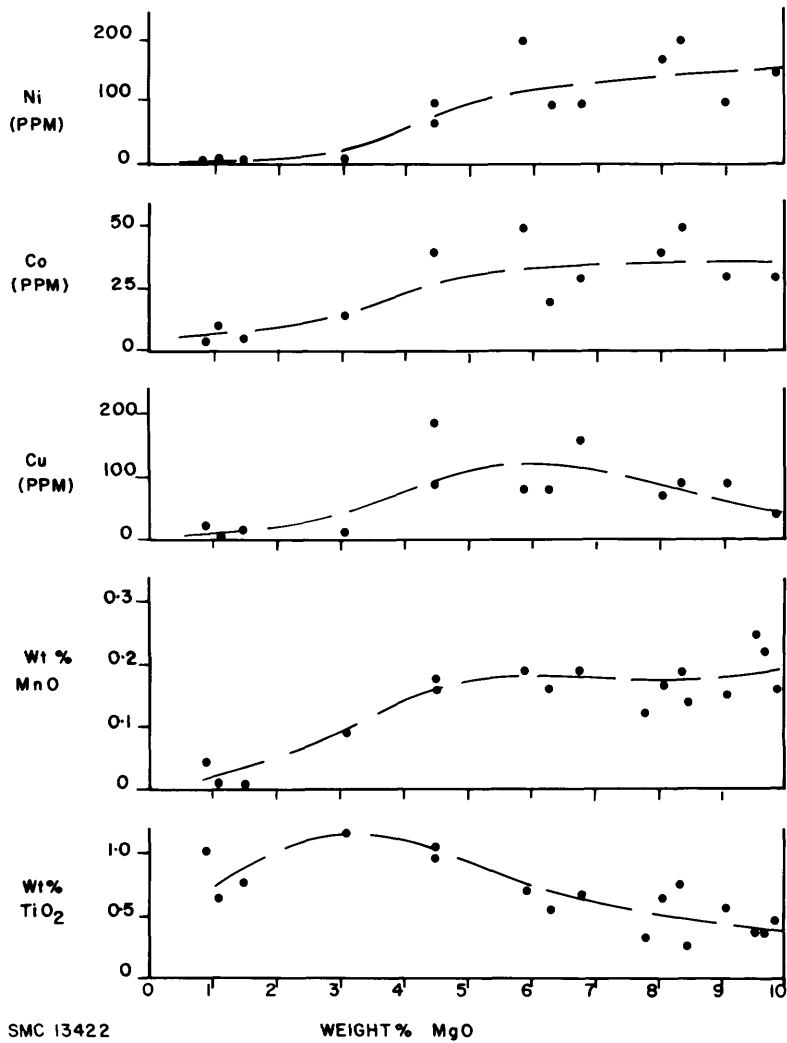


Figure 27b—Minor elements versus MgO variation diagrams for Nipissing Diabase Intrusions, Sudbury-Manitoulin Area.

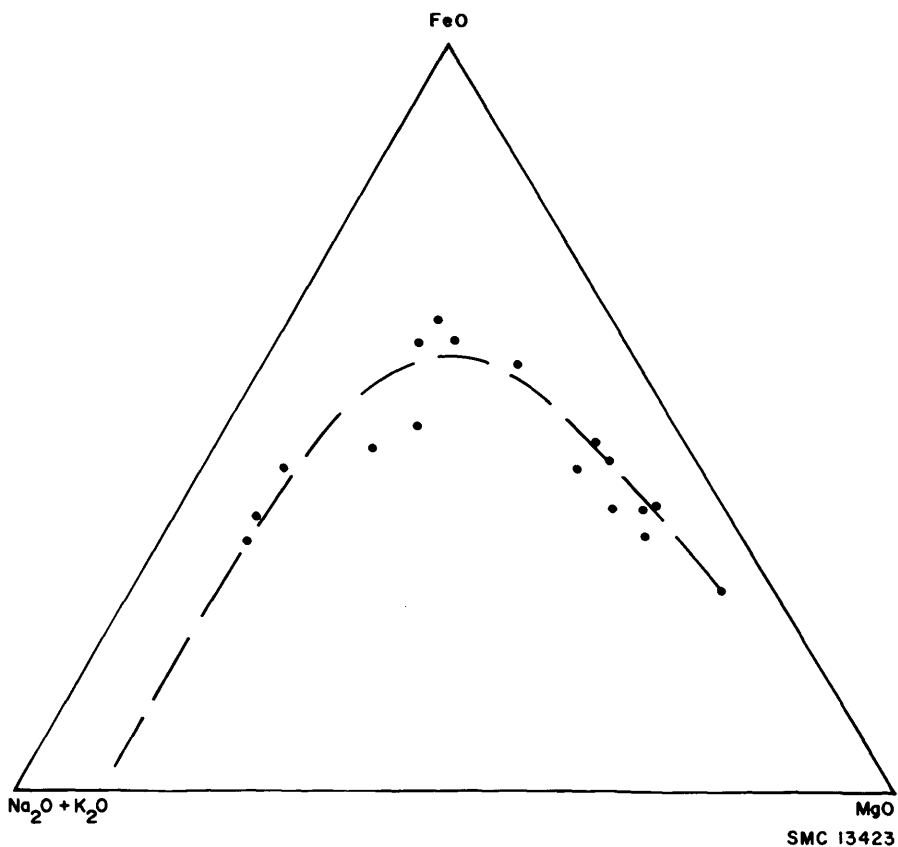


Figure 27c—AFM diagram for Nipissing Diabase Intrusions, Sudbury-Manitoulin Area.

Chemical analyses and standard cell calculations according to the method of Barth (1952) of gabbro-metagabbro pairs taken a few inches from each other in outcrop indicate that metamorphic alteration involved essentially no change in bulk composition other than addition of water, and, possibly sulphur (Table 15). Increase in these components upon alteration is consistent with the mineralogical changes from anhydrous minerals like pyroxene and plagioclase to hydrous minerals like amphibole, mica, chlorite, and with the increase in the number of sulphide mineral occurrences in metagabbro.

Numerous occurrences of copper- and nickel-bearing sulphides are associated with the largely metamorphosed Nipissing Diabase Intrusions of the map-area. In contrast, the Nipissing Diabase Intrusions in the Cobalt-Gowganda area are associated with native silver and cobalt-nickel arsenide and sulpharsenide deposits. Much of the copper-nickel sulphide mineralization in the Sudbury area intrusions may have been formed by metamorphic sulphurization reactions (Card and Pattison 1973). These deposits, and the regional metallogenic variations, will be dealt with more fully under "Economic Geology".

Whitewater Group

The Whitewater Group, comprising in ascending order the Onaping, Onwatin, and Chelmsford Formations, is confined to the Sudbury Basin, a northeast-southwest trending elliptical area about 30 miles (48 km) long and up to 10 miles (16 km) wide enclosed by the Sudbury Nickel Irruptive. Only the lower part of the Onaping Formation is exposed within the Sudbury-Manitoulin area. The Whitewater strata are little metamorphosed and mildly deformed for the most part, and are intruded by the Sudbury Nickel Irruptive and by late northwest-trending diabase dikes. Radiometric age determinations indicate that the Whitewater rocks are at least 1,800 m.y. old and probably only slightly older than the Sudbury Nickel Irruptive (Fairbairn *et al.* 1969).

The Chelmsford Formation, the uppermost formation, comprises about 2,800 feet (850 m) of greywacke with the thick, differentiated bedding, ripple-drift crossbeds, flute casts, and convolute laminations typical of proximal turbidites. Petrographic and paleocurrent studies indicate that the Chelmsford sediments were derived from a granitoid terrane and were transported by turbidity currents flowing mainly southwest parallel to the present major axis of the Sudbury Basin (Cantin and Walker 1972; Rousell 1972).

The Onwatin Formation comprises about 1,000 feet (300 m) of carbonaceous and pyritic siltstone with an excellent slaty cleavage. The contact with the underlying Onaping Formation is conformable and gradational through a thin sequence of carbonate-rich rocks, which immediately north of the map-area at the Errington and Vermilion Mines contain an appreciable amount of copper, lead, and zinc sulphide mineralization of possible exhalative origin.

Onaping Formation

The lowermost unit, the Onaping Formation, has been described by numerous workers, including Williams (1956), Peredery (1972), and Stevenson (1961; 1972) as a massive sequence some 6,000 feet (1800 m) thick consisting of rhyodacitic tuff or breccia composed of brecciated, partly melted granitic and metasedimentary rock fragments set in a finer grained, commonly carbonaceous matrix of devitrified glass shards and mineral fragments. Minor andesitic to rhyolitic flows or dikes, and a discontinuous basal zone up to 300 feet (90 m) thick of very coarse breccia, the "Trout Lake Conglomerate" of Coleman (1905b) are present. Stevenson (1972) excluded the lower coarse breccia unit from the Onaping Formation because he considered it to be composed mainly of quartzite blocks in an igneous matrix. Stevenson (1972) subdivided the remainder of the sequence into a lower unit 500 feet (150 m) of coarse lapilli-tuff with blocks of quartzite and basement granite followed by some 3,000 feet (900 m) of coarse lapilli-tuff; 2,000 feet (600 m) of lapilli-ash tuff, and finally by about 500 feet (150 m) of ash-tuff. Although stratiform units are revealed to some extent by variations in fragment size, density, and type, and by variations in the amount of disseminated carbon, most workers have commented on the lack of bedding in these rocks. Williams (1956) and Stevenson (1972) concluded that the Onaping Formation represents a

thick ash-flow sheet or glowing avalanche deposit erupted and deposited rapidly from marginal fissure vents.

Also present in the Onaping Formation are phenomena indicative of shock metamorphism, including planar features in quartz and feldspar, recrystallization and plastic deformation of feldspar, and partial and complete melting of mineral and rock fragments with formation of heterogeneous glasses (now devitrified). These features, along with breccias and shatter cones in the extra-basin rocks, are believed to be of meteorite impact origin, and according to this model, the Onaping would represent the "fallback breccia" (Dietz 1964; French 1972; Peredery 1972).

Within the Sudbury-Manitoulin map-area, only the lower part of the Onaping Formation is exposed in a limited area in the north. The lower part (approximately 500 feet; 150 m) of the preserved sequence consists of several coarse, stratiform breccia units intercalated with fine- to medium-grained breccia (lapilli-ash tuff). Rock fragments are rounded (now tectonically flattened), range from less than 1 inch to several hundred feet in maximum dimensions, and commonly constitute about 50 percent of the coarse breccia units. Some rock fragments display clastic textures, quartz pebbles, or bedding, demonstrating that they are derived from metasandstones. Others are obviously of felsic plutonic derivation. However, a great number consist of fine-grained intergrowths of quartz and feldspar and resemble rhyolite or welded felsic pyroclastic blocks. The author was unable to find fragments of other rock types.

The matrix is grey and consists of quartz, feldspar, devitrified glass fragments, amphiboles, epidote, sphene, iron oxides, and sulphides. The texture is fragmental, although locally it has an igneous appearance, probably the result of welding or melting. The fine- to medium-grained breccias which form part of the lower unit and also the thick overlying units are essentially similar to the coarse breccia except that most fragments are less than 1 inch (2.5 cm) in maximum dimension. However, larger rock fragments and glass bodies, some of which have bomb-like shapes, are scattered throughout. The upper part of the formation exposed immediately north of the map-area consists of fine- and medium-grained breccia (ash-lapilli-tuff) with abundant carbonaceous matrix material, lensoid and ovoid muddy bodies, and, locally, poorly developed bedding possibly indicative of deposition in water.

The repetition of coarse breccia units in the lower part of the formation suggests that the breccia-forming process was a repetitive one and would consequently fit an explosive volcanic model better than meteorite impact model with production of "fallback breccia" at one instant. Also, if the breccia fragments were derived totally from the fragmentation of pre-existing country rocks in the meteorite "target" area, they should constitute, in a general way at least, a representative sample of those country rocks. The breccia fragments, apparently all of felsic igneous and siliceous sedimentary derivation, are not a representative sample of the country rocks which surround the Sudbury structure. The abundance of metasandstone fragments could be explained by having only the rocks of the Lorrain Formation of the Huronian Supergroup involved, but to do so would necessitate invoking a very special paleogeographic setting for the Sudbury structure.

The presence of shock metamorphic features, both in the Onaping Formation and in the surrounding formations, is strong evidence for passage of hyper-

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velocity shock waves through these rocks, and unless it can be demonstrated that earth-bound processes such as explosive volcanism can produce such phenomena, they must be taken as "prima facie" evidence for impact.

SUDBURY NICKEL IRRUPTIVE

The Sudbury Nickel Irruption is a differentiated, tholeiitic intrusion that forms a northeast-southwest-trending elliptical ring approximately 37 miles (59.2 km) long and 17 miles (27.2 km) wide. In plan view, the ring has an outcrop width of 1 to 3 miles (1.6 to 4.8 km). The Sudbury Nickel Irruption has the form of an asymmetrical lopolith with a steeply dipping south limb and a relatively shallow dipping north limb. The intrusion consists of an upper (inner) part of granitoid rock referred to as "micropegmatite" or "granophyre", and a lower outer gabbroic portion, the "norite". In addition, there is a sulphide ore- and inclusion-bearing unit, the "sublayer" which forms a thin, discontinuous layer about the outer margins of the Irruption and the Copper Cliff and Worthington Offsets which are dike-like offshoots from the main body of the Sudbury Nickel Irruption.

In general, the South Range rocks are more highly altered and deformed than those of the North Range. In the South Range norite, fresh gabbro occurs as isolated remnants within dominantly altered rocks. The granophyre is pervasively altered. Alteration of the South Range rocks is similar to that previously described in the Nipissing Diabase, a metamorphic phenomenon involving addition of water, saussuritization of plagioclase, and uralitization of pyroxenes. The South Range rocks, like the adjacent Whitewater Group and Huronian Supergroup sequences, display the effects of Middle Precambrian deformation and metamorphism in the form of faults, cleavages, lineations, and mineralogical alterations.

Rubidium-strontium isochron age determinations by Fairbairn *et al.* (1965) indicate that the Sudbury Nickel Irruption was emplaced at least 1,730 m.y. ago. This figure probably represents a minimum metamorphic age as recent work by Gibbins *et al.* (1972) suggests that the Sudbury Nickel Irruption has a Rb-Sr isochron age of about 1900 to 2000 m.y. Recent preliminary zircon age determinations by Krogh (Krogh, T.E., personal communication, 1974) indicate that the norite zircons have a U/Pb age of about 1,840 million years.

Petrography and Petrology

The norite and granophyre of the Sudbury Nickel Irruption can be subdivided into a number of grossly conformable, intergradational units on the basis of variations in modal and mineralogical composition. Naldrett *et al.* (1970) have given a detailed description of the textural and mineralogical variations displayed by the Nickel Irruption rocks and the following summary is taken largely from their work.

The norite is a medium- to coarse-grained rock consisting of primary plagi-

clase, hypersthene, augite, titaniferous magnetite, quartz, and micrographic intergrowths of quartz, plagioclase, and potassic feldspar. Hypersthene and plagioclase form subhedral crystals while augite, quartz, and micrographic intergrowths of quartz, plagioclase, and potassic feldspar are anhedral and interstitial. In some units, plagioclase crystals are preferentially oriented to form an igneous lamination. Uralitic amphiboles, both blue-green hornblende and actinolite, replace pyroxenes and are especially prevalent in the South Range rocks. Similarly, primary plagioclase is commonly saussuritized.

The North Range norite consists, in ascending order, of the following: 1,000 to 1,500 feet (300 to 450 m) of "felsic norite", (50 percent plagioclase, 15 percent hypersthene, 7 percent augite, 25 percent quartz and micrographic intergrowth), and 700 feet (200 m) of oxide-rich gabbro (47 percent plagioclase, 22 percent augite, 8 percent oxides, 23 percent micrographic intergrowth, apatite) which grades upward into the granophyre by increasing micrographic intergrowth content. The North Range granophyre is about 4,500 feet (1350 m) thick and consists of the following: about 70 percent micrographic intergrowth; 20 percent plagioclase; and 10 percent augite, biotite, hornblende, and secondary minerals.

The South Range sequence, which differs notably from that of the North Range, consists of a lower unit some 1,500 feet to 2,000 feet (450 m to 600 m) thick of "quartz norite" composed of plagioclase (40 to 50 percent), pyroxenes or amphiboles (10 to 30 percent), biotite (10 to 30 percent), and quartz and micrographic mineral intergrowth (10 to 25 percent). The quartz norite is characterized by abundance of biotite, bluish quartz, and micrographic mineral intergrowth; the amount of micrographic intergrowth increases toward the footwall. The grain size generally decreases in this direction also. The quartz norite is succeeded by a unit approximately 3,000 feet (900 m) thick, the "South Range norite" composed of plagioclase (62 percent), hypersthene or amphiboles (20 percent), augite (4 percent), biotite (5 percent), and quartz (8 percent). At the top of the norite there is a layer 1,000 feet (300 m) thick composed of oxide-rich gabbro similar to that of the North Range which grades upward into the overlying granophyre. In the South Range oxide-rich gabbro, ilmenite, titaniferous magnetite, and apatite are concentrated in the lower half, and the upper half is rich in sphene and micrographic intergrowth. The South Range granophyre is approximately 5,000 feet (1500 m) thick. Two varieties of granophyre are present in that part of the South Range granophyre exposed in the map-area, a light pink phase and a grey phase. Both are foliated, medium-grained rocks composed of plagioclase tablets in an abundant mesostasis of micrographic intergrowth, biotite, amphibole, muscovite, epidote, carbonates, and sulphides. In general, the amount of mafic minerals and plagioclase is higher in the grey granophyre than in the pink.

The Sudbury Nickel Irruptive rocks display cryptic layering, variations in the composition of minerals such as plagioclase and pyroxenes which form solid solution series, and phase layering; for example, the magmatic phase transition from pyroxene to amphibole. In the North Range rocks, the composition of the plagioclase varies from about An_{65} at the base of the norite to about An_{50} in the lower part of the oxide-rich gabbro, then changes abruptly to about An_5 in the upper part of the gabbro, and remains relatively constant at about An_4 or less throughout the granophyre. Similarly, hypersthene shows a steadily increasing iron (ferrosilite) content upward. In hypersthene, the Fe/Fe + Mg atomic ratio

increases from about 0.33 near the base to about 0.40 near the top of the felsic norite, above which it is rare or absent, its place being taken by augite or amphibole. The Fe/Fe + Mg ratio of the augite varies from about 0.24 at the base to about 0.38 in the oxide-rich gabbro. The Fe/Fe + Mg ratio of granophyre augite is approximately 0.50, but very iron-rich (ratios up to 0.75) augites are also present.

In the South Range rocks, the plagioclase composition remains relatively constant at about An₆₂₋₆₅ in the quartz norite, decreases upward from about An₆₀ to An₄₀₋₅₀ in the South Range norite and oxide-rich gabbro, then decreases abruptly to An_{0.5} in the granophyre. In the lower quartz norite unit, the iron content of augite and orthopyroxene increases toward the footwall. The hypersthene Fe/Fe + Mg ratio varies from 0.40 at the base to about 0.30 in the upper part of the quartz norite, then remains relatively constant in the range 0.30 to 0.35 throughout the South Range norite. Augite Fe/Fe + Mg ratio variations parallel these and are in the range 0.24 to 0.32.

The sublayer, which occupies embayments or depressions along the footwall contact of the Sudbury Nickel Irruptive and also forms the offset dikes, consists of rock fragments in a matrix of silicate rock of gabbro-diorite composition, and are sulphides, mainly pyrrhotite, pentlandite, and chalcopyrite. The proportion of rock fragments varies greatly from place to place, and every gradation is present in the matrix from a nearly pure silicate with minor disseminated sulphides, to almost pure sulphide with scattered mineral and rock fragments. The rock fragments are commonly rounded, range in maximum dimension from less than 1 inch (2.5 cm) to about 100 feet (30 m) and average 1 to 2 feet (0.3 to 0.6 m). These include local country rock types and also exotic blocks of peridotite, pyroxenite, gabbro, and amphibolite. Rock fragments generally contain little or no sulphide mineralization, but are commonly rimmed by chalcopyrite. The silicate matrix is a dark grey, fine- to medium-grained rock composed of zoned, altered plagioclase, hornblende, actinolite, biotite, quartz, epidote, chlorite, and carbonate.

The Worthington and Copper Cliff offset dikes extend outward from footwall embayments of the Sudbury Nickel Irruptive and transect structural-stratigraphic trends in the Huronian and Nipissing Diabase country rocks. The offsets appear to be somewhat discontinuous at the present exposure level, are cut by the olivine diabase dikes, and are displaced by the Creighton and Murray Faults. These offsets are long, about 7 miles (11 km) and 5 miles (8 km) respectively, and narrow, being approximately 100 feet (30 m) wide throughout most of their lengths.

The age relationships between the sublayer and the remainder of the Sudbury Nickel Irruptive are not clear-cut. Within the offsets, there is field evidence locally for multiple intrusions of silicate magma. Probably the sublayer is approximately the same age as the main body of the Sudbury Nickel Irruptive, and was emplaced in a pulsating manner.

Chemical data on rocks of the Sudbury Nickel Irruptive are given by Collins (1934), Coleman *et al.* (1929), Knight (1923) and others, and variations in bulk chemistry generally correspond to the modal-mineralogical variations described previously. Hamilton (1960) and Fairbairn *et al.* (1968) cited similarities in bulk chemical composition as evidence for comagmatism of the norite, granophyre, and Onaping tuff. The Onaping Formation is approximately intermediate in

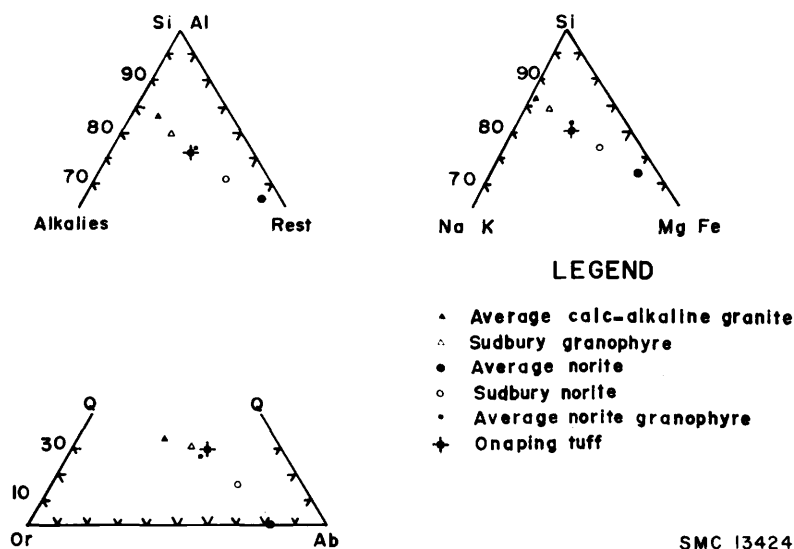


Figure 28—Triangular diagrams showing chemical characteristics of norite, granophyre, and Onaping "tuff" relative to average norite and granite (after Fairbairn *et al.* 1968).

bulk chemical composition between the norite and the granophyre, and is almost identical to an average combined norite-granophyre composition (Figure 28). These authors suggest that the Onaping Formation represents the extrusive phase, and norite and granophyre the intrusive phases of a major magmatic cycle. The chemical and petrographic data also demonstrate that the norite of the Sudbury Nickel Irruption is very siliceous in comparison to equivalent rocks from other intrusions, and that the proportion of granophyre is far too high to be explained as the differentiation product of a normal mafic magma.

Origin

Various models for the Sudbury Nickel Irruption have been proposed, including the following: a folded, differentiated sill (Coleman 1905a; Collins 1934), a multiple, ring-dike intrusion (Knight 1917; Thomson 1956), and a funnel-shaped asymmetric lopolith (Wilson 1956; Popelar 1972). The lopolithic model would appear to best fit the known geological and geophysical data. However, the Sudbury Nickel Irruption has been deformed, and until the nature and extent of deformation are determined, the original shape of the intrusion cannot be deduced. Although the South Range has probably been uplifted and rotated (Souch *et al.* 1969; Sopher 1963) with respect to the North Range, the exact amount and nature of this movement has not been documented. Naldrett *et al.*

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(1970) pointed out that much of the iron-titanium oxide of the North Range rocks is partly oxidized, and consequently the paleomagnetism of these rocks may be largely chemo-remnant rather than thermo-remnant. The author's observations indicate that some of the magnetite of the South Range rocks was formed by metamorphic alteration reactions, and consequently the present magnetism of these rocks probably dates from this alteration rather than from their original cooling. Paleomagnetic data will only be useful in reconstructing the original shape of the Sudbury Nickel Irruptive when such studies are carried out in conjunction with detailed mineralogical and petrographic investigations.

Souch *et al.* (1969) suggested that the ultramafic rock inclusions in the sub-layer represent cognate xenoliths derived from an ultramafic layered sequence beneath the Sudbury Nickel Irruptive. The existence of an extensive body of ultramafic rocks beneath the Sudbury Nickel Irruptive would fit a funnel-shaped lopolith model and could explain the apparent anomalously high proportion of granophyre relative to mafic rocks. However, the gravity data do not support the existence of any large mass of high density, ultramafic rock immediately beneath the structure. Also as Naldrett *et al.* (1970) pointed out, the composition of the Sudbury Nickel Irruptive magma was probably such that it could not crystallize olivine. The ultramafic xenoliths were probably derived from a remote source, such as the upper mantle.

The textural and mineralogical data of Naldrett *et al.* (1970) clearly indicate that *in situ* gravitational crystal settling played an important role in the crystallization and differentiation of the Sudbury Nickel Irruptive. Naldrett *et al.* (1970) also concluded the following: that the contact between the norite and granophyre is gradational; that continuous fractional crystallization apparently operated across this boundary; and that the entire Sudbury Nickel Irruptive is anomalously rich in silica. Naldrett *et al.* (1970) postulated that there was appreciable assimilation of siliceous country rocks by the Sudbury Nickel Irruptive magma with lateral migration and concentration of granophyric liquids produced by assimilation and fractional crystallization. Stevenson and Colgrove (1968) proposed that much of the granophyre was formed by assimilation of the lower part of the Onaping Formation by the Sudbury Nickel Irruptive magma.

It is difficult to assess the importance of assimilation in the genesis of the Sudbury Nickel Irruptive. Country rock inclusions, including siliceous varieties, are common in the norite, and some display evidence of minor assimilation. Rock fragments are rare in the upper part of the granophyre near the contact with the Onaping Formation. The granophyre near this contact is commonly richer in plagioclase and poorer in micrographic intergrowth than the rocks in the lower part of this unit. The metamorphic aureoles about the lower and upper contacts of the Sudbury Nickel Irruptive are narrow suggesting that the Sudbury Nickel Irruptive magma contained little super-heat to effect assimilation. The foregoing features suggest that at the present exposure level assimilation of siliceous country rocks was negligible. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of the norite (0.706) and granophyre (0.708) indicate derivation of the Nickel Irruptive magma from a mantle-lower crust source similar in composition to the source of the Nipissing Diabase magma (Gibbins, W.A., personal communication, 1973).

MIDDLE TO LATE PRECAMBRIAN

GRENVILLE FRONT AND EDEN LAKE PLUTONS

Middle Precambrian felsic plutons occur along the Grenville Front Tectonic Zone in the eastern part of the map-area where the plutons intrude Huronian metasediments and Nipissing Diabase of the Southern Province on the northwest, and metasedimentary gneisses of the Grenville Province on the southeast. The plutons post-date the main deformational and metamorphic events of the Southern Province, are transected by the Grenville Front Tectonic Zone as defined by Lumbers (1975), and display the effects of Late Precambrian deformation and metamorphism which are concentrated mainly within the Grenville Province. The main batholithic complex extends along the Grenville Front Tectonic Zone from Killarney in the south to the Sudbury area in the northeast, a distance of some 65 miles (85 km), and it is up to 5 miles (8 km) wide. In addition, numerous isolated intrusions of similar age and composition are in the Sudbury-Manitoulin area of the Southern Province, and within the northwestern part of the Grenville Province.

Various parts of the Grenville Front Tectonic Zone plutonic complex have been termed "Killarney granite", "Chief Lake batholith", "Bell Lake granite", and "Eden Lake Intrusions". The rocks comprising these intrusions range in composition from granite to gabbro, but most consist largely of quartz monzonite. Radiometric age dating by Rb-Sr isochron and U-Pb zircon methods indicate that there were probably two ages of granite emplacement, one about 1,730 m.y., and the other about 1,590 m.y. (Krogh *et al.* 1971). Near and within the Grenville Front Tectonic Zone and Grenville Province, these rocks commonly yield younger, diverse rock and mineral ages, a reflection of post-intrusion orogenesis concentrated in these areas.

Geological Relationships

The plutons are localized along the Grenville Front Tectonic Zone, and are transected by the Grenville Front Boundary Fault which marks the northward limit of Late Precambrian penetrative deformation and high-rank metamorphism within the Grenville Province and Grenville Front Tectonic Zone (Lumbers 1975). Geological evidence was presented earlier in this report to show that the Grenville Front Tectonic Zone may have originated in the early Middle Precambrian as a paleogeographic hinge zone marking a transition in the supracrustal sequence from a shelf or miogeosynclinal-type facies to the northwest to a more eugeosynclinal-type facies to the southeast. There is radiometric age evidence to show that the Grenville Front Tectonic Zone became an active tectonic feature some 1,700 to 1,800 m.y. ago, and emplacement of the Grenville Front Plutons is probably a manifestation of early tectonic activity along this structure (Krogh and Davis 1969; Lumbers 1975).

Within the Grenville Province, the effects of Late Precambrian deformation and metamorphism on the felsic plutonic rocks include cataclasis, mylonitization, mineralogical alteration, formation of augen structure, lineation, and gneis-

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sic foliation, and migmatization. Contact relationships with the paragneisses are generally obscured by deformation and recrystallization.

Within the Southern Province, the felsic rocks have suffered only low rank, retrogressive metamorphism, and minor cataclasis and mylonitization related to deformation along the Grenville Front Tectonic Zone. Relatively strong cataclasis is confined to narrow zones in the northwestern parts of these bodies, but increases markedly toward the southwest where the rocks display northeast-trending cataclastic foliations and southeast-plunging lineations, structures characteristic of the Grenville Front Tectonic Zone. The contacts between felsic plutons and Huronian metasediments and Nipissing Diabase are commonly abrupt and discordant. Agmatitic border zones consisting of sharp-bordered country rock inclusions in a granitic matrix are present, as are country-rock xenoliths or roof pendants within the batholithic complex. Some xenoliths are rotated and disoriented, but others define pre-existing fold structures in the country rocks which were passively invaded and preserved within the intrusions (Spaven 1967). Dikes and apophyses of granitic rock extend outward into the country rocks where they sharply transect pre-existing structural-stratigraphic trends. Some xenoliths show the effects of metamorphism and metasomatism in the form of feldspar porphyroblasts. Along the northwestern contact of the Chief Lake Pluton in Eden Township, there are marginal zones of injection migmatite consisting of numerous granitic dikes and sills injected into the Huronian metasediments that show evidence of incipient migmatization. The pelitic rocks here, are coarsely recrystallized, and contain quartzofeldspathic segregations generally parallel to the original bedding. Metasandstone from the Lorrain Formation shows alternating light coloured, quartzofeldspathic and dark coloured, biotitic layers also parallel to original bedding. Andalusite- and cordierite-bearing spotted hornfels are present in the aureole.

The emplacement of satellitic plutons within the Southern Province proper may have been controlled in part by pre-existing structures. For example, the Eden Lake Intrusions in the Lake Panache area occupy the axial zone of a complex domal fold structure in the Huronian rocks. Other satellitic intrusions may be related to faults.

Petrography

The Chief Lake Pluton consists of foliated and massive, porphyritic and equigranular quartz monzonite, quartz diorite, and granodiorite with minor amounts of trondhjemite, tonalite, pegmatite, aplite, granite, and agmatitic and migmatitic border zones with mafic segregations or schlieren developed about country rock xenoliths and contacts. Although various rock types intrude one another, no clear-cut order of intrusion is evident. The rocks consist of quartz, plagioclase, and microcline, with variable but generally minor amounts of primary hornblende, biotite, apatite, zircon, and iron-titanium oxides, and of secondary chlorite, muscovite, epidote, and carbonate. Perthitic microcline commonly forms large phenocrysts, and also occurs as myrmekitic intergrowths with quartz and plagioclase in the medium-grained groundmass. The plagioclase,

which is commonly zoned and saussuritized, varies in composition from albite to andesine. Henderson (1967) found that the composition of the plagioclase in these rocks is relatively restricted, with over 50 percent falling in the range An_{16} to An_{23} . Chemical analyses, modal analyses, and norms of typical specimens are given in Table 12. Figure 29 shows that these rocks have a relatively restricted compositional range with respect to quartz, potassic feldspar, and plagioclase that is comparable to minimum melting compositions of experimental granitic systems (Tuttle and Bowen 1958).

The Killarney Pluton consists mainly of massive to foliated, equigranular and porphyritic, medium-grained quartz monzonite and granite. A few small pegmatitic, aplitic, and porphyritic felsic dikes are present, as are gneissic and agmatitic rocks. The granite and quartz monzonite consist of sodic plagioclase ($An_{10 \pm 5}$), perthitic potassic feldspar, and quartz, with minor biotite, chlorite, muscovite, sphene, iron-titanium oxides, pyrite, apatite, and zircon (Table 12). These rocks, like the Chief Lake rocks, display a relatively restricted compositional range (Figure 29).

The Eden Lake Intrusions, which comprise a number of mafic and felsic plutons, sills, and dikes immediately east of the Chief Lake Pluton, are more variable in composition than the Chief Lake and Killarney Plutons. The Eden Lake Intrusions consist mainly of trondhjemite, but also comprise gabbro, diorite, granodiorite, quartz monzonite, and syenite. The ratio of felsic to mafic phases is about 6 to 1, and mafic rocks are dominant only in the northern part of the intrusive complex. The various rock types are characteristically interlayered and intergradational; sharp contacts between various intrusive phases are rare. Layering, apparently of magmatic origin, is locally present.

Hornblende gabbro and diorite is a medium-grained, equigranular rock composed of zoned plagioclase (andesine-labradorite), green hornblende, and biotite, and minor amounts of quartz, apatite, and iron-titanium oxides (Table 12). Minor garnet is present locally, as are secondary micas, chlorite, and epidote. Trondhjemite, granodiorite, quartz monzonite, and syenite are medium- to coarse-grained, equigranular or porphyritic rocks composed of zoned plagioclase (oligoclase-andesine), biotite, quartz, and iron oxide. Potassic feldspar is absent or present only in minor amounts in the trondhjemite, and forms perthitic microcline phenocrysts in the other felsic rock types where it is present in amounts of about 10 percent to 50 percent. Minor amounts of amphibole, garnet, white micas, epidote, and chlorite, are also present. Although no reliable radiometric age data are available for the Eden Lake Intrusions, their geological relationships and location indicate that they are probably about the same age as the Killarney and Chief Lake Plutons. The preponderance of trondhjemite over gabbro-diorite in the intrusions suggests that the original magma was probably dioritic in composition, and the paucity of potassic feldspar could indicate that the magma had a high water content. According to Barth (1952, p.222), a high water content promotes early crystallization of biotite and results in so much potassium being extracted from the melt that none is left for formation of potassic feldspar in the later stages of crystallization.

Sudbury-Manitoulin Area

TABLE 12 | CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF LATE CAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Sample Number	Major Components				
	1	2	3	4	5
SiO ₂	58.80	71.20	71.80	68.30	71.36
Al ₂ O ₃	17.50	14.80	15.50	17.00	14.88
Fe ₂ O ₃	2.05	0.94	0.85	1.70	0.90
FeO	5.30	1.52	1.32	0.78	1.22
MgO	3.30	0.50	0.87	0.26	0.56
CaO	6.30	1.78	1.40	0.78	1.77
Na ₂ O	3.30	4.04	4.00	3.88	3.23
K ₂ O	2.06	3.85	3.71	5.95	3.52
H ₂ O ⁺	1.09	0.43	0.96	0.78	0.18
H ₂ O ⁻	0.06	0.03	0.05	0.03	-
CO ₂	0.25	0.26	0.38	0.35	-
TiO ₂	0.84	0.27	0.20	0.34	0.18
P ₂ O ₅	0.11	0.05	0.01	0.05	0.30
S	0.02	0.01	0.01	0.01	-
MnO	0.13	0.05	0.04	0.03	-
Total	101.11	99.73	101.10	100.24	99.84
Specific Gravity	2.73	2.65	2.66	2.65	N.D.

Trace Elements

Ag	-	-	-
As	-	-	-
Ba	400	1000	1500
Be	3	5	3
Co	9	6	8
Cr	100	50	80
Cu	30	14	14
Ga	15	20	20
Li	-	-	-
Mo	-	-	-
Ni	20	20	10
Pb	10	40	10
Sb	-	-	-
Sc	20	-	-
Sn	-	-	-
Sr	300	200	200
V	100	20	20
Y	20	20	-
Zn	70	60	40
Zr	150	150	100

FELSIC PLUTONIC INTRUSIONS IN THE SUDBURY-MANITOULIN AREA. CHEMI-

in Weight Percent						
6	7	8	9	10	11	12
72.14	72.39	74.83	49.40	54.60	53.40	70.70
13.32	13.78	12.91	22.50	18.60	18.40	14.50
1.91	1.14	0.98	1.70	2.38	0.42	0.84
2.31	1.28	0.55	5.16	6.55	7.75	1.99
0.24	0.78	0.60	5.87	4.07	4.00	0.49
1.11	0.74	0.32	10.60	7.90	7.06	2.54
3.41	3.74	3.37	1.96	2.94	2.22	4.04
4.41	5.10	5.65	0.89	1.51	1.57	1.86
0.32	0.46	0.44	2.00	1.21	2.22	0.57
0.04	-	-	0.08	0.04	0.06	0.11
-	0.16	0.13	0.18	0.19	0.20	0.23
0.35	0.31	0.13	0.24	0.95	1.04	0.12
0.06	0.13	0.06	0.08	0.01	0.21	0.02
-	-	-	0.02	0.01	0.03	0.01
0.11	0.09	0.07	0.14	0.18	0.16	0.06
99.73	100.10	100.04	100.82	101.14	98.74	98.10
N.D.	N.D.	N.D.	2.86	2.86	2.88	2.68

in ppm

-	-	-	-
-	-	-	-
150	400	500	-
-	3	-	-
20	30	20	-
150	150	30	100
20	30	13	9
20	30	20	15
-	-	-	-
-	-	-	-
60	30	7	5
-	10	10	10
-	-	-	-
20	30	20	20
-	-	-	-
700	500	400	10
100	150	100	-
-	30	30	-
60	80	70	40
30	70	60	-

Table 12 continued next page

Sudbury-Manitoulin Area

Table 12 – continued

Sample Number	Norms				
	1	2	3	4	5
Apatite	0.26	0.12	0.02	0.12	
Pyrrhotite	0.06	0.03	0.03	0.03	
Ilmenite	1.60	0.52	0.38	0.65	
Orthoclase	12.22	23.00	22.01	33.51	
Albite	28.00	34.53	33.94	33.12	
Anorthite	26.93	8.95	6.90	3.57	
Corundum	0.00	0.88	2.39	2.90	
Acmite	0.00	0.00	0.00	0.00	
Magnetite	2.98	1.38	1.24	1.57	
Hematite	0.00	0.00	0.00	0.66	
Wollastonite	0.00	0.00	0.00	0.00	
Enstatite	7.43	1.26	2.17	0.65	
Ferrosilite	6.15	1.64	1.43	0.00	
Quartz	11.33	28.08	29.49	21.21	
Diopside	1.76	0.00	0.00	0.00	
Hedenbergite	1.28	0.00	0.00	0.00	
Colour Index	21.20	4.79	5.22	3.54	
Normative Plagioclase	47.55	18.99	16.08	9.23	

	Modal Analyses								
	A Avg.	B Avg.	Range	C Avg.	Range	D Avg.	Range	E Avg.	F Avg.
Plagioclase	46.8	30.7	20-39	45.7	39-60	31.4	20-44	43.0	49.3
Potassic Feldspar	6.9	26.7	22-35	17.0	5-25	26.6	18-35	36.4	
Quartz	22.3	29.0	27-30	26.9	19-35	26.8	19-48	16.5	6.3
Hornblende	2.2			4.0					33.4
Biotite	17.3	9.8	8-11		1-10	10.8	0-15		4.6
Chlorite					0-10		0-2	2.3	x
Muscovite					0-8		0-14		
Epidote	4.3	3.7	0-5	5.9	0-10	3.9		x	x
Zircon								x	x
Apatite								x	
Garnet									
Sphene			1-5	0.5		0.5	0-1	1.8	
Iron-titanium Oxides	0.2	0.1			0-1				6.4
Sulphides									x
Plagioclase Composition	An _{20±5}	N.D.		N.D.		N.D.		An _{10±5}	An _{60±5}

(Weight Percent)

6	7	8	9	10	11	12
			0.19	0.02	0.51	0.05
			0.06	0.03	0.09	0.03
			0.46	1.81	2.05	0.24
			5.34	8.96	9.65	11.32
			16.83	24.95	19.52	35.18
			50.70	33.20	34.96	12.83
			0.00	0.00	0.74	1.31
			0.00	0.00	0.00	0.00
			2.50	3.46	0.63	1.25
			0.00	0.00	0.00	0.00
			0.00	0.00	0.00	0.00
			14.29	8.85	10.35	1.26
			7.68	7.67	12.82	2.92
			0.23	6.07	8.68	33.62
			1.18	2.84	0.00	0.00
			0.55	2.15	0.00	0.00
			26.65	26.78	25.86	5.66
			73.96	55.64	62.81	25.59

(Volume Percent)

G		H		I		J		K	
Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
50.2	44-60	41.9	34-41	30.6	27-38	53.0	37-65	51.0	39-73
x	0-1	12.1	10-15	24.2	6-27	1.1	0-1	0.9	0-3
6.7	5-10	31.5	30-35	29.0	24-40	22.9	16-34	30.4	11-49
30.4	25-35					5.0		x	0-5
3.0	2-9	9.3	1-10	11.2	5-23	12.8	12-22	13.1	6-23
6.0	2-10		0-10						0-2
	1-10		0-5					2.1	0-5
2.0		x		4.5	0-5	5.0	3-5	2.5	0-5
			0-5					x	
		x				x			
		4.5						x	0-2
			0-3					x	0-.05
1.7	1-3	0.7		0.5	0-4		0-2		
x				x		0.2			
An45±5	An35-An50	An35±5		An35±5		An30±5			An27-An43

Table 12 continued next page

Sudbury-Manitoulin Area

Table 12 – continued

Notes

Chief Lake Batholith

1. Porphyritic quartz diorite, Eden Township.
2. Quartz monzonite, Eden Township.
3. Quartz monzonite, Eden Township.

Killarney Batholith

4. Albite quartz monzonite, Killarney Bay.
5. Granite, from Quirke and Collins (1930).
6. Granite, from Quirke and Collins (1930).
7. Average of 7 analyses of massive granitic rocks of the Killarney Batholith, from Jones (1930).
8. Average of 7 analyses of gneissic or cataclastic granitic rocks, from Jones (1930).

Eden Lake Intrusions

9. Altered hornblende gabbro, Eden Township.
 10. Hornblende diorite, Eden Township.
 11. Hornblende diorite, Eden Township.
 12. Biotite trondhjemite, Eden Township.
-

Abbreviations

- N.D. Not determined
- Not detected
x Trace amounts

Chief Lake Batholith

- (A) 2 quartz diorites, Eden Township.
- (B) 3 quartz monzonites, Eden Township.
- (C) 20 quartz diorites and granodiorites (from Henderson 1967).
- (D) 12 quartz monzonites (from Henderson 1967).

Killarney Batholith

- (E) Quartz monzonite, Killarney Bay.

Eden Lake Intrusions

- (F) 2 hornblende gabbros, Eden Township.
 - (G) 4 diorites, Eden Township.
 - (H) 3 granodiorites, Eden Township.
 - (I) 4 quartz monzonites, Eden Township.
 - (J) 3 trondhjemites, Eden Township.
 - (K) 11 trondhjemites (from Henderson 1967).
-

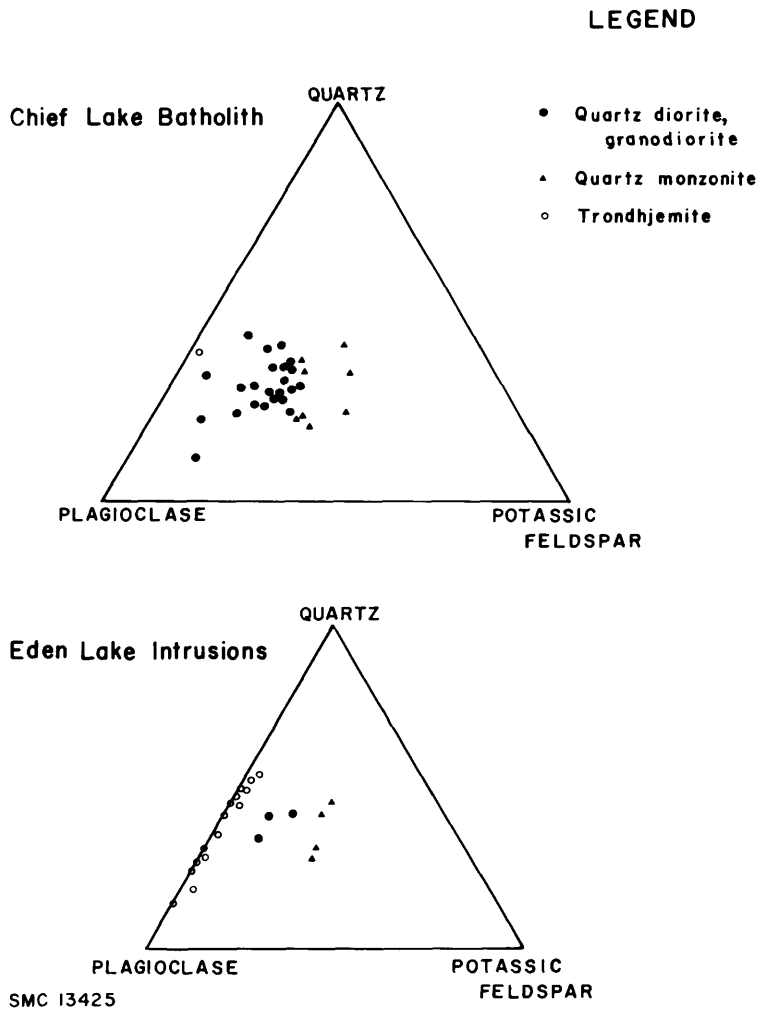


Figure 29—Ternary diagrams showing quartz-potassic feldspar-plagioclase compositions of Late Felsic Intrusions; Sudbury-Manitoulin Area.

Origin

Emplacement of the post-Huronian felsic plutons was controlled by the Grenville Front Tectonic Zone, a zone of major dislocation, and the plutons are probably manifestations of early tectonic activity along this structure. The intrusions are post-orogenic with respect to the major events in the Southern Province, and syn- and pre-orogenic with respect to events along the Grenville Front Tectonic Zone and within the adjacent Grenville Province.

The Grenville Front Tectonic Zone granitic rocks were regarded as the products of extensive alkali metasomatism of Huronian metasediments and Nipissing Diabase by Phemister (1960) and Grant *et al.* (1962). However, work by Lumbers (1968; 1975), Henderson (1967), and Card *et al.* (1972) indicate that these rocks are of magmatic intrusive origin, although feldspathization of metasediments and metagabbro has locally occurred as a result of contact metamorphism and metasomatism by the granitic magma. Evidence for a magmatic intrusive origin includes the following:

- (1) Sharp, discordant contacts.
- (2) Rotation of metasedimentary xenoliths and sharply defined contacts of xenoliths with the granitic rocks.
- (3) Dikes and apophyses from the granitic rock masses which transect stratigraphic-structural trends in the country rocks.
- (4) The presence of marginal intrusion breccia or agmatite bodies.
- (5) The presence of contact metamorphic aureoles with the development of spotted hornfels.
- (6) The presence of primary igneous zoning in plagioclase and zircon.
- (7) The restricted compositional range of plagioclase and of the granitic rock themselves, features which would not be expected if these rocks were formed by metasomatism of such diverse rock types as metasandstone and metagabbro.

The plutons were emplaced mainly by a passive stopping mechanism, probably at relatively high crustal levels. Evidence for this includes:

- (1) The presence of country rock inclusions or roof pendants which define pre-existing fold structures passively invaded and preserved within the intrusive complex.
- (2) The sharp, discordant nature of the contacts and the presence of an agmatitic border zone.
- (3) High-level type contact metamorphic aureoles.
- (4) The porphyritic character of the intrusive rocks.
- (5) The presence of abundant, sharp-bordered country rock xenoliths or roof pendants.
- (6) The presence of myrmekitic or granophyric intergrowths of quartz and feldspars.

With the exception of the Eden Lake bodies, the intrusive rocks have a relatively restricted compositional range corresponding to the minimum melting compositions of experimental granitic systems. Consequently, the granitic magma could have been derived by fusion of crustal rocks or by partial melting of mantle materials. Their generally low initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios (approximately 0.705) and the high degree of fit of Rb-Sr isotopic data to individual isochrons suggests derivation from subcrustal sources with only a short pre-emplacement crustal history.

Sudbury-Manitoulin Area

The variability of the Eden Lake Intrusions may be caused by factors such as crystal settling and high water content of the magma. It is also possible that the Eden Lake Intrusions represent only the upper part of a more extensive intrusive body at depth because they are associated with an irregularity in the local gravity field (Popelar 1971).

LATE PRECAMBRIAN

Mafic Intrusive Rocks

Relatively late mafic intrusions of various ages cut the Huronian rocks and Nipissing Diabase of the Sudbury-Manitoulin map-area. Included in this group of rocks are: the Mongowin Pluton, a small ultramafic intrusion approximately 1,770 m.y. old (Van Schmus 1971), fenite bodies which intrude the Huronian rocks, and amphibolite, metagabbro, trap and lamprophyre dikes, some of which were emplaced before regional metamorphism and are consequently older than about 1,800 m.y., whereas others are younger and have a Rb-Sr radiometric age of 1,415 m.y. (Van Schmus 1971). Also included are northwest-trending diabase dikes which were emplaced some 1,250 to 1,450 m.y. ago (Van Schmus 1965; Gates and Hurley 1973).

These various intrusions, ranging in age from about 1,250 to 1,800 m.y. show that this part of the Canadian Shield had a long history of periodic igneous activity, indicative of continued sporadic tectonic activity and crustal instability. Some of the crustal instability was probably related to orogenic events in the nearby Grenville Province and to the formation of the Lake Superior Structure in the western part of the Southern Province.

MONGOWIN PLUTON

The Mongowin Pluton, described in some detail by Card (1968b), is a small, elliptical (1,450 feet by 2,600 feet; 400 m by 800 m) composite pluton consisting of ultramafic, dioritic, and trondhjemitic rocks which intrude metasediments of the Gowganda Formation in lots 11 and 12, Concession VI, Mongowin Township. The intrusion was emplaced at high (epizonal) crustal levels, is discordant with respect to country rock structural-stratigraphic trends, and there is a narrow contact metamorphic aureole of biotite hornfels developed in the country rocks about the body. According to Rb-Sr isochron age data of Van Schmus (1971), the Mongowin Pluton was emplaced about 1,770 m.y. ago.

Ultramafic rocks with the composition of peridotite form the northern two-thirds of the pluton, and consist of partly serpentinized forsteritic olivine, pyroxenes (pigeonite and augite), and amphiboles (anthophyllite, cummingtonite, and hornblende). The texture is commonly poikilitic with large (1 to 5 cm) platy crystals of amphibole and pyroxene enclosing olivine crystals about 1 mm in diameter. Alteration of the olivine has resulted in formation of fibrous chrysotile, platy antigorite, and magnetite.

Quartz diorite, which forms the central one-third of the body, is a medium-grained (½ to 1 mm), equigranular rock composed essentially of zoned intermedi-

TABLE 13

CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF ROCKS OF THE MONGOWIN PLUTON IN THE SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Major Components in Weight Percent										
Sample No.	1	2	3	4	5	6	7	8	9	10
	CM-65-M2	CM-65-M5	CM-65-M6	BRM-65-8	CM-21	CM-65-M8	CM-65-M17	CM-65-M18	CM-65-M11	CM-65-M12
SiO ₂	38.20	38.73	38.42	41.23	42.44	49.76	50.99	64.50	58.98	70.03
Al ₂ O ₃	4.12	4.46	4.98	4.40	5.45	19.43	17.02	14.70	17.55	14.93
Fe ₂ O ₃	4.86	7.07	6.43	2.95	2.25	2.22	1.50	1.15	4.98	2.75
FeO	6.71	5.77	6.35	7.94	7.65	5.91	9.45	4.26	3.18	0.65
MgO	26.24	21.28	25.91	28.30	26.31	7.54	3.54	1.69	0.52	0.04
CaO	6.80	10.73	6.52	4.80	5.86	8.71	6.30	2.95	2.60	1.94
Na ₂ O	0.32	0.26	0.71	0.31	0.49	1.75	3.68	3.44	4.58	4.50
K ₂ O	0.12	0.07	0.12	0.16	0.18	1.30	0.89	2.46	2.70	2.38
H ₂ O ⁺	9.22	8.86	8.08	7.09	6.14	2.22	2.97	2.15	1.54	0.79
H ₂ O ⁻	0.60	0.74	0.33	0.11	0.09	0.02	0.03	0.05	0.05	0.00
CO ₂	0.52	0.22	0.34	0.20	0.41	0.38	1.57	2.29	2.26	1.50
TiO ₂	0.24	0.23	0.26	0.80	1.15	0.22	1.28	0.46	0.18	0.05
P ₂ O ₅	0.03	0.02	0.03	0.12	0.25	0.02	0.51	0.03	0.11	0.02
S	0.14	0.00	0.10	0.00	0.00	0.06	0.00	0.00	0.43	0.59
MnO	0.14	0.11	0.16	0.10	0.12	0.11	0.13	0.08	0.04	0.03
Cr ₂ O ₃	0.69	0.62	0.64	0.76	9.91		0.01	0.15	0.01	0.01
V ₂ O ₃	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.01
Total	98.24	99.20	99.40	99.29	98.80	99.68	99.89	100.38	99.72	100.22

Modal Analyses (Volume Percent)										
Olivine	59.5	52.1	60.4			-	-			
Serpentine										
Plagioclase	-	-	-			15.2	44.7		45.6	40.3
Pyroxenes	4.7	37.1	27.8							
Amphiboles	20.6					47.4				
Talc	x	x	-							
Chlorite	x	x	x			26.2	22.0		6.4	
Biotite	-	-	-							

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Table 13 continued next page

Table 13 – continued

Modal Analyses (Volume Percent)

Sample Number	1	2	3	4	5	6	7	8	9	10
Quartz	-	-	-			11.2	14.3		22.6	36.7
Muscovite	-	-	-			x	-		21.1	20.0
Apatite	-	-	-			-			x	-
Clinozoisite	-	-	-			x			-	-
Carbonate	-	-	-			x	13.3		-	3.0
Sphene	-	x	-			x			4.3	-
Leucoxene	-	-	-			x			-	-
Iron-titanium Oxide	15.2	10.8	11.8			x			x	x
Sulphides	-	-	-			-	5.7		-	-
Plagioclase Composition	N.D.	N.D.	N.D.			An ₂₈₊₅	An ₃₀₊₅		An ₃₊₃	An ₃₊₃

Norms (Weight Percent)

Sample Number	1	2	3	4	5	6	7	8	9	10
Apatite	0.08	0.05	0.08	0.31	0.63	0.05	1.24	0.07	0.27	0.05
Pyrrhotite	0.44	0.00	0.31	0.00	0.00	0.17	0.00	0.00	1.23	1.66
Ilmenite	0.52	0.49	0.55	1.67	2.37	0.43	2.55	0.91	0.36	1.39
Orthoclase	0.81	0.47	0.79	1.04	1.16	7.93	5.52	15.20	16.70	14.42
Albite	3.08	2.48	6.68	2.88	4.50	15.26	32.67	30.41	40.52	39.00
Anorthite	10.76	12.17	11.17	11.13	13.17	42.60	28.64	15.08	12.74	9.73
Magnetite	8.02	11.55	10.37	4.69	3.54	3.32	2.28	1.74	7.06	0.00
Enstatite	9.47	5.94	5.92	21.85	21.66	18.87	9.15	4.40	1.35	0.10
Ferrosilite	1.10	0.51	0.53	3.41	3.48	8.66	14.78	6.54	0.00	0.00
Quartz	0.00	0.00	0.00	0.00	0.00	1.25	2.61	24.51	16.69	31.33
Forsterite	39.12	26.38	40.31	35.70	30.91	0.00	0.00	0.00	0.00	0.00
Fayalite	5.01	2.51	3.99	6.15	5.47	0.00	0.00	0.00	0.00	0.00
Hematite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	2.82
Hedenbergite	1.99	2.62	1.40	1.34	1.61	0.42	0.32	0.00	0.00	0.00
Corundum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.13	2.75	1.51
Rutile	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78
Diopside	19.61	34.83	17.90	9.84	11.52	1.05	0.23	0.00	0.00	0.00
Plagioclase Composition	76.69	82.23	61.19	78.47	73.41	72.46	45.24	31.86	22.85	19.03

Table 13 - continued

Sample Number	1	2	3	4	5	6	7	8	9	10
Differentiation Index	3.89	2.95	7.47	3.92	5.65	24.44	40.81	70.12	73.91	84.75
Colour Index	84.84	84.83	80.98	84.65	80.54	32.74	29.30	13.59	9.11	1.53

Notes

1. Altered peridotite.
2. Altered peridotite.
3. Altered peridotite.
5. Altered peridotite.
6. Hornblende quartz diorite.
7. Biotite quartz diorite.
8. Biotite quartz diorite from the contact zone.
9. Equigranular trondhjemite.
10. Granophyric trondhjemite.

Abbreviations

- Not detected
- N.D. Not determined
- x Trace amounts

Sudbury-Manitoulin Area

ate plagioclase (oligoclase-andesine), quartz, iron-titanium oxides, and either green hornblende or biotite. Secondary minerals, including chlorite, clinozoisite, muscovite, carbonate, sphene, and leucoxene are prevalent.

Trondhjemite, which forms the southern one-third of the intrusion, is a pink, medium-grained (1 mm) rock composed of albite, quartz, and muscovite with minor amounts of chlorite, carbonate, zircon, tourmaline, apatite, and sphene. Muscovite forms radiating sheaves and in some of the trondhjemite, albite and quartz are intergrown to form a distinctive granophyric texture. Chemical analyses, norms, and modal analyses of typical rocks are given in Table 13.

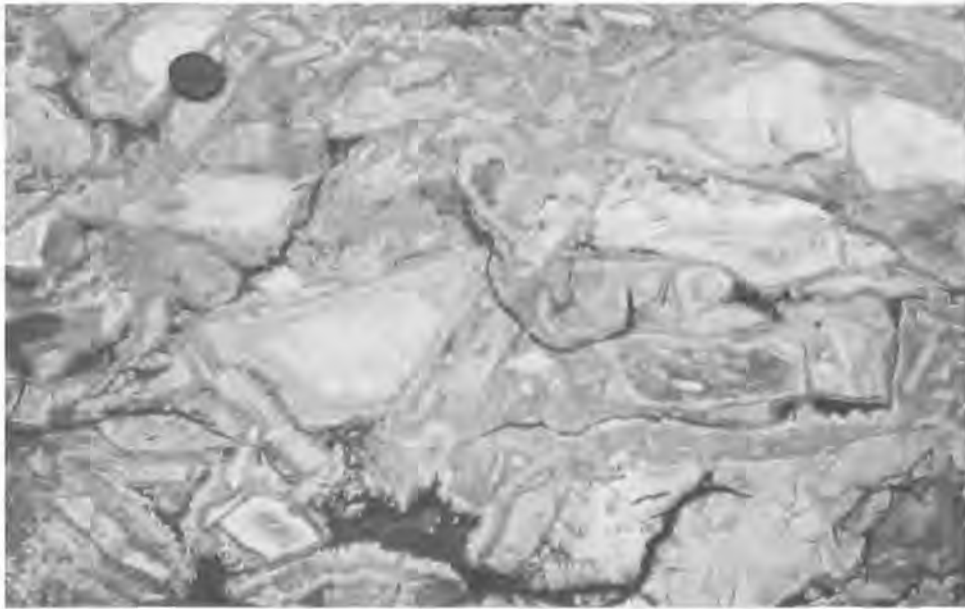
The ultramafic rocks commonly contain 10 percent to 15 percent magnetite in the form of disseminations and veins, and consequently give rise to a pronounced circular magnetic anomaly on Geological Survey of Canada, Map 1522G, Whitefish Falls (GSC 1965a). A vein of unusual colloform, radiating magnetite associated with massive serpentine and carbonate is present. Pyrrhotite, chalcopyrite, and pyrite, containing copper, nickel, and minor cobalt and gold, occur as disseminations and massive pods in the ultramafic rocks.

Investigations of the mineralogical and chemical variations displayed by the pluton (Card 1968b) suggest that its various rock types were derived from a common magma source, but were emplaced as two successive injections of magma, a peridotitic magma followed closely by a dioritic or granodioritic magma. The peridotitic magma apparently solidified rapidly, or was injected in a partly crystalline state, and no significant crystal settling or differentiation occurred. The dioritic magma did differentiate, or was contaminated by assimilation of country rocks to produce trondhjemitic liquids strongly enriched in Na_2O . Card (1968b) suggested that differentiation was effected by diffusion normal to the vertical walls of the intrusion; and was a result of diffusion gradients set up by border contamination of the magma. Such contamination is indicated by a chemical analysis of a contact quartz diorite which shows that it is enriched in SiO_2 and K_2O relative to similar rocks away from the contact zone (compare analyses 7 and 8, Table 13), and by the high initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio (0.7113) obtained by Van Schmus (1971), mainly from the trondhjemite.

NEMAG LAKE AND KUSK LAKE FENITES

Two small, irregular fenite bodies each about $\frac{1}{4}$ mile (0.5 km) in diameter occur north of Panache Lake in Whitefish Indian Reserve No. 6 within metasandstone of the Mississagi Formation. The fenites also affect Nipissing Diabase Intrusions. The fenites are cut by late olivine diabase dikes, and consequently are older than 1,250 to 1,450 m.y. The bodies are close to the northeast-trending Kusk Lake Fault. The geology and geochemistry of these bodies have been described in detail by Siemiatkowska (1971), Siemiatkowska and Martin (1975), and in Card *et al.* (1975).

The fenite consists of broken metasandstone fragments cemented by, and extensively replaced by, aegerine, a sodic pyroxene, riebeckite, a sodic amphibole, and alkali feldspars. The bodies can be subdivided into several units which generally correspond to an increasing degree of fenitization and to different stages of the fenitization process. In each body, there are several centres of rela-



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Photo 38—Nemag Lake fenite, Whitefish Indian Reserve No.6. Angular fragments of quartz-feldspar sandstone replaced to variable degrees by aegirine and riebeckite. The matrix consists of aegirine (grey) riebeckite (black patches), and albite (white crystals).

tively intense alteration, and progressively less altered rocks are distributed outward from these centres. Abundant evidence exists in the form of crosscutting vein relationships and replacement textures for repeated metasomatic alteration and mechanical brecciation. Siemiatkowska (1971) concluded that five and seven stages of fenitization activity could be discerned in the Kusk Lake and Nemag Lake bodies respectively.

Nonfenitized metasandstone of the Mississagi Formation in this area typically consists of 60 to 75 percent quartz, 5 to 15 percent potassic feldspar, 2 to 10 percent sodic plagioclase, and 5 to 20 percent phyllosilicate matrix. In an area of unknown dimensions about the fenite, metasandstone shows evidence of incipient fenitization, including the straining and granulation of minerals, and replacement of detrital feldspars by albite. In the outer margin of the fenites, metasandstone is granulated and exhibits numerous joints and fractures, many of which are filled with riebeckite and aegirine. Near the fractures, quartz and feldspars in the country rock are replaced by aegirine, riebeckite, and albite. In the central parts of the bodies, where the intensity of fenitization reaches a maximum, partly replaced metasandstone is broken up to form a rock consisting of angular fragments of altered metasandstone that range from less than 1 inch to about 5 feet (2.5 cm to 1.5 m) in maximum dimension. These fragments are set in a matrix of massive aegirine, riebeckite, and albite. Spectacular reaction rims are present about many of the blocks (Photo 38). Potassic feldspar occurs as

Table 14 - continued

Number Sample	Trace Elements in ppm																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Ba	400	200	-	150	-	-	-	-	-	-	-	-	-	-	-	-	-
Be	-	-	-	5	-	3	-	3	-	-	10	-	5	-	-	-	5
Co	6	-	3	10	-	5	-	5	-	-	9	-	-	-	-	-	10
Cr	200	100	250	400	250	500	300	500	-	-	400	-	80	-	-	-	800
Cu	10	6	4	8	6	6	5	6	-	-	6	-	11	-	-	-	25
Ga	15	10	10	25	30	20	15	20	-	-	5	-	30	-	-	-	15
Li	-	-	-	100	50	-	50	-	-	-	60	-	-	-	-	-	-
Mn	50	40	40	150	80	160	190	160	-	-	360	-	20	-	-	-	10
Mo	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	30	10	10	20	30	20	40	20	-	-	120	-	-	-	-	-	15
Pb	10	10	20	-	10	-	10	-	-	-	-	-	-	-	-	-	10
Sb	-	-	-	-	70	-	-	-	-	-	-	-	-	-	-	-	1
Sc	-	-	-	40	-	220	120	220	-	-	150	-	-	-	-	-	150
Sn	-	-	-	-	10	30	-	30	-	-	-	-	-	-	-	-	15
Sr	30	80	10	80	10	10	10	10	-	-	10	-	10	-	-	-	50
V	-	15	20	200	400	300	400	300	-	-	300	-	20	-	-	-	1500
Y	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zn	6	8	10	70	40	50	160	50	-	-	200	-	12	-	-	-	80
Zr	30	20	30	150	200	150	200	150	-	-	300	-	-	-	-	-	400
Nb	-	-	-	-	50	-	100	-	-	-	40	-	-	-	-	-	-
Rb	-	30	30	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Notes

1. Subarkose of the Mississagi Formation, Township 156 (From Robertson, 1963).
2. Partly albitized Mississagi subarkose adjacent to the Kusk Lake fenite.
3. Partly albitized Mississagi subarkose adjacent to the Nemag Lake fenite.
4. Metasandstone partly replaced by riebeckite, Kusk Lake fenite.
5. Metasandstone veined by aegirine and albite, Nemag Lake fenite.
6. Massive aegirine fenite, Kusk Lake fenite.
7. Fenite breccia, Nemag Lake fenite.
8. Aegirine, Kusk Lake fenite.
9. Magnesioriebeckite, Kusk Lake fenite.

10. Aegirine, Nemag Lake fenite.
11. Magnesioriebeckite, Nemag Lake fenite.
12. Potassic feldspar, Kusk Lake fenite.
13. Albite, Nemag Lake fenite.
14. Niobium-bearing ilmenorutile, Nemag Lake fenite.
15. Magnetite, Nemag Lake fenite.
16. Ilmenite, Nemag Lake fenite.
17. Magnetite-rich mafic dike cutting the Nemag Lake fenite.

Abbreviations

- * Total iron recalculated to Fe₂O₃
- Not detected
- N.D. Not determined
- tr Trace amounts

cream-coloured veins and as intergrowths with other fenitic minerals in the Kusk Lake body, and late-stage albite and quartz veins and masses are common in both bodies. Late breccia veins consisting of small, about 1-inch (2.5 cm) sized fragments of albite, aegirine, and fenitized metasandstone are set in a matrix of aegirine and riebeckite, cut the previously fenitized rocks, and locally extend outward into apparently unfenitized country rock.

Also present are niobium-bearing ilmenorutile, pyrite, hematite, magnetite, and ilmenite veins and disseminations, and in the Kusk Lake body, a sphalerite-bearing ankerite vein about 2 feet (0.6 m) wide. Both fenites are cut by several narrow mafic dikes composed mainly of amphiboles, quartz, plagioclase, and iron oxides. One dike in the central part of the Nemag Lake Fenite has a marginal chill zone with abundant biotite and magnetite.

Chemical analyses of fenite minerals and rocks are given in Table 14. The chemical data show that the fenitization process involves essentially addition of alkalis and iron to, and subtraction of silica from, the country rocks. Plots of chemical variations versus increasing degree of fenitization in Figure 30 show that Si decreases as Na and Fe, especially ferric iron, increase. Magnesium, Al, Ti, P, also generally increase, but show oscillatory variations. In the Nemag Lake body, K remains relatively constant, whereas in the Kusk Lake body, K increases markedly at the expense of Na in the late stages. With increasing alteration, trace elements such as V, Zn, La, Sn, Ba, and Nb increase, Ga, Cr, Ni, Rb, and Y vary irregularly, and Li and Pb decrease (Figure 30). Trace-element variation diagrams display maxima, indicating that introduction of specific trace elements occurred at specific stages of the fenitization process.

Fenites typically occur as alteration aureoles about intrusive carbonatite-alkalic complexes, but at Kusk Lake and Nemag Lakes, no true magmatic rocks of this type are present at the present level of exposure. The fenitizing elements were probably transported, and introduced as a gas phase. The albite of the fenites is a highly ordered, low temperature variety, suggesting that fenitization occurred at temperatures of about 400°C (Siemiatkowska and Martin 1975). Emplacement of the bodies was probably accomplished by a combination of metasomatic replacement, explosive activity, and fluidization processes. Cross-cutting relationships and oscillatory distribution patterns of introduced elements suggest that the composition of the fenitizing gases varied, and that these gases were introduced in a pulsating fashion, or during a series of explosive events.

AMPHIBOLITE, METAGABBRO, TRAP, AND LAMPROPHYRE DIKES

Narrow, fine-grained amphibolite, metagabbro, and trap dikes are prevalent throughout the map-area and form northwest-southeast and east-west trending swarms. Individual dikes are generally 10 to 20 feet (3 to 6 m) wide, and some can be traced along strike for several miles. These rocks intrude the Huronian rocks, Nipissing Diabase, and the Sudbury Nickel Irruptive and are intruded themselves by the late olivine diabase dikes. Also, these rocks transect major fold structures in the Huronian strata, but are metamorphosed and deformed, and are consequently older than the regional metamorphism and secondary de-

SMC 13426

KUSK LAKE FENITE ———

NEMAG LAKE FENITE - - - -

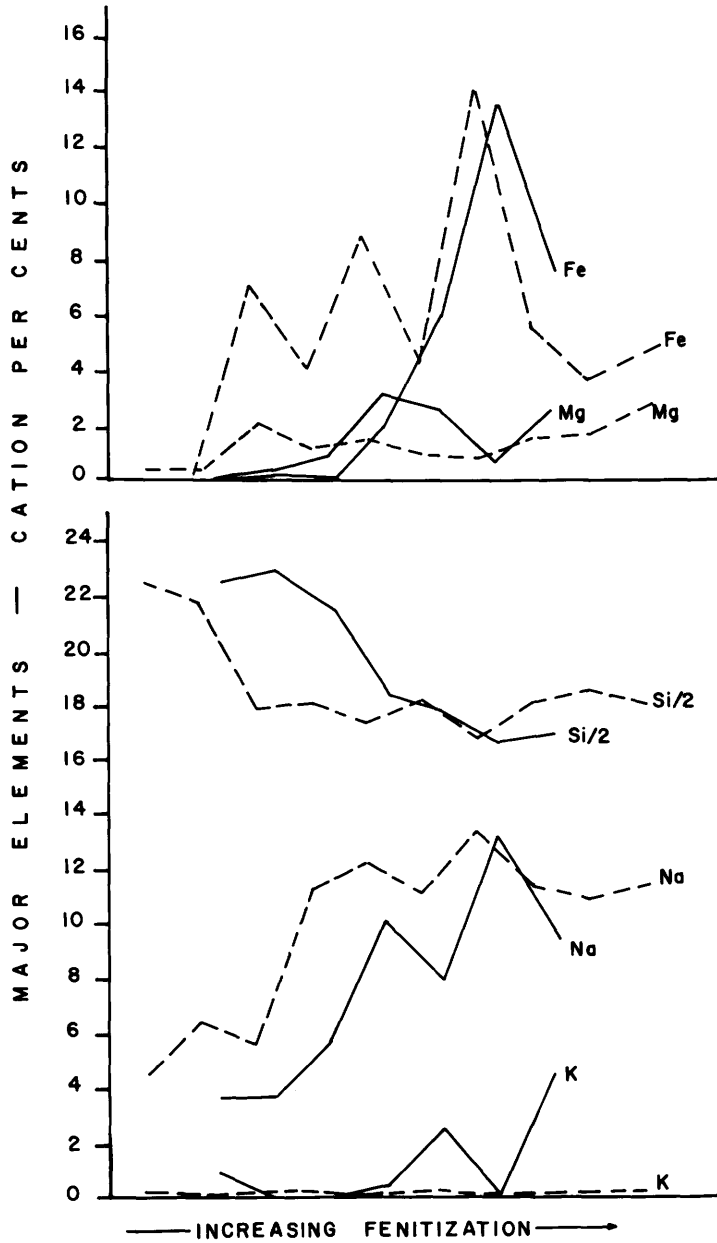


Figure 30a—Major elements versus increasing fenitization variation diagram, Nemag Lake and Kusk Lane Fenites (after Siemiakowska 1971); Sudbury-Manitoulin Area.

Sudbury-Manitoulin Area

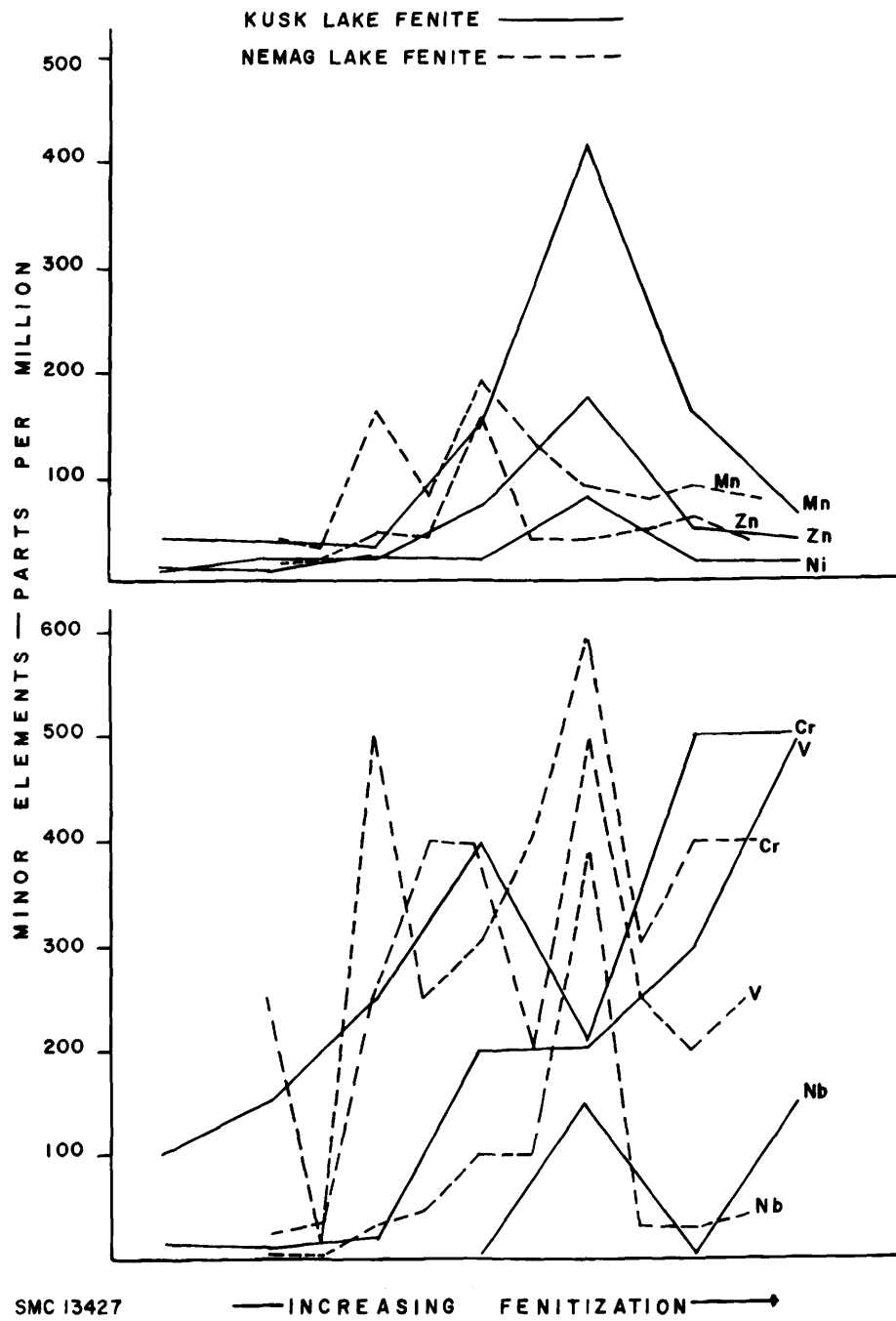


Figure 30b—Minor elements versus increasing fenitization variation diagram, Nemag Lake and Kusk Lane Fenites (after Siemiatkowska 1971); Sudbury-Espanola Area.

formational events in the Southern Province. Their absolute age or ages are unknown, but the geological relationships already described would indicate an age of about 1900 ± 100 m.y.

Amphibolite and metagabbro are fine-grained, dark green to black, equigranular or porphyroblastic rocks composed mainly of amphiboles (hornblende, actinolite) and saussuritized plagioclase, with variable amounts of biotite, epidote, muscovite, chlorite, quartz, granophyre, sphene, carbonate, iron-titanium oxides, and sulphide minerals. Chemical and modal analyses given in Table 15 show that compared to the Nipissing Diabase, the dike rocks analyzed are poor in quartz and CaO and enriched in mafic minerals and iron. These chemical-mineralogical differences would indicate that the dikes do not represent feeders for the Nipissing Diabase, nor could such a relationship be established in the field.

Only a few, small lamprophyre dikes were encountered in mapping, but because they are easily weathered, may be more abundant than is apparent in the field. The dikes are narrow, less than 10 feet (3 m) wide, and can be traced only short distances. These rocks intrude the Huronian rocks, but post-date the main deformational-metamorphic events. The lamprophyre is a minnette type composed mainly of biotite or phlogopite, with variable amounts of calcite, potassic feldspar, and plagioclase. Minor amounts of chlorite and epidote are present in some dikes.

Rb-Sr age determinations by Van Schmus (1971) indicate that similar lamprophyre dikes in the Blind River area are $1,415 \pm 40$ m.y. old.

DIABASE AND OLIVINE DIABASE DIKES

In the Southern Province unmetamorphosed, post-tectonic diabase dikes form a prominent northwest-trending swarm termed the "Sudbury Swarm" by Fahrig and Jones (1969). Some dikes occupy pre-existing faults and fractures but they are offset by late movements on the east, northeast, and northwest faults, and near the Grenville Front Tectonic Zone, are commonly mineralogically altered. Most apparently do not cross the Grenville Front Tectonic Zone, and are consequently older than the Late Precambrian metamorphism and deformation there. Metamorphosed diabase dikes in the northwest Grenville Province exist which may be equivalent to the Sudbury Swarm dikes. Late, post-tectonic diabase dikes also exist in the Grenville Province and some of these extend into the adjacent Southern Province (Lumbers 1975).

K-Ar and Rb-Sr age investigations by a number of workers, including Van Schmus (1965) and Fahrig and Wanless (1963) show that most of the Sudbury dikes are about $1,250 \pm 50$ m.y. old. Dates over the range 1,000 m.y. to 1,400 m.y. however are common, and Gates and Hurley (1973) recently obtained a Rb-Sr isochron age of $1,460 \pm 130$ m.y. on dikes in the Sudbury area. Within the Grenville Front Tectonic Zone near Killarney, Fahrig and Wanless (1963) have determined K-Ar whole rock dates of 431 ± 80 m.y. and 416 ± 76 m.y. on diabase dikes that apparently extend across the Grenville Front into the Southern Province. This great range in apparent radiometric age may be caused in part by post-emplacement metamorphism, but it is probable that northwest-trending dikes of more than one age are present.

Sudbury-Manitoulin Area

TABLE 15 | **CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF AMPHIBOLITE METAGABBRO, AND LATE DIABASE DIKES IN THE SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.**

Sample Number	Major Components in Weight Percent		
	1	2	3
SiO ₂	48.50	47.44	45.9
Al ₂ O ₃	12.80	15.70	15.1
Fe ₂ O ₃	3.07	3.19	2.9
FeO	11.20	13.11	12.1
MgO	8.90	4.50	4.2
CaO	10.60	8.19	8.5
Na ₂ O	2.16	2.54	3.5
K ₂ O	0.48	0.97	1.2
H ₂ O ⁺	1.07	1.89	1.7
H ₂ O ⁻	0.09	0.70	-
CO ₂	0.25	0.19	0.1
TiO ₂	1.23	0.50	3.1
P ₂ O ₅	0.14	0.29	-
S	0.13	0.16	-
MnO	0.22	0.18	0.2
Cr ₂ O ₃	-	0.01	-
V ₂ O ₃	-	0.10	-
Total	100.80	99.66	98.5
	3.06	2.90	N.D.

Trace Elements in ppm

Ag	1
As	5
Ba	-
Be	-
Cr	100
Co	30
Cu	110
Ga	20
Pb	10
Li	20
Mn	1200
Mo	10
Ni	70
Sb	-
Sc	50
Sr	100
Sn	5
Ti	6000
V	300
Y	20
Zn	80
Zr	100

Table 15 – continued

Norms (Weight Percent)				
Sample Number	1	2	3	4
Quartz	0.00	0.00	0.00	
Orthoclase	2.86	5.93	7.34	
Albite	18.39	22.23	26.90	
Anorthite	23.97	29.55	22.70	
Nepheline	0.00	-	2.02	
Diopside	14.13	3.44	7.76	
Enstatite	9.88	7.77	0.00	
Ferrosilite	7.08	14.06	0.00	
Forsterite	4.12	1.56	5.06	
Fayalite	3.25	3.12	8.03	
Magnetite	4.48	4.78	4.35	
Ilmenite	2.35	0.98	6.09	
Apatite	0.33	0.70	-	
Pyrrhotite	0.36	0.45	0.00	
Hedenbergite	7.99	5.43	9.76	
Normative Plagioclase Composition Differentiation Index Colour Index	55.12 21.25 54.10	55.62 28.16 41.14	41.13 36.26 41.05	

Modal Analyses (Volume Percent)				
			Average	Range
Plagioclase	23.8	23.7	66.0	60-70
Pyroxene	-	-	10.4	5-15
Olivine	-	-	13.2	0-25
Amphibole	73.0	58.4	-	-
Quartz	x	3.3	-	-
Granophyre	2.6	-	-	-
Biotite	-	x	1.7	0-5
Chlorite	0.2	x		
Muscovite	-	x		
Carbonate	-	-		
Apatite	-	x	1.5	0-2
Epidote	x	3.0		
Sphene	-	-		
Iron-titanium oxides	x	11.6	7.1	2-10
Sulphides	-	x		
Plagioclase Composition	-	-		An ₅₀ -An ₇₀

Notes

1. Amphibolitic metagabbro dike, Bay of Islands.
2. Metagabbro dike, Mongowin Township.
3. Olivine diabase, Sudbury Swarm (from Fahrig *et al.* 1965).
4. Average of 5 olivine diabases, Sudbury Swarm, Sudbury-Manitoulin Map-area.

Abbreviations

- x Trace amounts
- Not detected
- N.D. Not determined

Sudbury-Manitoulin Area

In the Southern Province, olivine diabase forms narrow, (1 to 600 feet, average 100 feet; 0.3 to 180 m, average 30 m), elongate dikes, some of which are in excess of 50 miles (80 km) in length. These dikes are steeply dipping and produce linear aeromagnetic anomalies of moderate to low intensities. Most dikes trend northwest and are regularly spaced at intervals of 1 mile (1.6 km), or even multiples thereof. Rectangular joint sets and spheroidal weathering are common features, and because of their weathering characteristics, many dikes are marked by narrow linear valleys.

The dikes consist mainly of dark grey, brown-weathering medium- to coarse-grained alkali olivine diabase, and have a subophitic texture. Primary minerals include zoned calcic plagioclase, titaniferous augite with minor exsolved pigeonite or inverted pigeonite, olivine, apatite, and magnetite-ilmenite. Minor amounts of secondary chlorite and biotite are common, and in altered diabase, uraltic amphibole, epidote, and muscovite are prevalent (Table 15). Most dikes have fine-grained chilled margins, and several have abundant, coarse (up to 6 inches (15 cm), in length) phenocrysts of plagioclase. Felsic segregations, consisting of albite and hornblende or granophyric intergrowths of quartz and alkali feldspar are locally present.

The compositional homogeneity of the dikes examined indicates that they were derived from a common magma; their chemical composition and low initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.703 (Gates 1971) indicate derivation from a homogeneous mantle source. The constant orientation and spacing of the dikes implies emplacement under a regional tensional stress system, possibly in faults or fractures produced by broad regional flexuring or incipient rifting. Fahrig *et al.* (1965) have determined a paleomagnetic pole position of 166°W Longitude, 4°S Latitude for the dikes of the "Sudbury Swarm".

Grenville Province

MIDDLE TO LATE PRECAMBRIAN

The Grenville Province part of the map-area was mapped by Frarey and Cannon (1969), and the geology as shown on Map 21-1968 was taken, with some generalization and re-interpretation by the writer, from that source. In addition, Lumbers (1971a; 1971b; 1972; 1975) has described the geology of the adjacent Burwash map-area and since the rock units there are contiguous with those in the Sudbury-Manitoulin area, much of the following descriptive material comes from that source. For further details on the geology of the northwest Grenville Province, the reader is referred to Lumbers (1971a; 1971b; and 1975).

The Grenville rocks of the map-area include Middle Precambrian metasediments and Middle and Late Precambrian plutonic rocks which were highly deformed and metamorphosed during Middle and Late Precambrian orogenic events. These rocks lie within the Grenville Front Tectonic Zone and exhibit structures such as, northeast-trending foliation, southeast-plunging lineations,

and high rank metamorphic mineral assemblages, features which resulted mainly from Late Precambrian orogenesis. Metamorphism and deformation have rendered the distinction of orthogneiss and paragneiss difficult, but Lumbers (1971a; 1975) has outlined field and petrographic criteria for their subdivision.

Paragneiss and Metasediments

Gneissic rocks of metasedimentary origin display prominent compositional layering, reflecting in part their original bedding, and in part, migmatitic layering developed during metamorphism and deformation. Interstratified, intergradational metasediments present include quartz-rich, biotitic, feldspathic, and muscovitic paragneiss, orthoquartzite, para-amphibolite, hornblende- and pyroxene-bearing gneiss, metaconglomerate, and their migmatitic equivalents. The original rock types locally possess relic primary sedimentary structures such as bedding, crossbedding, and facies changes which, along with compositional criteria, indicate they represent highly deformed and metamorphosed sediments. These rocks include thin-bedded, turbidite-type greywacke and siltstone, thicker bedded argillaceous sandstone, arkose and orthoquartzite, calcareous sandstone and siltstone, and polymictic paraconglomerate. Some of the thin-bedded turbidite-type sequences are lithologically similar to the McKim and Pecors Formations of the Huronian Supergroup; some of the feldspar- and quartz-rich paragneisses are similar to rocks of the Mississagi Formation and Lorrain Formations; thin conglomeratic greywacke units resemble rocks of the Gowganda Formation.

The paragneiss of the Grenville Province represents a highly deformed and metamorphosed sequence of greywacke and argillaceous rocks that was probably deposited in a relatively deep-water environment, with intercalations of shallow-water sandstone. Radiometric age studies by Davis *et al.* (1970) indicate that the paragneiss is older than 1,700 m.y., and consequently is probably equivalent in age to the Huronian Supergroup of the Southern Province. Like the Huronian Supergroup, the sediments from which these rocks formed were probably derived from the Superior Province to the north. The southeastward facies changes noted in the Huronian Supergroup, essentially thickening of turbidite-type units such as the McKim and Pecors Formations, and incoming of increasing amounts of argillaceous material in sandstone formations such as the Mississagi Formation, are continued in the Grenville Province supracrustal sequence.

Mafic Intrusive Rocks

AMPHIBOLITE AND METAGABBRO

Small dikes and stocks of mafic intrusive rocks are present in the part of the map-area occupied by Grenville rocks. Some deformed, metamorphosed gabbroic bodies are apparently older than the felsic plutonic rocks, and consequently may

Sudbury-Manitoulin Area

be correlative with the Nipissing Diabase Intrusions of the Southern Province. Other metamorphosed mafic dikes intrude the felsic plutons and some may be equivalent to the late "Sudbury Swarm" diabase dikes of the Southern Province.

Felsic Plutonic Rocks

Most of the Grenville felsic plutonic rocks in the map-area are probably of Middle Precambrian age because these rocks display the effects of Late Precambrian deformation and metamorphism in the form of gneissosity and migmatization. Radiometric age studies by Davis *et al.* (1970), Krogh and Davis (1969) and others indicate that many are about $1,700 \pm 150$ m.y. old, and are approximately equivalent in age to the Grenville Front Zone plutons which intrude the Huronian Supergroup.

The felsic intrusive rocks are mainly medium- to coarse-grained, equigranular or porphyritic gneissic quartz monzonite and granodiorite with pronounced augen structure and locally developed migmatitic facies. Despite deformation and metamorphism, abundant evidence is preserved to show that these rocks were emplaced as magmatic intrusions, and are not the products of granitization (Lumbers 1971a; 1975).

Early, gneissic, recrystallized pegmatite and late, post-orogenic pegmatite dikes are present. Lumbers (1975) suggested that the older pegmatites were formed during an early period of regional metamorphism, possibly equivalent in age to the Middle Precambrian metamorphism which affected the Southern Province rocks.

Lumbers (1971a; 1975) found that development of migmatitic facies in the felsic plutonic rocks, and in the metasediments as well, is strongly controlled by bulk chemical composition. Migmatite is confined to units with compositions lying close to the ternary minimum of synthetic granite systems. This would indicate that migmatization occurred during high rank regional metamorphism by anatexis, or partial melting without wholesale introduction of granitic material by metasomatic agencies.

Other Rock Units

Lumbers (1975) recorded the presence of post-orogenic diabase and lamprophyre dikes of Late Precambrian or early Phanerozoic age, and of Late Precambrian plutonic igneous rocks of the anorthosite suite in the adjacent Burwash area. A number of diabasic dikes which intrude the Grenville paragneiss and felsic plutonic rocks of the map-area have been grouped with the "Sudbury Swarm" diabase on Map 2360 (back pocket). However, most of the diabasic dikes in the Grenville Province are probably appreciably younger than the Southern Province dikes (Lumbers 1975).

Phanerozoic

PALEOZOIC

Ordovician and Silurian Strata

Nearly flat-lying Paleozoic sedimentary strata unconformably overlie Precambrian rocks in the southern part of the map-area. Quaquaversal dips occur in the Paleozoic rocks over hills in the Precambrian basement, but generally these strata dip southward at about 35 feet per mile (6 m/ km). Relief on the Paleozoic-Precambrian unconformity is probably comparable to the present-day relief of the area. The Paleozoic rocks form the northern part of the St. Lawrence Lowland-Michigan Basin Phanerozoic sequence which was deposited in shallow, epicontinental seas.

According to Liberty (1972), these strata belong to the Middle Ordovician Gull River, Bobcaygeon, Verulam, and Georgian Bay Formations, and the Lower Silurian Manitoulin Formation. Locally, at the base of the Paleozoic rocks, there is a thin succession of thin-bedded red and green mottled shale that locally contains abundant angular fragments of the underlying Precambrian rocks, which are commonly metasandstones of the Lorrain and Bar River Formations. Where formations higher in the sequence overlap onto Precambrian basement, they too commonly have a basal "rubble" facies with abundant fragments of Precambrian rocks and fossil debris. On the shore of the Bay of Islands, immediately west of the Birch Island railway station there is a small exposure of well-sorted sandstone consisting of rounded quartz grains with quartz overgrowths and pyrite cement. This rock unit lies at the base of the Paleozoic sequence and may be either of early Phanerozoic or Late Precambrian age.

Excellent exposures of the Paleozoic-Precambrian unconformity, with features such as "sharpstone" conglomerate and exhumed pre-Paleozoic weathering surfaces, can be viewed along Voyageur Channel and Highway 68 on Great Cloche Island, around the shores of Badgeley Point and nearby islands, and on Manitoulin Island at Sheguiandah. Limited study of the physical-chemical nature of the pre-Paleozoic weathering surface indicates the possibility of desert-like climatic conditions during the "Lipalian Interval", the lengthy period of erosion marked by the Paleozoic-Precambrian unconformity (Card 1976b).

The Gull River, Bobcaygeon, Verulam, and Lindsay Formations consist mainly of grey, finely crystalline to lithographic limestone with minor argillaceous limestone, dolostone, and shale. The Whitby Formation consists of black, grey, and brown shale with minor black, petroliferous limestone. The Georgian Bay Formation consists of finely crystalline limestone, dolostone, argillaceous limestone and shale. The Silurian Manitoulin Formation includes brown and grey finely crystalline dolostone with reef structures.

The Paleozoic rocks contain a rich assemblage of invertebrate fossil remains and for further details and photographs the reader is referred to Robertson and Card (1972).

CENOZOIC

Quaternary

PLEISTOCENE AND RECENT

The Cenozoic history of the map-area is dominated by the effects of glaciation during the Pleistocene Epoch which began some one million years ago. During this period, continental glaciers moved southward, scoured away the soil and weathered rock, striated, grooved, and polished the bedrock, and deposited material in the form of glacial drift, eskers, and drumlins. Probably several major glacial advances and retreats took place, although there is evidence for only the last major stage in the map-area, the Wisconsin advance. A series of glacial lakes, the Algonquin Lakes, were formed some 12,000 to 10,500 years ago in the present Great Lakes Basin. Some of these glacial Great Lakes stages attained higher elevations than the present Great Lakes, although during one, the Stanley Stage, lake levels were much lower than at present (Hough 1958, 1963; Chapman and Putnam 1966).

The Wisconsin ice withdrew from the map-area approximately 10,000 to 11,000 years ago, retreated northward, and periodic halts and readvances of the ice front are marked by latitudinal morainic belts (Boissonneau 1968). Glacial meltwaters were ponded to form inland lakes and post-glacial lakes in the Great Lakes Basin. The various inland lakes and post-glacial Great Lakes stages, in particular the Nipissing Great Lakes, are marked by raised beaches, wave-cut terraces, glaciolacustrine deposits, and areas of wave-washed bedrock at several elevations. Meltwaters flowing southward from the retreating glaciers formed outwash and valley-train deposits extending southward from the end moraine belts which disrupted the pre-glacial drainage pattern.

Isostatic rebound of the earth's crust following withdrawal of the glaciers resulted in formation and elevation of a series of shorelines about the glacial Great Lakes. Lewis (1970) estimated that Manitoulin Island and adjacent areas have been uplifted at a rate of about 2.2 mm per year over the past 5,000 years. The present-day shoreline of Lake Huron is an emergent one.

Direction of Ice Movement

The movement of the Pleistocene glaciers, as revealed by the orientation of glacial striae, drumlins, and eskers, was generally north-south. Ice pressure crescents and the shapes of drumlins and *rôche moutonnées* indicate southward advance.

Most glacial striae strike approximately S15°W to S25°W, but locally an older set of striae trending about S40°W is present (Figure 31). Boissonneau (1968) has interpreted the two sets to belong to two separate lobes of Wisconsin ice.



ODM9610

Photo 39—Crossbedded Pleistocene sand and gravel, Drury Township.

Surficial Geology

The surficial geology of the map-area consists of a thin, discontinuous mantle of glacial till overlying bedrock. Local pockets of glaciolacustrine, glaciofluvial, and morainic deposits, and areas of bare, wave-washed bedrock also occur. The main elements of the surficial geology are shown in Figure 31.

Glacial deposits include: ground moraine, which is a sandy, silty boulder till composed mainly of fragments of the underlying bedrock; crag-and-tail deposits on the lee sides of bedrock cliffs; and drumlin and kame deposits.

Glaciofluvial deposits include eskers and outwash deposits, mainly in the form of valley trains extending southward from moraine belts to the north of the present map-area. These deposits mark the courses of glacial streams, and many valleys are occupied by modern streams such as the Spanish River. The deposits consist mainly of sorted sand, gravel, and silt, and display sedimentary structures such as scour-and-fill structures, bedding, crossbedding, and ripples (Photo 39). Some sequences have characteristics of point-bar deposits formed by meandering rivers flowing through and reworking glacial outwash materials.

Glaciolacustrine sediments form locally thick terrace and delta deposits composed of varved clay, massive silty clay, silt, and fine sand. Accumulations of varved clay occur along the Spanish River at Espanola and along the shores of Agnew Lake in Shakespeare and Dunlop Townships. In the map-area the major

glaciolacustrine sequences occur at maximum elevations of about 1,000 feet (300 m) above mean sea level and are probably mainly the deposits of glacial Lake Algonquin.

Along the North Shore of Lake Huron and on the numerous islands, especially Manitoulin Island, a series of raised beaches and wave-cut terraces occur at various elevations marking the strand lines of glacial and post-glacial lake stages. The best developed and most persistent strand line is that developed during the main Lake Nipissing stage some 5,500 years ago which presently stands at an elevation of about 650 feet (200 m) above mean sea level (Figure 31).

Recent deposits include swamp, beach, and stream deposits which mainly represent reworked Pleistocene sediments. Many modern streams follow Pleistocene drainage systems, and these meandering streams are incised into broad valleys filled with Pleistocene deposits. Pleistocene sand and gravel deposits are being actively worked at a number of localities for road building, construction, and mine fill purposes.

STRUCTURAL GEOLOGY

The map-area includes parts of three tectonic provinces of the Canadian Shield, the Superior, Southern, and Grenville Provinces (see Figure 2), and the rocks of these provinces have been affected by a series of deformational and metamorphic events ranging in age from Early Precambrian to Early Phanerozoic. The Superior Province was affected mainly by Early Precambrian events, including deformation, emplacement of granitic plutons, and high rank regional metamorphism during the Kenoran Orogeny some 2,500 million years or more ago. The Early Precambrian rocks toward the southern margin of the Superior Province were also affected by Middle Precambrian orogenic events which occurred mainly in the adjacent Southern and Grenville Provinces.

The rocks of the Southern Province were affected to varying degrees by Middle Precambrian deformation and metamorphism depending on their age and location with respect to the following: the Superior basement; the northwest margin of the Grenville Province; and the mobile belts within the Southern Province itself. The Huronian Supergroup, Nipissing Diabase Intrusions, and Sudbury Nickel Irruptive were deformed and metamorphosed under conditions of low to middle rank regional metamorphism during a protracted series of events that occurred during the interval 1,700 to 2,200 million years ago. These events have been assigned to the Penokean (Goldich 1968) or Hudsonian (Stockwell *et al.* 1970) Orogenies by various workers.

Rock units younger than about 1,700 million years of age, such as the Grenville Front Felsic Intrusions, the Mongowin Pluton, and Late Diabase Dikes post-date the main Middle Precambrian deformation and metamorphism. These rocks and the older rocks of the Southern Province were affected by later deformation and retrograde metamorphism, probably the reflection of Late Precambrian orogenesis concentrated in the nearby Grenville Province.

The rocks of the Grenville Province and Grenville Front Tectonic Zone underwent deformation and high rank regional metamorphism, mainly during the Late Precambrian. Evidence exists for Middle Precambrian deformation and

metamorphism accompanied by emplacement of felsic intrusions as well.

The orogenic history of the area is summarized in Table 1 and the major regional tectonic elements are portrayed in Figures 2 and 32 (Chart C, back pocket).

SUPERIOR PROVINCE

The Superior Province within the map-area consists mainly of felsic plutonic rocks of the Birch Lake Batholith, a complex of composite plutons that are relatively homogeneous, massive, diapir-like bodies of general quartz monzonite composition. These bodies were probably emplaced in the mesozoone during the later stages of the Kenoran Orogeny some 2,500 million years or more ago (Stockwell *et al.* 1970). The plutons are bounded on the east and north by layered migmatitic gneiss which probably represents highly deformed and metamorphosed Early Precambrian supracrustal rock. Gneissic layering in the migmatite is generally concordant with the margins of the plutons. Contacts between the migmatitic and plutonic rocks are in some places gradational, in other places sharp and discordant. Agmatitic contact zones are common.

Following the Kenoran Orogeny, the Superior Province craton was stabilized, uplifted, and eroded to form an extensive paleoplain of low relief during the Ep-Archean interval. This was followed, in the early part of the Middle Precambrian, by a period of normal faulting and downwarping of the Superior craton to initiate the Huronian depositional basins. The early layered gabbro-anorthosite plutons, mafic dike swarms and outpourings of mafic lavas at the base of the Huronian Supergroup are probably expressions of this early tensional tectonic activity. Volcanism was accompanied and succeeded by deposition of a thick wedge of clastic sediments derived mainly from uplifted Superior cratonic blocks.

The Superior Province rocks, northward to about Latitude 47°N in the map-area, show the following effects of Middle Precambrian deformation and metamorphism: general lowering of apparent radiometric ages (Van Schmus 1965); retrograde mineralogical alteration; cataclastic granulation; mylonitic foliations; and faults which displace both the Early Precambrian basement and Middle Precambrian cover rocks. The massive Superior Province rocks acted as a buttress against which the more mobile Southern Province sequence was thrust by tectonic forces acting from the south. The southern part of the Superior Province was deformed as well as the Southern Province sequence, yielding mainly by brittle fracture. Within the Southern Province the Superior basement was uplifted to form broad arches occupying the cores of anticlinal structures.

In the Sudbury-Manitoulin area, the dominant faults, cataclastic cleavage and mylonitic foliation in the Superior Province strike east or northeast parallel to the main structural trends in the adjacent Southern Province and are probably mainly of Middle Precambrian age. Immediately north of the map-area are two prominent fault sets, one striking north-northwest, the Onaping System, the other northeast. Middle Precambrian movements on these structures have displaced the Huronian cover rocks and the Sudbury Nickel Irruptive as well as the basement. Evidence that the faults originated before deposition of the Huro-

nian exists because displacements of Early Precambrian rock units on some faults differ in sense and amount from post-Huronian displacements (Card and Meyn 1969). These faults were probably initiated in the Early Precambrian marking the onset of Middle Precambrian tectonism; normal movements on them formed graben-style basins in which the Huronian sediments were deposited.

SOUTHERN PROVINCE

The map-area lies within the eastern part of the Penokean Fold Belt, the most highly deformed and metamorphosed part of the Southern Province (Card *et al.* 1972). This part of the Penokean Fold Belt is an arcuate, concave to the north, generally synclinal belt underlain mainly by tightly to moderately folded, highly faulted, metamorphosed Huronian strata. It is divisible into two parts, a southern subzone in which the major tectonic elements trend east, and a northern subzone in which the major structures trend east-northeast (Figure 32). The two subzones are separated in a general way by the Apsey Lake and Lake Parnache Faults, which are major faults of the Murray System. In addition, near the Grenville Front Tectonic Zone late movements on northeast-striking faults and cleavage zones which parallel it have resulted in rotation and partial obliteration of earlier east-west structures. In the northwest a synclinal embayment of Huronian rocks trends north-south, approximately normal to the structural trends in the main belt to the south (Figure 32, Chart B, back pocket).

Folds

Major folds in the Huronian strata are moderately open to tightly appressed, flattened, concentric buckles. The axial surfaces of the folds are upright to slightly overturned northward and are commonly curved. These folds are buckle-style folds formed by combinations of flexural slip on bedding and flexural slip and flow on foliation planes. The dominant mechanism of folding is dependent on lithology and degree of flattening; pelitic sequences yielded mainly by slip and flow on foliation planes, sandstone units by slip on bedding planes. Notable variations in tectonite fabric occur from one rock type to another and in a single rock type from one area to another. For example, a single foliation may appear as a well-defined schistosity in pelitic rocks, and as a coarse fracture cleavage in interbedded sandstone. Concentric folds in thick sandstone units appear as similar folds in adjacent pelitic units. These lithological competency differences have resulted in discordant fold patterns. In some folds in massive sandstone units, sharp flexural folding has led to extreme buckling with collapse and brecciation of the axial zones.

In the northern subzone, major folds such as the Porter Synclinorium and Baldwin and Lorne Anticlinoria are tight, composite structures consisting of *en echelon* series of doubly plunging synclines and anticlines whose axial surfaces dip vertically to 80°S, are commonly curved, and strike approximately N75°E

(Figure 32). The axes of these folds display rapid culminations and plunge at angles of 10° to 50° east and west. The Vernon Syncline, in the northern part of this subzone, strikes approximately north-south, is asymmetric and has a curved, easterly dipping axial surface. The axis plunges southward. This structure, striking at right angles to the main structural trends in the rocks to the south, probably represents a tectonically modified salient of Huronian strata filling an embayment in the Early Precambrian basement topography.

In the northern part of the southern subzone, major folds such as the Bass Lake Syncline strike east, and are moderately open with curved, upright axial surfaces. Fold axes plunge at low angles east and west forming a dome-and-basin pattern. In the southern part, folds such as the La Cloche Syncline, McGregor Bay Anticline, and Frazer Point Syncline (see Figure 32) are approximately cylindrical, tightly appressed structures with upright to slightly overturned axial surfaces, and axes plunging gently to moderately eastward for the most part. Axial traces of some gently plunging folds extend many miles.

In both the northern and southern subzones near the Grenville Front Tectonic Zone the fold pattern is irregular, the result of interference between the main east-west structures and northeast-trending structures parallel to the Front (Figure 32). There is evidence for refolding in the form of asymmetric folds with associated northeast-trending cataclastic axial plane foliation and south-east-plunging rodding lineation.

Faults

Faults of several ages and orientations (Figure 32) are prevalent throughout the area, and marked by shearing, brecciation, silicification, hematization, and truncation and displacement of rock units. Faults of the Murray System, including the Hunter Lake, Murray, Espanola, Apsey Lake, Lake Panache, Charlton Lake, and Narrow Bay Faults, strike east to east-northeast and are approximately parallel to the axial traces of the major folds and probably dip steeply southward. Movements of these structures have produced major repetitions and omissions of strata that indicate total displacements of several thousands of feet. Appreciable reverse dip-slip (south side up) as well as tight lateral (south side west) strike slip components of movement have occurred. Steeply plunging and subhorizontal slickensides are present in the fault zones. Some of the present Murray System faults may approximately mark the locii of early, graben-style faults, normal movements (south side down) on which initiated the Huronian depositional basin. There is evidence for repeated, diverse movements on many faults, such as during and after folding of the Huronian strata, and after emplacement of the late diabase dikes. Consequently, faults of the Murray System were periodically active for at least 1000 million years.

Northeast-trending faults such as the Graham Fault and Fox Lake Fault, and northwest-trending faults such as those in the Bay of Islands–McGregor Bay area probably belong to a conjugate set of early, normal faults. These faults strike approximately $N40^{\circ}E$ and $N45^{\circ}W$, apparently dip steeply, and have produced apparent horizontal offsets of Huronian units of a few hundred to a few thousand feet.

Sudbury-Manitoulin Area

Faults striking N60°W, for example the Webbwood Fault and others, striking N60°E, such as the West Lake Fault, probably belong to a conjugate set of late normal faults formed after the major east-west folding and faulting. The faults which strike N60°W are approximately parallel to the early amphibolite and late diabase dike swarms.

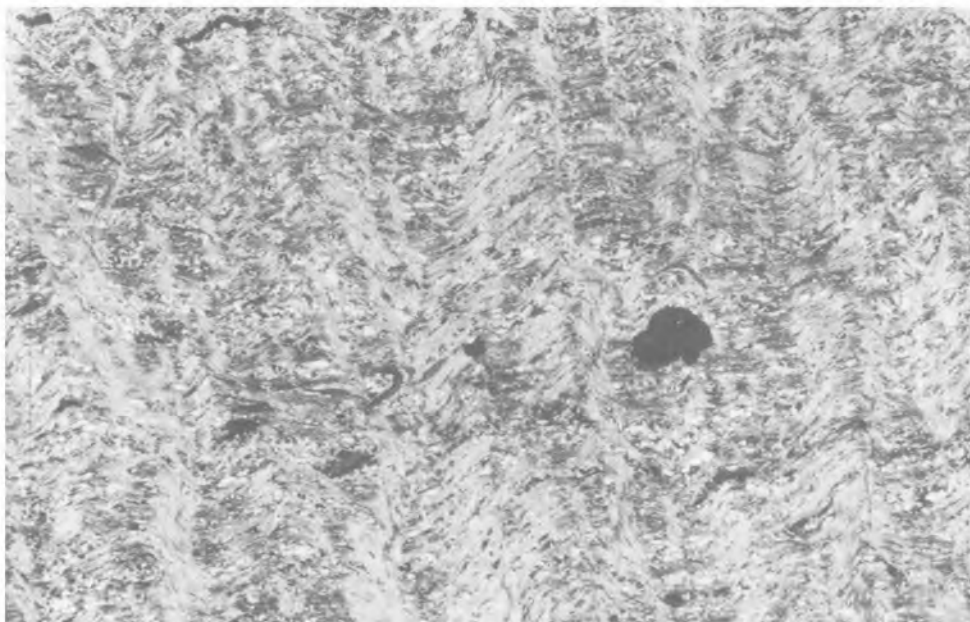
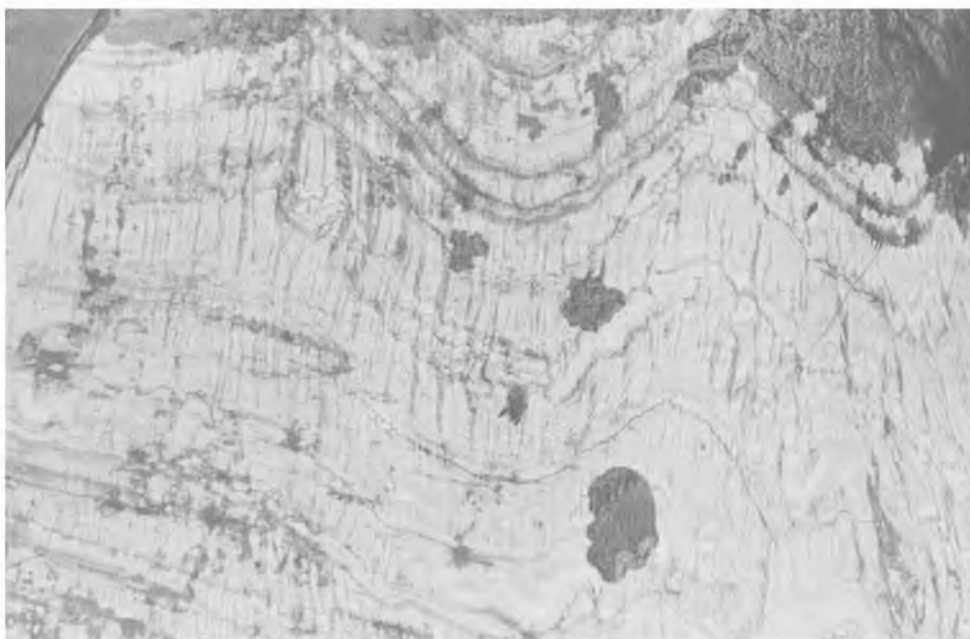
In central Creighton Township, a fault, trending north-northwest is indicated by displacement of rock units and contacts. This structure may represent the southward continuation of the Onaping Fault which occurs mainly north of the Sudbury Basin.

Near the Grenville Front Tectonic Zone late northeast-trending faults such as the Long Lake and Wallingford Faults (Figure 32) are parallel to this structure. Movements on these faults were probably in response to the orogenic events occurring in the nearby Grenville Province. Movements on several west-to northwest-trending faults, for example the Wavy Lake Fault, have apparently displaced rock units and older structural elements in the Southern and Grenville Provinces. These faults may represent the continuation of a system of graben-style faults which extends westward from the Ottawa River through the Lake Nipissing area to the Grenville Front Tectonic Zone (Lumbers 1975; Card and Hutchinson 1972)(see Figure 2).

Minor Structures

Crosscutting relationships between structures permit the distinction of several generations of minor tectonic elements (Photo 40). An early, approximately east-striking, steeply dipping bedding plane foliation is present in the Huronian strata throughout the area, and is most prominent in the southern subzone. A later east-west to east-northeast-striking, steeply dipping slaty type penetrative cleavage is the most prominent structure in the northern subzone. This foliation which was formed by flattening, affects Huronian strata and Nipissing-type intrusions, and is axial planar to major folds such as the Baldwin Anticlinorium. Conjugate sets of late, non-penetrative northwest- and northeast-trending strain-slip cleavages and kink bands occur sporadically throughout the area. These structures crenulate the older foliations and destroy metamorphic porphyroblasts. In addition, near the Grenville Front Tectonic Zone are irregularly distributed, non-penetrative cataclastic cleavage zones trending northeast parallel to the Front and late, east-west and west-northwest-trending cataclastic and mylonitic foliations associated with late faults cutting across the Front zone.

Lineations present include the following: rodding in foliation planes formed by elongated minerals and rock fragments, slickenside-type lineations on bedding planes; and various intersection lineations formed by intersections of bedding and foliations. The dominant rodding lineation in the Southern Province plunges steeply within the planes of the main east and east-northeast foliations. Near and within the Grenville Front Tectonic Zone, the dominant lineation plunges southeastward at moderate angles in the plane of the northeast foliation (Figure 32).



ODM9611

Photo 40—Outcrop and thin-section photographs showing two foliations in folded pelitic rocks of the Gowganda Formation, McGregor Bay. Early bedding plane foliation (east-west in upper photograph) is cut by a superimposed cleavage (north-south in lower photograph).

Other Structures

In addition to the foregoing tectonic elements, various structures present in the Huronian sequence are apparently the result of early tectonic activity. These structures were probably formed by gravity sliding induced by movements on faults within and marginal to the depositional basin at various stages of its development. Included are slump folds, slump breccias, and clastic dikes, excellent examples of which are to be found in rocks of the Espanola Formation in the McGregor Bay-Bay of Islands area (Card 1976b). There are also larger-scale structures which may be the result of gravity sliding of large blocks of supracrustal rocks. For example, in the Sampson Island area of McGregor Bay, there is a large fold-like structure that involves the Gowganda and Serpent Formations. This is not a regular tectonic fold, as bedding in the sedimentary strata does not conform to the contacts between formations. In the Lang Lake-Plunge Lake area in Curtin and Roosevelt Townships there is a block of rocks of the Gowganda Formation approximately 8,000 feet (2400 m) thick and 8 miles (13 km) long which represents an almost complete double section of the Gowganda Formation. From north to south, the succession proceeds from the base of the formation to near the top, a stratigraphic interval of some 4,000 feet (1200 m). Across a poorly defined disturbed zone practically the entire Gowganda sequence is again repeated. The eastern and western ends of the block are complexly folded, brecciated, and faulted.

Sudbury Structure

The Sudbury Structure comprises three main elements (a) the Sudbury Nickel Irruptive, (b) the synclinal area inside the Sudbury Irruptive occupied by the Whitewater Group, the Sudbury Basin, and (c) the brecciated country rocks of the Superior and Southern Provinces which surround the Irruptive (Figure 2).

REGIONAL SETTING

The relationships of the Sudbury Structure to regional tectonic, stratigraphic, and metallogenic elements has been outlined by Card and Hutchinson (1972). These authors concluded that the structure is of endogenic origin, possibly formed by explosive volcanism and intrusive and extrusive igneous activity along a major graben-type crustal structure. The Sudbury Structure is located near the common junction between the Superior, Southern and Grenville Provinces in an area which has suffered polyphase deformation and metamorphism. It is located along the "line of junction" of major regional faults and is related to regional gravity-magnetic anomalies. It is also associated with particular rock sequences such as thick accumulations of volcanic rocks and turbidites. The association of the Sudbury Nickel Irruptive with nickel-copper sulphide deposits fits the regional metallogenic pattern.

It has been suggested by Dietz (1964) and others that the Sudbury Structure was formed by the impact of a large meteorite which excavated a crater, brecciated the country rocks, and produced other shock metamorphic phenomena such as shatter cones. Part of the breccia so produced formed the Onaping Formation of the Sudbury Basin. French (1970) suggested that meteorite impact triggered magmatic activity which resulted in emplacement of the Sudbury Nickel Irruptive and its ores from subcrustal sources.

NICKEL IRRUPTIVE

The Sudbury Nickel Irruptive is a differentiated intrusion approximately 1 mile (1.6 km) thick which outlines a northeast-southwest-trending elliptical area some 37 miles (58 km) long and 17 miles (26 km) wide. The Sudbury Nickel Irruptive has the form of an asymmetric funnel-shaped lopolith with a steeply dipping south limb (45 to 90 degrees) and a relatively shallow dipping north limb (30 to 50 degrees). Detailed gravity studies by Popelar (1972) suggest that this form does not change with depth, that the main body of the Sudbury Nickel Irruptive extends to a depth of about 9 km (5.5 miles) on the south, and that the south limb has been uplifted with respect to the north limb by major thrusting on trans-basin faults. Paleomagnetic data (Sopher 1963; Larochelle 1969) suggest that there has been a post-emplacement differential rotation of some 30 degrees between the north and south limbs. The rocks of the south limb of the Sudbury Nickel Irruptive and of the adjacent Onaping Formation display the effects of this deformation in the form of steeply dipping northeast-trending cleavages and associated southeast-plunging lineations in the cleavages planes.

SUDBURY BASIN

The Sudbury Basin, the faulted, doubly plunging synclorium inside the Irruptive, is occupied by rocks of the Whitewater Group which have been moderately to weakly folded to form a series of open, *en echelon* synclines and anticlines whose axes plunge gently northeast and southwest. Associated with these folds is a single, steeply dipping, slaty-type axial plane cleavage. Mineral grains, rock fragments, and concretions are flattened in the plane of the cleavage. Except in the Onaping Formation in the south, these are not elongated to form a rodding lineation. The amount of flattening is approximately that required for deformation of an originally circular structure to its present elliptical shape (Brocoum, S.J., personal communication, 1972). Consequently, it is probable that the Sudbury Nickel Irruptive and Sudbury Basin were originally circular in plan, and owe their present shape to post-emplacement deformation. This deformation consists essentially of flattening accompanied by uplift and rotation of the southern part of the basin, by thrust (reverse dip-slip) movement on major faults which transect the basin and apparently dip steeply to moderately southward. Total cumulative displacement across the basin on these structures probably amounts to several thousand feet, if not several miles (Souch *et al.* 1969).



ODM9612

Photo 41—Sudbury breccia, Waters Township.

The trans-basin faults strike east-northeast at the western end of the basin, and west-northwest at the eastern end. It is not known if this change in trend is gradational or caused by superimposition of two different fault sets. A prominent zone of west-northwest faults has been traced from the Ottawa River through Lake Nipissing to the Grenville Front near Sudbury by Lumbers (1971a; 1971b; 1975). It is possible that the west-northwest faults which affect the Sudbury Structure represent the continuation of this system northwest of the Grenville Front Tectonic Zone.

In addition, north-northwest faults of the Onaping System displace both the northern and southern limbs of the Sudbury Nickel Irruptive as well as the rocks outside the basin, but no evidence for such faults is present in the Chelmsford Formation of the basin.

EXTRA-BASIN ROCKS

The rocks of the Superior and Southern Provinces surrounding the Sudbury Nickel Irruptive bear evidence of repeated deformation as outlined in the previous subsection, and in addition contain abundant bodies of Sudbury-type breccia (Photo 41), shatter cones (Photo 42) and microscopic shock metamorphic phenomena (Dence 1972) which are genetically associated with the formation of the structure. The Superior Province rocks in the north, mainly felsic plutonic



ODM9613

Photo 42—Shatter cone in micaceous sandstone of the Mississagi Formation, Waters Township.

rocks and high-rank migmatitic gneiss, contain ramifying dike swarms of pseudotachylite-type breccia consisting mainly of rounded, granitoid rock fragments in a dark coloured, very fine grained rock flour. The stratified metavolcanic, metasedimentary, and intrusive rocks of the Southern Province in the south part of the map-area also contain abundant Sudbury-type breccia bodies, again consisting dominantly of locally derived, rounded rock fragments in a recrystallized, dark coloured rock flour. These breccias are abundant in an area some 10 miles (16 km) wide surrounding the Sudbury Nickel Irruptive, and affect all rock units older than the Irruptive. The bulk chemical composition of the matrix materials corresponds closely to the average composition of the contained rock fragments indicating that the breccias were formed primarily by an "*in situ*" milling process, (Card 1968a; Speers 1957). Apparently the only significant additions were water and carbon. The presence of a few "exotic" fragments suggests transport of some material over longer distances. The occurrences of long, hairline seams

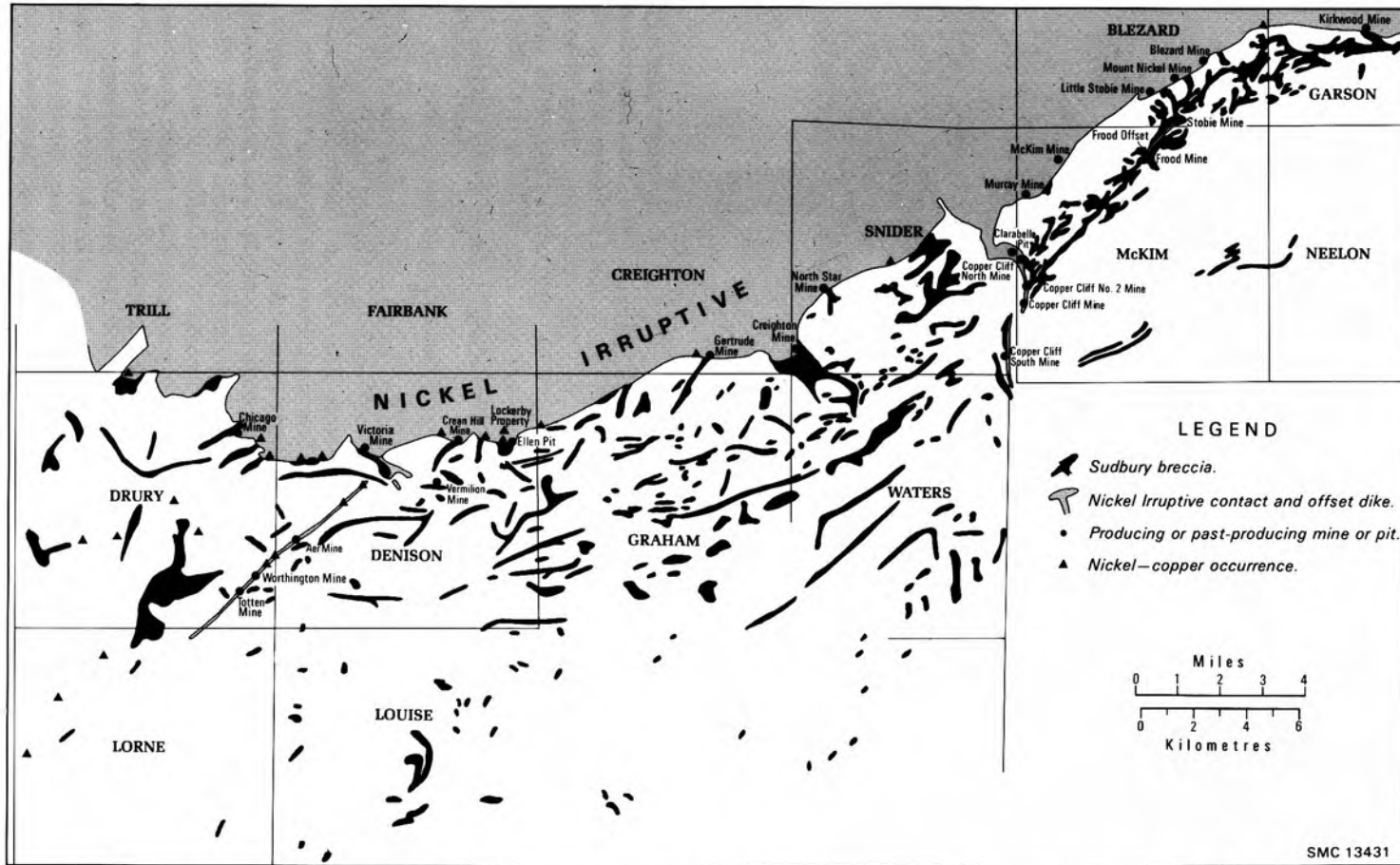


Figure 33—Generalized distribution of breccia zones about the South Range of the Sudbury Nickel Irruptive and the locations of sulphide deposits in the Sudbury-Manitoulin Area.

of breccia in massive rock units suggests a very forceful injection process. Breccias were formed after early major folding because some bodies display transgressive relationships to early fold structures in the country rocks and some breccia fragments contain older, rotated foliations. The breccias were affected by regional metamorphism and "secondary" deformation because their matrices display late foliations and are recrystallized. Distribution and trends of breccia bodies are notably irregular, but there is a suggestion of both radial and concentric patterns about the Sudbury Nickel Irruptive (Figure 33). Sudbury breccia may have influenced the emplacement of the Irruptive into the footwall rocks, because offset dikes or embayments of this intrusion into the country rocks commonly occur in areas where breccias are prevalent.

Shatter cones, curved, cone-shaped fracture surfaces with lineations which radiate outward from an apex, are abundant in approximately the same area as the breccias. Shatter cones appear in all rock-types older than the Sudbury Nickel Irruptive, but are best developed in micaceous metasandstone. Guy-Bray *et al.* (1966) concluded that, for the most part, the shatter cones point upward and inward toward the centre of the Sudbury Structure if the strata in which they occur are rotated back to the horizontal. However, the geometric relationship between bedding, cleavages, and shatter cone axes indicate that the country rocks had already been folded before imposition of the shatter cones, and were further deformed afterwards (Church, W.R., personal communication, 1973). These structural complexities will have to be taken into account before the true original orientations of the shatter cones can be deduced.

Microscopic phenomena, indicative of shock deformation, exist in the Onaping Formation and extra-basin rocks and include planar structures in quartz, deformation of plagioclase twin lamellae, and kink bands in biotite (French 1972).

ORIGIN OF THE SUDBURY STRUCTURE

The origin of the Sudbury Structure and its various elements has been and still is a matter for debate. Essentially there are two main theories:

1. The structure was formed by volcanic explosive processes with elevation of a large dome followed by caldera collapse, explosive volcanism, formation of the basin and its rocks, and brecciation of the surrounding country rocks. The Sudbury Nickel Irruptive represents a high-level intrusion emplaced somewhat later along the contact between the country rocks and the caldera fill, the Whitewater Group.
2. The impact of a large meteorite excavated a crater possibly some 100 miles (160 km) in diameter and brecciated and formed shatter cones in the country rocks. The Onaping Formation represents the "fallback breccia" produced by impact. Dietz (1972) concluded that at least part of the Nickel Irruptive was derived directly from the meteorite. Others, such as Guy-Bray (1972) and French (1972) considered the Sudbury Nickel Irruptive to be of endogenic origin, an intrusion from below triggered by impact.

Evidence for a meteorite impact origin includes the following: the probable original circular shape of the structure; the nature of the Onaping Formation

Sudbury-Manitoulin Area

which is similar to suevite breccias of known meteorite impact sites, the abundant Sudbury breccias and shatter cones; and the microscopic evidence for shock metamorphism. Arguments against a meteorite impact origin include the following: the relationships of the Sudbury Structure to major tectonic elements such as the Grenville Front; to major structures such as faults of the Murray and Onaping Systems; to magnetic-gravity anomalies indicative of larger scale crustal peculiarities; to pronounced facies variations in the adjacent Huronian rocks; and to regional orogenic events. These relationships indicate that the Sudbury Structure is an integral part of its regional setting in space and time, and is not simply the product of fortuitous meteorite impact at this particular site. For further discussion and information, the reader is referred to papers in Guy-Bray (1972).

GRENVILLE PROVINCE

Rocks of the Grenville Province within the map-area lie within the Grenville Front Tectonic Zone, the zone of contact between the Grenville and other provinces as defined by Lumbers (1975), (see Figure 2). These rocks consist mainly of gneissic metasedimentary and felsic plutonic rocks of Middle Precambrian age which suffered deformation and regional metamorphism during Middle and Late Precambrian orogenic events. The Grenville Front Tectonic Zone in this area is up to 20 miles (32 km), wide and is characterized by northeast-trending faults and mylonitic foliations, and southeast-plunging rodding lineations (Figure 32). The zone was also the locus of felsic and mafic intrusive activity during the Middle and Late Precambrian. Highly deformed and metamorphosed rocks of the Grenville Province are in juxtaposition with relatively little deformed and metamorphosed rocks of the Southern Province across this zone, and the Grenville Front Tectonic Zone structures transect earlier-formed structures in both the adjacent Grenville and Southern Provinces. Major deformation, essentially constriction of the relatively mobile Grenville Province sequence against the relatively rigid Southern Province block, culminated in the Late Precambrian before emplacement of late pegmatite dikes some 1000 million years ago (Lumbers 1971a; 1975).

Northwest Grenville Province

According to Lumbers (1971a; 1975), rocks of the northwestern part of the Grenville Province immediately east of the present map-area have experienced a complex history of repeated deformation, plutonism, and regional metamorphism, which culminated in the Late Precambrian some 1,200 million years ago with high rank regional metamorphism and intense deformation. A deformational-metamorphic history older than the Late Precambrian events is suggested by the plutonic history, complex fold patterns in the gneiss, and radiometric age determinations by Davis *et al.* (1970) that indicate metamorphism of the Grenville gneiss about 1800 ± 100 million years ago. Quirke and Collins

(1930) concluded that the gneissic metasediments of the northwestern Grenville Province are the lithostratigraphic equivalents of the Southern Province Huronian sequence, a conclusion generally supported by later workers such as Lumbers (1968; 1975) and Frarey and Cannon (1969).

The Grenville Province metasediments show gneissic stratiform foliation which probably reflects original stratification. Folds in this stratiform foliation are passive flow folds, many of which are inclined to recumbent. The folds form complicated dome and basin structures that to the south of the map-area have north-trending axes.

Felsic plutonic rocks commonly occupy the core zone of dome and basin structure in the country rocks. Foliation in both the intrusions and surrounding metasediments are concordant, indicating that the country rocks and intrusions underwent a similar tectonic history. Northeast- and west- to northwest-trending faults of Late Precambrian to Early Paleozoic age are present and mafic stocks, diabase, and lamprophyre dikes were emplaced in connection with this late fault activity. The west to northwest faults have had a long, complicated history of movement during the Middle to Late Precambrian and Early Paleozoic. The faults apparently continue across the Grenville Front Tectonic Zone into the Southern Province and are part of a system of graben faults which extends eastward through the Lake Nipissing area to join the Ottawa-Bonnechere graben system (Lumbers 1971a). In addition, Lumbers (1975) has described a north-northwest-trending fault, the Murdock River Fault, which has the same trend as the Onaping Faults to the north and is apparently interrupted by the Grenville Front Tectonic Zone. Lumbers suggested that the Murdock River Fault represents reactivation of an older zone of faulting of the Onaping System.

Grenville Front Tectonic Zone

As the Grenville Tectonic Zone is approached from the south, foliation and fold trends in the Grenville Province rocks change from northwest to northeast, foliations steepen, and southeast-plunging lineations become prominent. Across this zone, which in this area is up to 20 miles (36 km) wide, the dominant northeast-trending cataclastic-mylonitic foliations become steeper, as do the southeast-plunging rodding lineations. Near the northwestern margin of the Grenville Front Tectonic Zone, high rank metamorphic gneisses of the Grenville Province are in fault contact with lower rank metamorphic rocks of the Southern Province along a fault zone, the Grenville Front Boundary Fault (Lumbers 1971b). Non-penetrative northeast-trending macroscopic cataclasis and mylonitization extend up to several miles into the Southern Province northwest of the Boundary Fault (Card 1976b; Lumbers 1975), (Figure 32).

The Grenville Front Boundary Fault is a northeast-trending zone of extreme cataclasis and mylonitization up to 100 feet (30 m) wide which probably dips steeply southeastward (Lumbers 1971a; 1975). The Boundary Fault is offset by late movements on some east-west faults, but other structures such as the Creighton and Murray Faults appear to be truncated at the Grenville Front Tectonic Zone. Foliations and lineations steepen near the Boundary Fault, but total relative displacement on this structure is probably not great.

The Boundary Fault is apparently a zone of constriction along which there has been relatively little displacement. The Boundary Fault probably follows an older dislocation initiated early in the tectonic history of the area.

Although major deformation along the Grenville Front Tectonic Zone culminated after the Late Precambrian high rank metamorphism between 1,200 and 1,400 million years ago, evidence exists that this zone has had a long, complex history possibly extending back into the early Middle Precambrian. Facies and thickness changes in the metasedimentary sequences across this zone indicate that it may have influenced early Middle Precambrian sedimentation (Card *et al.* 1975; Lumbers 1975). The Grenville Front Tectonic Zone approximately marks the boundary between a wedge of coarse, miogeosynclinal-type clastic sediments to the northwest, the Huronian Supergroup, and a trough of eugeosynclinal-type sediments to the southeast. The Grenville Front Tectonic Zone was tectonically active during Middle Precambrian orogenic events that affected both the Southern Province and Grenville Province rocks. Dalziel *et al.* (1969) have presented evidence for such deformation. The Front Zone was also the locus of felsic plutonic activity during the Middle Precambrian with emplacement of the Grenville Front Plutons 1,600 to 1,730 million years ago. Deformation of the rocks of this zone occurred during and after the Late Precambrian regional metamorphism and deformation which affected the Grenville Province some 1,200 to 1,400 million years ago (Lumbers 1975).

METAMORPHISM

The rocks of the Sudbury-Manitoulin map-area, with the exception of some late intrusions in the Southern and Grenville Provinces, have suffered mineralogical and textural alteration of varying degrees of intensity during regional metamorphic events ranging in age from Early to Late Precambrian. In addition, rocks in the thermal aureoles of some intrusions have been contact metamorphosed.

SUPERIOR PROVINCE

In the Superior Province, high rank regional metamorphism occurred during the Early Precambrian before or accompanying emplacement of the felsic plutonic rocks of the Birch Lake Batholith. This metamorphism, probably corresponding to the amphibolite facies of regional metamorphism for the most part, resulted in the formation of hybrid, migmatitic gneiss which represents metamorphosed, metasomatized sedimentary and volcanic rocks. Locally there is evidence, in the form of orthopyroxene-bearing gneiss, that this metamorphism attained granulite facies pressure-temperature conditions (Card and Meyn 1969). Retrograde metamorphic effects, mainly saussuritization of plagioclase and chloritization of feric minerals, are prevalent in the gneiss and younger felsic plutonic rocks, and are probably attributable to Middle Precambrian metamorphism.

SOUTHERN PROVINCE

The northern part of the Sudbury Nickel Irruptive and adjacent rocks of the Whitewater Group are relatively fresh and unaltered. In the south, these rock units show the effects of low rank regional metamorphism corresponding to low greenschist facies (chlorite and biotite grades) conditions. Alteration of the calcic plagioclase to albite and epidote, of pyroxene to amphiboles, and of amphiboles to chlorite is prevalent in the South Range of the Sudbury Nickel Irruptive. Chlorite, biotite, and rarely, garnet porphyroblasts are present in the rocks of the Whitewater Group. The southern parts of the Sudbury Nickel Irruptive and the Whitewater Group may have been affected by the same prograde metamorphism that affected the Huronian rocks. It is more likely, however, that metamorphism of these units occurred during a later event that produced widespread retrograde metamorphic effects in the Huronian rocks in this area.

Huronian rocks and Nipissing Diabase Intrusions of the Southern Province were affected by low to middle rank regional metamorphism during the Middle Precambrian. Typical index minerals include the following: chlorite, biotite, garnet, chloritoid, andalusite, and staurolite in pelitic metasediments; scapolite, tremolite, hornblende, and diopside in calcareous metasediments; and actinolite, hornblende, and garnet in mafic meta-igneous rocks. Metamorphic mineral assemblages demonstrate that metamorphic grade ranged from low greenschist to low amphibolite facies conditions (Card 1964), (Figure 34). Albitic plagioclase is present in lower and middle greenschist facies pelitic rocks, but its place is taken by more calcic plagioclase in the upper greenschist and lower amphibolite facies. Staurolite and andalusite coexist, indicating that the pressure-temperature conditions correspond for the most part to the low pressure-intermediate type of regional metamorphism as defined by Miyashiro (1961). The local occurrence of chloritoid and kyanite may indicate local higher pressure conditions. Fox (1971) estimated that the chloritoid-staurolite transition, which here marks the change from greenschist facies to amphibolite facies conditions, occurred at temperatures of 500 to 550°C and pressures of 4.45 to 4.75 kilobars.

Aluminous metasandstone of the Lorrain Formation in the McGregor Bay area contains kaolinite which fills interstices between quartz grains and occurs as thin bedding-plane partings. The kaolinite is probably partly of sedimentary origin, and is partly the result of *in situ* alteration of detrital feldspar. Metamorphism of the sandstone has resulted in the formation of a variety of aluminosilicate minerals, including pyrophyllite, kyanite, and andalusite. Church (1967) concluded that the kyanite was formed during early dynamothermal metamorphism under high pressure conditions existing in the axial zones of major fold structures. He also postulated that andalusite formed later, after relaxation of the tectonic stresses at the same time as post-kinematic biotite-garnet assemblages were formed in nearby pelitic rocks. However, the author's observations, such as undeformed intergrowths of kyanite and andalusite, indicate that these minerals formed simultaneously. Also, judging from the mineral assemblages in the nearby pelitic rocks, these minerals formed under regional metamorphic conditions no higher than the upper greenschist facies. Possibly, these aluminous minerals owe their origin to a combination of a reactive starting material (kaolinite) and local high pressure conditions produced by tight folding of a massive sandstone unit.



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Photo 43—Scapolite porphyroblasts developed in interbedded calcareous siltstone and silty limestone of the Espanola Formation, Truman Township.

Scapolite is regionally developed in calcareous metasediments of the Espanola Formation along with minerals such as muscovite, biotite, phlogopite, and tremolite-actinolite (Photo 43). The scapolite examined optically is sodic (marialite-rich). Chemical analyses show that scapolite-rich calcareous metasilstone and marble contain appreciably more Na_2O than do similar but non-scapolitic rocks (Card 1976a). The Na_2O required for scapolite formation may have been present in the rocks originally in the form of sodic minerals such as halite or may have been metasomatically introduced by gabbroic intrusions.

Although textural evidence exists for several generations of metamorphic porphyroblasts and for growth, reorientation, or destruction of metamorphic minerals during each of the several deformational events described previously, the high grade assemblages are apparently in equilibrium, and were probably formed during one thermal metamorphic episode. Textural evidence exists for prekinematic, synkinematic, and postkinematic growth of porphyroblasts of minerals such as garnet and staurolite with respect to deformation structures and implies a relatively close connection in time between regional metamorphism and secondary deformation. There is also great variation in the degree of development of secondary structures and textures. In many localities, growth of porphyroblasts occurred under relatively static conditions resulting in the formation of a hornfels texture and in the preservation of pre-existing structures and textures.

In detail, the distribution of metamorphic isograds and metamorphic mineral assemblages is notably irregular. The generalized distribution of metamorphic zones portrayed in Figure 34 shows that there are two northeast-trending belts of higher grade metamorphism with rocks in the upper greenschist and lower amphibolite facies superimposed on a lower grade terrane with rocks in the lower to mid-greenschist facies. The areas of highest metamorphic grade have the form of elliptical "nodes" similar to those described by James (1955) in the western part of the Penokean Belt.

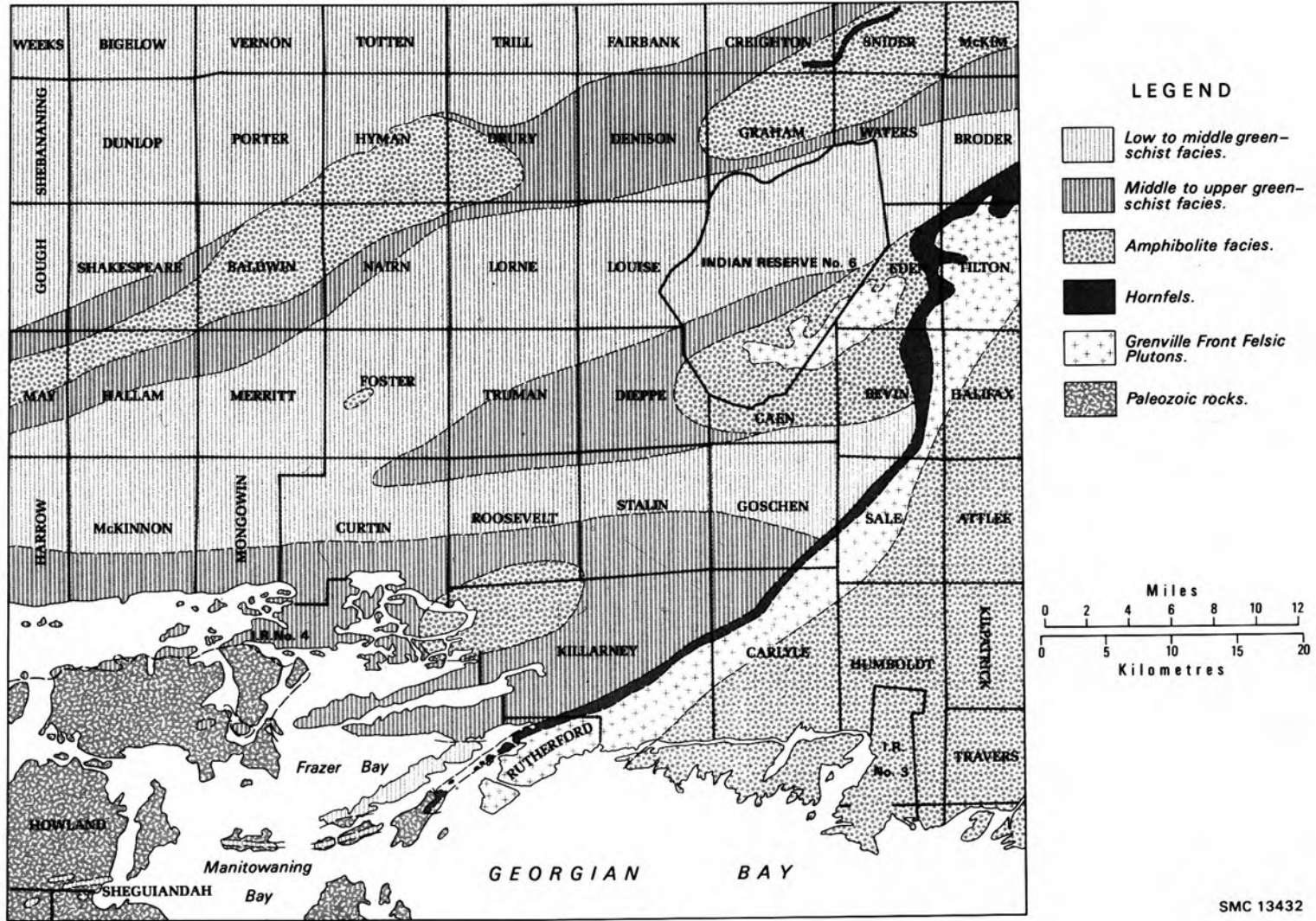
General correspondence is evident between areas of higher grade metamorphism, relatively intense deformation, and felsic plutonic activity. The higher grade zones are elongated parallel to the structural trends, and occur along the axis of the Baldwin Anticlinorium and adjacent to the Grenville Front Tectonic Zone, both areas of relatively intense deformation and felsic intrusion. However, in detail, these relationships are not straightforward. Metamorphic isograds apparently transect fold structures and the felsic plutons present are either pre-metamorphic (Creighton Pluton) or post-metamorphic (Grenville Front Plutons). As far as can be determined, metamorphic isograds are probably steeply dipping, and geothermal gradients were apparently high. The high grade "nodes" may represent zones of active upward heat transfer, possibly effected by rising hot fluids.

Contact metamorphic effects are present in narrow zones about some of the Nipissing Diabase Intrusions, although later regional metamorphism has largely masked the characteristics of this alteration. Metasomatic effects are still discernible and include migration of magnesia, iron, and soda from the intrusions into the country rocks to form narrow metasomatic aureoles rich in minerals such as chlorite, amphibole, and iron oxides. Migration of elements such as silicon, potassium, and aluminium from the country rocks into the intrusions has also occurred, resulting in narrow contaminated border zones rich in muscovite and garnet. Narrow contact metamorphic aureoles are present about the Eden Lake Intrusions and the Grenville Front Tectonic Zone felsic plutons have produced a contact metamorphic aureole in the adjacent Huronian rocks which is up to one-half mile (0.8 km) in outcrop width (Figure 34). Pelitic metasediments of these aureoles display excellent "spotted hornfels" texture and contain chlorite, biotite, andalusite, and cordierite porphyroblasts. This metamorphism occurred under conditions corresponding to the hornblende-hornfels facies of contact metamorphism and is superimposed on previously regionally metamorphosed rocks.

GRENVILLE PROVINCE

According to Lumbers (1975), the rocks of the Grenville Province have experienced a complex history of deformation, plutonism, and metamorphism during the Middle and Late Precambrian. Regional metamorphism, contact metamorphism, and local granitization probably accompanied emplacement of the Middle Precambrian felsic plutons. However, major regional metamorphism here during the Late Precambrian has largely obscured the effects of this earlier event.

Late Precambrian high rank regional metamorphism of the rocks of the



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Figure 34—Generalized distribution of metamorphic zones in the Sudbury-Manitoulin Area.

Grenville Province and Grenville Front Tectonic Zone occurred under high temperature-moderate pressure conditions, probably at temperatures of 600°C to 700°C and pressures of 8 to 9 kilobars (Winkler 1967) to produce rocks with mineral assemblages indicative of the staurolite-almandine and sillimanite-almandine-orthoclase subfacies of the almandine-amphibolite facies (Lumbers 1975). Typical index minerals include garnet, staurolite, orthoclase, sillimanite, and kyanite. Lumbers also concluded that these mineral assemblages were not developed simply as a consequence of deep burial because the available geological evidence does not permit this interpretation, but that metamorphism occurred under moderate depth conditions and a high geothermal gradient with the pressures necessary being tectonically induced. Geochronologic data indicate that this metamorphism culminated between 1,200 and 1,400 million years ago (Lumbers 1971b). Retrograde metamorphism accompanied still later movement along the Grenville Front Tectonic Zone resulting in alteration of metamorphic mineral assemblages here, as well as in the adjacent Southern Province.

SUMMARY

In summary, Early Precambrian metamorphism in the Superior Province and Late Precambrian metamorphism in the Grenville Province occurred under conditions of relatively uniform moderate to high pressure (approximately 7 to 9 kilobars) and temperatures approximately 600°C to 800°C corresponding to the amphibolite and pyroxene-granulite facies of the kyanite-sillimanite facies series of Miyashiro (1961).

Middle Precambrian metamorphic rocks of the Southern Province contain the mixture of mineralogical characteristics of low pressure and high pressure facies series typical of the low pressure-intermediate facies of Miyashiro (1961). Pressure and temperature of metamorphism were probably in the range of 4 to 5 kilobars and 300°C to 550°C. Metamorphism in the Southern Province was notably irregular in space and time. This implies irregular distribution of thermal energy and complex, overlapping relationships between deformation and metamorphism.

OROGENIC HISTORY

Deformation and high rank regional metamorphism in the Superior Province occurred during the Early Precambrian, and were accompanied and succeeded by emplacement of granitic plutons some 2,500 m.y. or more ago. These events have been collectively referred to as the "Kenoran Orogeny" (Stockwell *et al.* 1970).

During the early part of the Middle Precambrian, normal faulting and crustal downwarping led to the formation of graben-style basins. This activity was accompanied by emplacement of mafic dike swarms, gabbro-anorthosite plutons, outpouring of mafic and felsic volcanic rocks, and deposition of the Huronian clastic sedimentary rocks. Tectonic activity, probably mainly sporadic move-

ments on faults and crustal warping, continued during deposition of the Huronian sequence, producing further basining as well as features such as slump structures, clastic dikes, and gravity slides in the Huronian. Uplift of the Early Precambrian terrane in the north provided a continuing supply of coarse detritus.

Compressive tectonism accompanied by low to middle rank regional metamorphism and igneous intrusive activity occurred in this part of the Southern Province in the Middle Precambrian. Variations in structural style, essentially relatively intense folding and flattening in the northern and southern parts of the area, and mild deformation in the central parts, imply that the mechanism of deformation was essentially active thrusting of the Huronian cover rocks northward against the relatively rigid Superior Province block. Assuming that the main foliations in the Southern Province rocks developed approximately normal to the direction of greatest finite shortening, and that the main, steeply plunging lineation present in the foliation planes developed parallel to the direction of greatest finite extension, then the axis of maximum shortening was subhorizontal and oriented north-south to northwest-southeast. The axis of maximum extension of the finite-strain ellipse was plunging steeply south to southeast. The foregoing assumption, although probably approximately valid, is open to question (Schwerdtner 1973).

Deformation of the Huronian strata was accomplished mainly by buckling, flattening, and shearing during several deformational stages or events. Early folding, probably accompanied by faulting and low rank regional metamorphism, was initiated before emplacement of the Nipissing Diabase Intrusions some 2,160 m.y. ago. Emplacement of Nipissing Diabase Intrusions was controlled in part by pre-existing structures and competency variation in lithological units. Particular rock units, notably the massive conglomeratic formations, were favoured locii of emplacement, presumably because of their rheological behaviour during deformation. However, in detail Nipissing Diabase Intrusions are transgressive toward early formed structural trends and locally, as in the McGregor Bay Anticline and the Vernon Syncline, cut across major fold axes. Sudbury breccia bodies also exhibit a transgressive relationship to the early structures, indicating that the "Sudbury event" occurred after the early deformation.

Following emplacement of the Nipissing Intrusions, tectonic compression led to further deformation of the Huronian strata, as well as the Nipissing Intrusions, and probably also at this time, the Sudbury Nickel Irruptive and White-water Group. Crystallization of metamorphic minerals such as biotite, garnet, and staurolite began at this time. Growth of metamorphic minerals accompanied and outlasted deformation. In some areas, notably around Agnew Lake, there is textural evidence for syntectonic and post-tectonic growth of porphyroblasts. Other events, including late fault movements, formation of strain-slip cleavages and kink bands, and retrograde alteration of metamorphic minerals, are relatively late phenomena possibly connected with Middle and Late Precambrian orogenic activity in the nearby Grenville Province. Some may also be associated with a "cryptic thermal event" which is revealed by Rb-Sr mineral ages in the range 1,300 to 1,400 m.y. in the area about Sudbury and elsewhere in the Southern Province (Fairbairn *et al.* 1969).

The available geological and radiometric age data indicate that the main deformation of the Southern Province rocks began before emplacement of the Nip-

issing Diabase some 2,160 m.y. ago and culminated before the emplacement of the Grenville Front granitic plutons some 1,590 to 1,730 m.y. ago. Metamorphosed Huronian rocks in the area commonly yield Rb-Sr whole rock dates in the range 1,600 to 1,800 m.y., the commonly accepted age of the "Hudsonian Orogeny" (Stockwell *et al.* 1970) and of the "Penokean Orogeny" (Goldich 1968). However, older Rb-Sr dates have been recorded for metamorphosed Huronian rocks (Fairbairn *et al.* 1969; Krogh and Davis 1969), and younger Rb-Sr and K-Ar mineral and whole rock dates are prevalent. Cannon (1973) has presented evidence that the Penokean Orogeny culminated at least 1,900 m.y. ago in the type areas of northern Michigan. In view of these conflicting "ages" and also the evidence that deformation began prior to 2,160 m.y. ago, correlation of the various deformational-metamorphic events here with the "Penokean Orogeny" of the "Hudsonian Orogeny" remains an unresolved problem.

Similarly, the two main phases of deformation recognized may represent episodes of a single, protracted orogenic event, or may represent two distinct events separated by an interval of several hundred million years. The available evidence indicates the possibility of two events separated by an appreciable time interval, the first occurring about 2,200 m.y. ago, the second about 1,700 to 1,800 m.y. The latter event was possibly penecontemporaneous with Middle Precambrian orogenesis in the adjacent Grenville Province.

Rocks of the Grenville Province, especially those of the Grenville Front Tectonic Zone, have a long history of deformation, regional metamorphism, and igneous intrusion which probably began in the early part of the Middle Precambrian with faulting, crustal downwarping, and deposition of a thick sequence of clastic sediments. There is evidence for Middle Precambrian deformation and regional metamorphism and emplacement of granitic plutons some 1,600 to 1,800 m.y. ago (Krogh *et al.* 1971). However, most of the deformational and high rank regional metamorphic effects displayed by these rocks is attributable to Late Precambrian orogenesis which occurred 1,200 to 1,400 m.y. ago (Lumbers 1975).

The tectonic fabric of the rocks of the Grenville Front Tectonic Zone indicates that deformation occurred under compressive conditions, which essentially consisted of northward thrusting of the relatively mobile Grenville Province sequence against the more rigid Southern Province block with the axis of maximum shortening being subhorizontal and directed northwest-southeast, and the axis of maximum extension plunging southeast. Major deformation along the Grenville Front Zone apparently culminated after Late Precambrian high rank metamorphism in the Grenville Province 1,200 to 1,400 m.y. ago and before emplacement of late pegmatite dikes 1,000 m.y. ago (Lumbers 1971a; 1975). Evidence for later, Late Precambrian to Early Paleozoic igneous activity and faulting probably related to the Ottawa-Bonnechere graben system, was recorded in the general area by Lumbers (1975).

GEOPHYSICAL CHARACTERISTICS

The general magnetic trends as shown on Geological Survey of Canada Aeromagnetic Maps 7067G, Sudbury (GSC 1965c), or Ontario Division of Mines-Ge-

ological Survey of Canada Map P-800 (ODM-GSC 1972) follow the regional structural-stratigraphic trends in the Grenville gneiss and Huronian metasediments for the most part. Several Huronian lithostratigraphic units, notably in the Gowganda and Gordon Lake Formations, have weak positive magnetic expressions attributable to the presence of detrital magnetite. The Sudbury Nickel Irruptive, the Mongowin Pluton, and the late northwest-striking diabase dikes all give rise to positive magnetic anomalies of appreciable amplitude that are attributable to the presence of magnetite in these rocks. Nipissing Diabase Intrusions have variable, generally weak positive or negative responses that are probably dependent on their oxide mineralogy. Diabase intrusions with magnetite have weak positive expression; diabase intrusions with ilmenite-magnetite intergrowths and solid solution phases are neutral or weakly negative.

The contact between the Superior and Southern Provinces is not geophysically expressed. In contrast, the contact between the Southern and Grenville Provinces, the Grenville Front Tectonic Zone, is expressed by a linear, northeast-trending belt of positive magnetic anomalies and by truncation of weaker east-west and northwest-trending anomalies associated with rock units in the Southern Province.

Gravity measurements (Popelar 1971; 1972) reveal the presence of positive gravity anomalies associated with the Sudbury Nickel Irruptive, gabbro-anorthosite plutons, and thick sequences of Huronian mafic volcanic rocks in the Sudbury area, and with anorthosite intrusions in the adjacent Grenville Province. A positive gravity-magnetic anomaly of relatively high intensity extends from the Sudbury area northeastward toward Lake Temagami. The origin of this anomaly is unknown, but it is apparently attributable to a dense magnetic body at a depth of no more than a few kilometres (Card *et al.* 1972). A gravity low extends along the North Shore of Lake Huron to the Grenville Front, and corresponds to the thickest part of the Huronian section. The anomaly apparently continues eastward across to the Grenville Front Tectonic Zone where it reflects the existence of a thick accumulation of supracrustal rocks in a northeast-trending trough south of the Front Zone. A circular gravity low of moderate intensity is situated over Lake Wanapitei northeast of the present map-area. Dence and Popelar (1972) have interpreted the Lake Wanapitei structure as a meteorite impact site.

Little is known about the deep crustal structure in this region. Seismic data reveal the presence of a band of low delay times that approximately coincides with the belt of gravity-magnetic anomalies in the Sudbury area and northeastward. This phenomena may be caused by a relatively thin crust, or by a slightly anomalous upper mantle structure (Card *et al.* 1972).

ECONOMIC GEOLOGY

The Sudbury-Manitoulin area includes part of the Sudbury Nickel Irruptive, an intrusion noted for its rich deposits of nickel-copper sulphide minerals. Such mines as the Creighton, Crean Hill, Victoria, Totten, and Worthington Mines are located at the base of the Sudbury Nickel Irruptive or on the Copper Cliff and Worthington Offsets within the map-area. There are also deposits of

base-metal sulphide minerals and gold associated with other mafic igneous rock units and silicified shear zones, uranium mineralization of the Elliot Lake-type in lower Huronian rocks, and tungsten in highly metamorphosed rocks of the Espanola Formation. Non-metallic mineral deposits of importance are present, notably high-quality silica in the upper part of the Huronian sequence. The most noteworthy known mineral deposits of the map-area are shown in Figure 35 (Chart A, back pocket).

In the following, an attempt shall be made to describe the metallogenesis of the area, rather than to describe individual mineral deposits. Further information on specific deposits or topics can be obtained from the references quoted in the text.

Regional metallogenic studies, for example the one carried out by Dupuis (1972) in the Sudbury District, represent attempts to establish patterns in the types and distribution of mineral deposits present, and in turn to attempt to relate these patterns to structural and lithological elements. Such studies are valuable in establishing the genesis of mineral deposits, and in identification of favourable areas for further exploration. In the present map-area a clear spatial relationship exists between base-metal sulphide deposits and particular rock units such as the Sudbury Nickel Irruptive and the Nipissing Diabase. Spatial relationships imply genetic relationships. Similarly, these intrusions are spatially, and probably genetically, related to major regional structural features such as faults and the Grenville Front Tectonic Zone. The implication is that major zones of crustal instability have been the focus of repeated deformation, regional metamorphism, igneous activity, and related metallization over protracted periods of earth history. The igneous rocks and their mineral deposits were probably ultimately derived from subcrustal sources, and are phenomena associated with the cooling and degassing of the earth.

COPPER

Base-metal sulphide deposits containing copper, and, commonly some nickel, are associated with the Huronian rocks, with the Nipissing Diabase, and with other post-Huronian mafic intrusions.

Copper sulphide mineralization in Huronian sedimentary rocks consists mainly of pyrite and chalcopyrite, although several deposits have appreciable amounts of cubanite, pyrrhotite, bornite, and hematite. These minerals occur as disseminations and massive lenses in quartz and quartz-carbonate veins in shear zones, and as disseminations in brecciated and silicified zones near faults. Minor amounts, less than 10 percent of pyrite and pyrrhotite with lesser but variable amounts of chalcopyrite are commonly present as stratabound disseminations in rocks of the Bruce and Espanola Formations.

The volcanic-sedimentary sequences in the lower part of the Huronian Supergroup, notably the Stobie and Salmay Lake Formations, contain appreciable amounts of pyrrhotite, pyrite, and chalcopyrite as stratabound disseminations, notably at the contacts between mafic volcanic flows and overlying sedimentary rocks. Innes (1972) concluded that these sulphide minerals were formed by volcanic exhalative processes involving sulphide-oxide-silicate reactions. Concentra-

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tions of sulphide minerals occur in quartz veins, silicified zones, shear zones, and brecciated zones in the metavolcanic-metasedimentary sequences.

Copper, commonly accompanied by nickel, occurs as disseminations and pods in metamorphosed Nipissing Diabase Intrusions at numerous localities, for example in Shakespeare (Card and Palonen 1976), Nairn (Ginn 1965), and Curtin (Card 1976a) Townships. The sulphide minerals, mainly pyrrhotite and chalcopyrite with minor pentlandite, are closely associated with granophyre-rich phases of the diabase. It has been suggested that some of the sulphide mineralization associated with the Nipissing Diabase Intrusions was formed by sulphurization processes during regional metamorphism (Card and Pattison 1973). Minor amounts of copper-nickel sulphide mineralization also occur as disseminations and pods in ultramafic rocks of the Mongowin Pluton (Card 1968b).

LEAD AND ZINC

Minor galena and sphalerite, commonly with minor amounts of pyrite, pyrrhotite, and chalcopyrite, occur as disseminations in quartz-carbonate veins associated with Nipissing Diabase Intrusions.

In Lorne Township, massive sphalerite with minor chalcopyrite, pyrite, and pyrrhotite occur in a carbonate replacement zone in impure sandstone and siltstone of the Pecors Formation (Ginn 1965). The deposit is spatially associated with a northeast-trending fault zone.

GOLD

Gold, generally with minor silver, is associated with arsenopyrite and pyrite in veins and silicified zones in Huronian rocks. In the southern part of the map-area, there is a prominent belt of gold deposits which are spatially associated with rocks of the Gowganda Formation and with mafic intrusive rocks (Figure 35). Gold, accompanied by arsenopyrite and pyrite, occurs in quartz and quartz-carbonate veins in interbedded impure sandstone and siltstone in the upper half of the Gowganda Formation. Many deposits, for example the Bousquet Mine in Curtin Township, are located at or near the contact of an approximately conformable Nipissing Diabase Intrusion. Others, for example the McMillan Mine in Mongowin Township, are more closely related in space to northwest-trending metagabbro dikes. Gold valued at \$163,528 and \$97,357 was produced from the Bousquet and McMillan Mines respectively during the 1930s (Card 1968c).

Gold, in association with arsenopyrite and pyrite, occurs in silicified meta-sandstone of the Mississagi Formation at the Long Lake Mine in Eden Township near the Grenville Front Tectonic Zone. The metasediments are extensively intruded in this area by Nipissing Diabase and by Eden Lake trondhjemite and diorite. Gold valued at \$1,352,164 was produced from the mine from 1909 to 1937 (Card *et al.* 1975).

At the Shakespeare Mine, Shakespeare Township, gold occurs in association with arsenopyrite and pyrite in quartz veins in sheared metasandstone of the Matinenda Formation. There are intercalations of mafic metavolcanics and numerous mafic intrusions in this area which is immediately south of the Murray Fault. Gold valued at \$38,237 was produced from this deposit during the period 1905 to 1907 (Card and Palonen 1976).

Noteworthy amounts of gold were recovered from the Vermilion Mine in Denison Township. Nickel and copper sulphide minerals, mainly pyrrhotite, pentlandite, and chalcopyrite, as well as native gold and platinum-bearing minerals such as sperrylite, are associated with mafic metavolcanic and intrusive rocks. The mafic intrusive rocks possibly represent an "offset" of the nearby Sudbury Nickel Irruptive. This deposit could be genetically related to the Sudbury Nickel Irruptive or to the Huronian volcanic sequence.

NICKEL

Nickel, intimately associated with copper, occurs in Nipissing Diabase Intrusions, in the Mongowin Pluton, in vein deposits in Huronian rocks at the Wallace Mine on the North Shore of Lake Huron, and most notably, in association with the Sudbury Nickel Irruptive and its offsets.

The Sudbury ore deposits were discovered in 1883 during construction of the Canadian Pacific trans-continental railway line, and since that time have yielded some \$12,000,000,000 worth of nickel, copper, cobalt, selenium, tellurium, platinum metals, gold, silver, iron ore, and sulphur. Some 15 mines are currently in production. The sulphide ores form part of the "sub-layer", a discontinuous layer of inclusion-bearing igneous intrusions which forms a distinct lower unit of the Sudbury Nickel Irruptive and the offset dikes. The massive to disseminated sulphide minerals are mainly pyrrhotite, pentlandite, and chalcopyrite, with minor cubanite, gersdorffite, niccolite, maucherite, and marcasite, pyrite, violarite, galena, and sphalerite. For more detailed descriptions of the ore the reader is referred to the excellent treatise of Hawley (1962).

IRON

Minor amounts of magnetite with a peculiar radiating, botryoidal structure occur in association with calcite and serpentine in altered ultramafic rocks of the Mongowin Pluton (Card 1968b).

Hematite of probable sedimentary origin occurs in the upper part of the Huronian sequence, notably in siltstone and sandstone of the Bar River Formation where it constitutes up to 15 percent by volume of some beds. This lean "iron formation" has little or no economic significance, but it does have metallogenetic significance in that it bears some resemblance to the "Michigan-type" sedimentary iron formation of the western part of the Southern Province.

TUNGSTEN

Tungsten mineralization in Foster Township is located in highly metamorphosed calcareous rocks of the Espanola Formation which have been brecciated, faulted, and silicified (Card 1968c). Several mafic intrusions are present in the general area. Scheelite and powellite, as well as minor but variable amounts of pyrrhotite, chalcopyrite, molybdenite, sphalerite, and arsenopyrite occur as disseminations and veinlets in quartz veins and in the metamorphosed country rocks which also contain garnet, idocrase, diopside, and wollastonite porphyroblasts. The mineralization, and the skarn-type metamorphism of the country rocks, are similar to that found about the felsic intrusions, but no such bodies are exposed in this area. Exploration by Texasgulf Incorporated and Cerro Mining Company of Canada Limited outlined numerous erratically distributed zones of mineralization which upon assay yielded up to about 0.5 percent WO_3 , 0.27 percent MoS_2 , 0.29 percent Cu, and 0.36 ounce Ag per ton (Resident Geologist's Files, Ontario Ministry of Natural Resources, Sudbury).

URANIUM

Elliot Lake-type uranium mineralization is present at a number of localities in rocks of the Matinenda Formation. Mineralization occurs mainly in oligomictic quartz-pebble conglomerate lenses on, or a few hundred feet above the Ep-Archean unconformity. The conglomerate is similar to that of the Elliot Lake area, consisting of rounded quartz pebbles in a coarse, pyritic, sandstone matrix. In general however, the uranium-bearing conglomerate from the map-area is not as well sorted or packed, the pyrite and uranium contents are lower, and the thorium-uranium ratio is higher than in the Elliot Lake ores. The conglomerate here also shows the effects of relatively intense deformation and regional metamorphism in the form of pebble flattening, foliations, steeply inclined bedding, and mineralogical alteration. Uranium- and thorium-bearing minerals present include uraninite, "uranothorite", "brannerite", monazite, and thorite. Alteration products, including thucholite and uranium-bearing aggregates resembling leucoxene, are prevalent. The most noteworthy deposit of this type in the map-area is the Agnew Lake Mine in Hyman Township where drilling and underground exploration has outlined some 2,500,000 tons of material averaging 2.10 pounds U_3O_8 per ton, plus 4,400,000 tons averaging 1.53 pounds, and 1,400,000 tons averaging 2.27 pounds per ton in several zones to a vertical depth of 3,500 feet (1070 m) (Canadian Mines Handbook, 1972-3, p.20).

The origin of the uranium mineralization which shows strong sedimentary control, and is consequently of probable syngenetic origin, is a matter of debate. The currently prevailing concepts are that the uranium-bearing conglomerates are stream-channel deposits localized by paleotopographic features near the northern paleolimit of the Matinenda Formation, and that the uranium minerals are of detrital origin, owing their survival to anoxygenic atmospheric conditions (Roscoe 1969). Exploration for additional uranium deposits based on the foregoing concepts has not been particularly rewarding. It is possible that the ura-

niium minerals are non-detrital, that the uraniferous conglomerates are marine deltaic rather than alluvial deposits, and that paleotopography exerted little control over deposition (Bottrill 1970). Recent work by Rupert *et al.* (1972) has demonstrated that there are no marked depressions in the basement surface beneath the main ore zones at Elliot Lake.

A factor which many of the Elliot Lake-type deposits have in common is an association with volcanic rocks. Roscoe (1969) viewed this association as one of sedimentary control with the volcanic accumulations representing topographic obstacles to streams depositing the Matinenda gravels. Bottrill (1970) suggested that volcanism exerted a chemical control, providing the proper conditions for precipitation of uranium from uranium-bearing waters. It is evident in the Sudbury-Manitoulin area that uranium-bearing sediments were deposited about the margins of volcanic accumulations while volcanism proceeded. There may well be a genetic connection between volcanism and uranium mineralization. The presence of abundant pyrite both in the uraniferous sediments and in the volcanic sequences may represent a connecting link.

If the uraniferous conglomerates at the base of the Huronian represent marine deltaic rather than alluvial stream channel deposits, concentrations of such sediments might be expected in areas somewhat removed from the mouths of paleostreams which emptied into the basin. The blankets would be "offshore" and "along shore" in the direction of long-shore current drift. Northwest-trending faults of the Onaping System, which probably originated in pre-Huronian time, may have constituted such paleostream channels. In the Sudbury-Manitoulin map-area, the embayment of Huronian rocks in Porter and Vernon Townships may represent a paleovalley. It is perhaps significant that uranium-bearing sediments occur both southeast and southwest of this structure.

SILICA

Lump silica for metallurgical purposes and glass manufacture is produced from pure orthoquartzite of the Lorrain and Bar River Formations in the southern part of the map-area. The Killarney Quarry on Badgeley Point was established in 1911 and was operated intermittently, mainly by Union Carbide Exploration Limited, until 1966 and produced some 5,000,000 tons of silica valued at about \$10,700,000 (Statistician, Ontario Division of Mines) from the upper part of the Lorrain Formation. The quarry was purchased by Indusmin Limited in 1968, and in 1971 this company established another quarry in orthoquartzite of the Bar River Formation on nearby Badgeley Island for the production of high purity silica for glass manufacture. According to the Northern Miner (1967), proven reserves amount to 10,000,000 tons grading 99.5 percent SiO_2 and less than 0.02 percent Fe_2O_3 .

The Lawson Quarry of the International Nickel Company of Canada Limited near Whitefish Falls has been in production since 1924 and currently produces some 2,000 tons per day of lump silica which is used as smelter flux in the company's Sudbury area operations.

The Sheguiandah or Trotter Quarry at Sheguiandah on Manitoulin Island was established in 1927 and was operated intermittently into the 1950s, mainly

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by Canadian Silica Corporation Limited, producing several million dollars worth of silica. There has been intermittent production of vein quartz, mainly from the Panache Lake Quartz Limited quarry in Goschen Township. The crushed material is used for facing precast concrete in building construction.

STONE

In 1967, a few tons of micaceous metasandstone with well developed, closely spaced cleavages were quarried from the Birch Island Quarry in I.R. 4 near Birch Island. This material was used for tiling purposes in parts of the Montreal subway system.

Some of the Nipissing Diabase is suitable for trap rock, and deposits in the Bay of Islands have been investigated (Card 1976b). Minor amounts of crushed stone for road construction purposes have been produced from quarries in Nipissing Diabase and the McKim Formation.

The part of the Espanola Formation in Vernon Township that consists of thin, alternating beds of white marble and black siltstone has potential for use as a decorative building stone.

SAND, GRAVEL, AND CLAY

Sand and gravel have been, or are currently being produced from some 40 pits in the map-area, mainly for road construction, concrete manufacture, and mine fill purposes. These are located in Pleistocene glacial deposits, the smaller gravel pits in crag-and-tail till deposits, and the larger sand and gravel pits mainly in glacial outwash deposits (Figure 31, Chart C, back pocket).

Small amounts of clay for construction purposes and fill have been produced from glaciolacustrine deposits. Varved clays near Espanola and at the west end of Agnew Lake are possibly suitable for ceramics or pottery manufacture.

REGIONAL METALLOGENIC VARIATIONS

The region about Sudbury represents a nickel metallogenic province in that rock units of different ages and variable characteristics all have nickel mineralization associated with them. The most noteworthy example is the Sudbury Nickel Irruptive, which is approximately 1,840 million years old. However, older rock units such as the Nipissing Diabase (2,160 m.y.) and younger units, such as the Mongowin Pluton (1,770 m.y.), also contain nickel-bearing sulphide minerals. Consequently, nickel sulphide deposits were generated in association with igneous intrusive activity over a long period of time in this area. These rock units are in turn spatially, and probably genetically related to major structural features, and to geophysically anomalous crustal zones.

The Nipissing Diabase intrusions display regional metallogenic variations. For instance, in the Cobalt-Gowganda area, the associated mineralization is mainly silver and cobalt-nickel arsenide vein deposits, whereas in the Sudbury area, copper-nickel sulphide minerals are dominant (Card and Pattison 1973). The only other apparent differences in the intrusions from one area to the other are their generally greater degree of alteration in the Sudbury area, and in the

greater abundance of associated carbonate and quartz-carbonate veins in the Cobalt-Gowganda area. Alteration of the Sudbury intrusions is attributable to regional metamorphism, and probably some of the sulphide minerals were formed by sulphurization processes during metamorphism (Card and Pattison 1973). The abundance of veins in the Cobalt-Gowganda area may be related to the nature of the country rocks into which the intrusions were emplaced. In the Sudbury area, the Huronian rocks were folded, and probably thoroughly lithified and dewatered before intrusion. In contrast, the Huronian rocks in the Cobalt-Gowganda area were, and are essentially undisturbed, and probably contained a relatively high proportion of water which reacted with the magma to facilitate vein formation.

Consequently, variations in mineral deposits associated with the Nipissing Diabase may be in part ascribable to different mechanisms of formation or concentration. Nevertheless, there must have been primary metallogenic differences. In the Cobalt-Gowganda area where Nipissing Diabase Intrusions have associated base-metal sulphide deposits of the "Sudbury type", these generally contain no or little nickel. Conversely, quartz-carbonate veins associated with the Nipissing Diabase in the Sudbury area contain gold and little silver. These primary differences are presumably caused by metallogenic variations in the zone of derivation of the intrusion in the lower crust or mantle.

The Sudbury Structure is spatially, and probably genetically, related to regional structural elements and to orogenic activity. The Sudbury Nickel Irruptive and associated ores were presumably derived from the deep crust or upper mantle. Three types of base-metal sulphide deposits are associated with the Sudbury Structure as follows:

1. Generally barren stratabound sulphide minerals in the Huronian volcanic-sedimentary sequence in the south which are possibly of volcanic exhalative origin.
2. The rich nickel-copper sulphide ores associated with the Nickel Irruptive that are probably of magmatic origin.
3. The copper-lead-zinc sulphide deposits of the Whitewater Group of the Sudbury Basin. These are stratabound, pyritic base-metal sulphide lenses at the top of the Onaping Formation that are associated with carbonate-rich and cherty rocks, and are probably of volcanic exhalative origin.

There is a close association in space between all three types, and an especially close relationship in time between the latter two.

Card and Hutchinson (1972) suggested that all three types of deposits may be genetically related to a prolonged cycle of volcanism, igneous intrusion, and related sedimentation. These events, rock units, and their associated mineral deposits are probably all ultimately associated with major crustal structures.

Comparison of the patterns of regional metamorphism (Figure 35) with those of mineralization (Figure 36) suggests the possibility of some genetic relationships, especially in the case of copper sulphide mineralization in quartz veins and silicified zones in Huronian rocks. There is a prominent belt of such deposits extending from the western boundary of the map-area, through the Agnew Lake area into Graham Township which coincides with the most northern belt of relatively high-grade metamorphism. There are undoubtedly lithological and struc-

tural controls on these deposits, but hydrous regional metamorphism may have played an important role as well.

CONCLUSIONS

In the Sudbury-Manitoulin area, definite interrelationships between mineral deposits, regional tectonic elements and metamorphism, and igneous intrusive and sedimentation events of various ages exist. The metallic mineral deposits are mainly related to major tectonic structures and events. The mineralization is presumably related to basaltic magmas repeatedly generated from sub-crustal sources along periodically reactivated zones of crustal weakness. This presumed sub-crustal source was notably rich in nickel.

The non-metallic deposits, including uranium in the lower part of the Huronian and silica in the upper part of the Huronian, are closely related to sedimentation processes which again were ultimately controlled by tectonics. It is possible that the uranium mineralization is the product of interaction between sedimentary and volcanic processes.

Suggestions for Future Exploration and Research

1. Further detailed structural studies of the Sudbury Structure are required to arrive at a better understanding of its origin, history, and mineral potential. Studies to investigate structural controls on the emplacement of the Sudbury Nickel Irruptive, especially the ore-bearing sublayer and offsets, could facilitate future mineral exploration which will become increasingly costly as mining depths increase.

2. Studies of the Sudbury Breccias are needed to determine what, if any, role they have played in emplacement of the Sudbury Nickel Irruptive, especially in controlling ore-rich embayments and offsets, and to investigate any relationships between these breccias and the sublayer breccias.

3. Further detailed structural studies of the Southern Province and Grenville Front Tectonic Zone, coupled with a carefully planned and controlled radiometric-age dating programme are required to better define the regional orogenic history.

4. Further work on the Nipissing Diabase on a regional basis should be carried out to investigate petrological and radiometric age variations, metallogenic relationships, and the possibility of associated large tonnage, low grade base-metal deposits.

5. Detailed work on the Foster Township tungsten occurrence is required to establish the origin of this unusual deposit. This type of mineralization could easily be overlooked, and similar deposits are possibly present in the region. Some parts of the Grenville Province that have an abundance of carbonate rocks, felsic intrusions, and a relatively high degree of metamorphism would also be likely places to prospect.

6. Exploration of the Huronian sequence on a regional scale for large, low-

grade stratabound base-metal deposits is probably warranted in view of the prevalence of sulphide minerals in units such as the Bruce and Espanola Formations. Other units, notably the Gowganda Formation, may be favourable for gold mineralization.

7. Assessment of the potential of the Lorrain and Bar River Formations for production of silica, and of the Paleozoic rocks for limestone is needed. The demand for such products will undoubtedly grow in future, and this region, because of its proximity to the Great Lakes will probably be a focus of such developments. Assessment of potential, not only from a geological viewpoint, but also from sociological and ecological viewpoints, should be carried out as soon as possible.

8. Detailed studies in this and other areas in the North Shore Region of Lake Huron are needed to establish the stratigraphic relationships between uranium-bearing sedimentary rocks and volcanic accumulations, and to investigate any genetic links between volcanism and uranium mineralization.

9. Regional geophysical work including gravity and seismic surveys is needed to define the physical nature of the crust which will in turn give insight into the origin and evolution of major features such as the Southern Province and Grenville Province depositional basins and the Sudbury Structure. More refined geophysical data on specific features such as the Grenville Front Tectonic Zone, the belt of gravity magnetic anomalies extending northeast from Sudbury, and the magnetic anomalies in the North Channel and Manitoulin Island areas are needed to properly interpret these phenomena. Paleomagnetic studies with good geological and petrographic control could profitably be undertaken on a number of rock units in the region, especially to determine the effects of post-emplacement metamorphism on paleomagnetic properties.

10. The Cenozoic surficial deposits deserve detailed study, not only to assess their potential for aggregate production, which is becoming increasingly important, but also to decipher the complex Pleistocene history of this part of the Great Lakes region.

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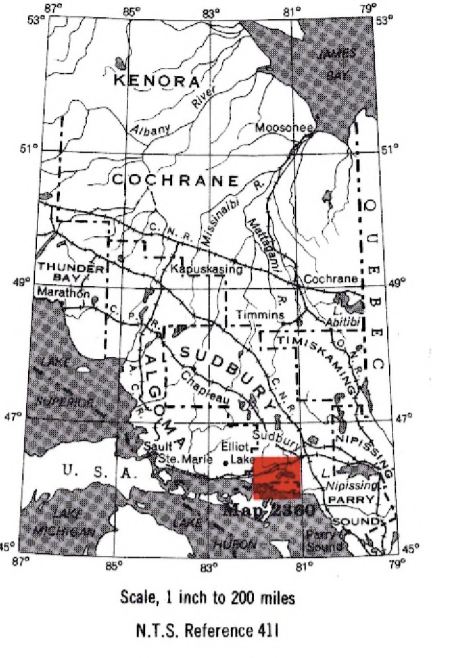
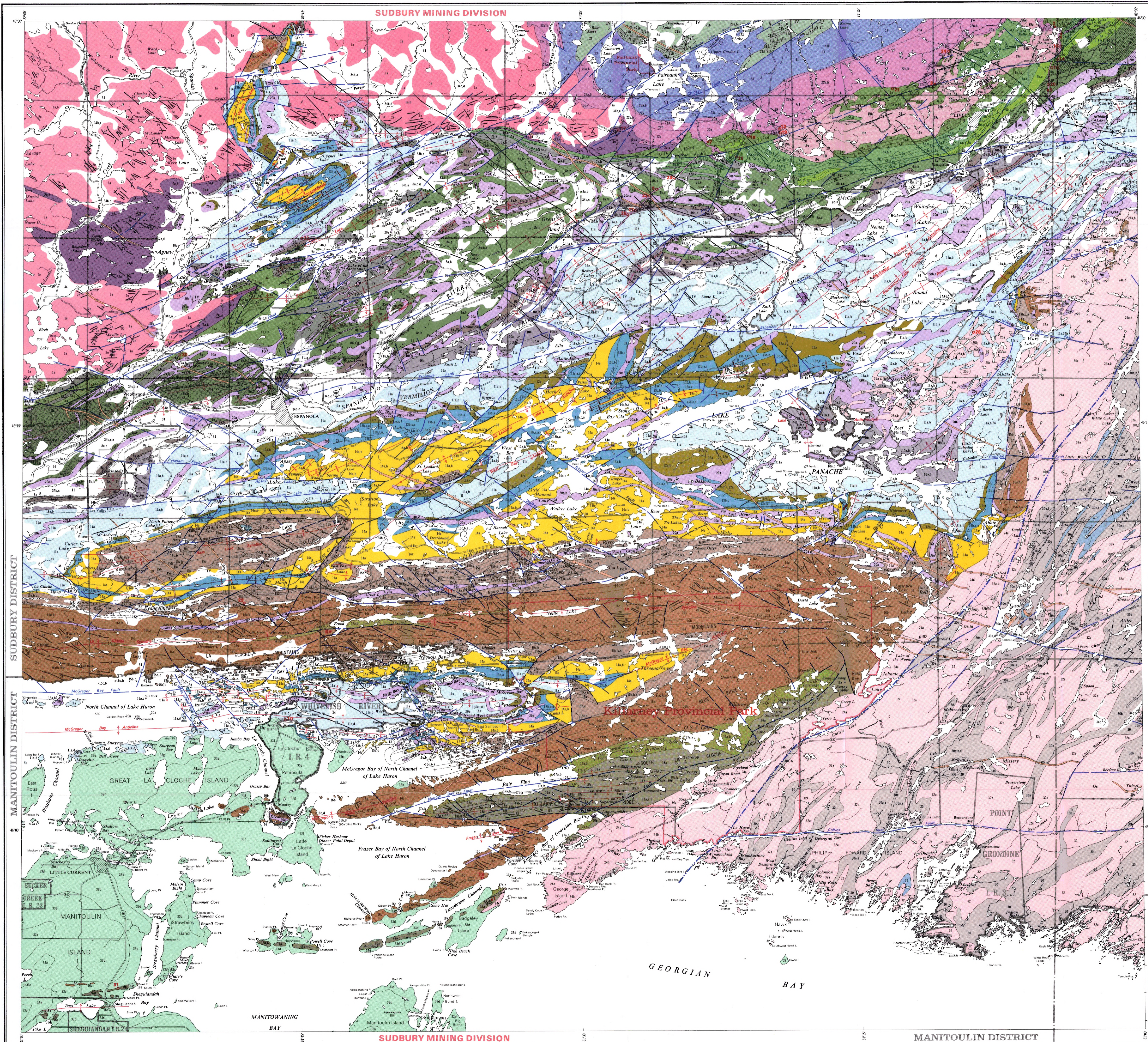
Sudbury-Manitoulin Area

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Sudbury-Manitoulin Area

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LEGEND

PHANEROZOIC

CENOZOIC

QUATERNARY

PLEISTOCENE AND RECENT

34 Unsubdivided
35 Gravels
36 Sand
37 Clay fill
38 Swamp deposits

PALEOZOIC

ORDOVICIAN-SILURIAN^a

14 Unsubdivided
14a Quartziferous sandstone, calcareous arenaceous
14b Siliceous, calcareous siltstone, silty micaceous
14c Conglomerate
14d Conglomerate

PRECAMBRIAN

GRENVILLE PROVINCE

MIDDLE TO LATE PRECAMBRIAN FELSIC PLUTONIC ROCKS

32 Unsubdivided
32a Granite and migmatitic quartz monzonite
32b Amphibolite, granodiorite, tonalite

MAFIC INTRUSIVE ROCKS

31 Amphibolite, metagabbro

PARAGENSIS AND METASEDIMENTS

30 Unsubdivided
30a Diabase gneiss and migmatitic diorite
30b Quartz-feldspar gneiss
30c Metacarbonate, siltstone
30d Calcareous metasediments, quartz-amphibolite and pyroxene-bearing
30e Orthoquartzite, muscovitic quartzite
30f Magnetitic quartz-feldspar gneiss

SOUTHERN PROVINCE

LATE PRECAMBRIAN

MAFIC INTRUSIVE ROCKS

29 Unsubdivided
29a Diabase, olivine diabase dikes,^b and amphibolite
29b Amphibolite, metagabbro, trapp, lamprophyre dikes
29c Agassiz-Riceville felsopar
29d Magnetite
29e Magnetite
29f Magnetite
29g Magnetite
29h Magnetite
29i Magnetite
29j Magnetite
29k Magnetite
29l Magnetite
29m Magnetite
29n Magnetite
29o Magnetite
29p Magnetite
29q Magnetite
29r Magnetite
29s Magnetite
29t Magnetite
29u Magnetite
29v Magnetite
29w Magnetite
29x Magnetite
29y Magnetite
29z Magnetite

MIDDLE TO LATE PRECAMBRIAN

MONSOON PLUTON

28 Unsubdivided
28a Amphibolite, pyroxene, amphibolite
28b Quartz diorite
28c Amphibolite, granophyre, leucophaea
28d Amphibolite, granophyre, leucophaea
28e Amphibolite, granophyre, leucophaea
28f Amphibolite, granophyre, leucophaea
28g Amphibolite, granophyre, leucophaea
28h Amphibolite, granophyre, leucophaea
28i Amphibolite, granophyre, leucophaea
28j Amphibolite, granophyre, leucophaea
28k Amphibolite, granophyre, leucophaea
28l Amphibolite, granophyre, leucophaea
28m Amphibolite, granophyre, leucophaea
28n Amphibolite, granophyre, leucophaea
28o Amphibolite, granophyre, leucophaea
28p Amphibolite, granophyre, leucophaea
28q Amphibolite, granophyre, leucophaea
28r Amphibolite, granophyre, leucophaea
28s Amphibolite, granophyre, leucophaea
28t Amphibolite, granophyre, leucophaea
28u Amphibolite, granophyre, leucophaea
28v Amphibolite, granophyre, leucophaea
28w Amphibolite, granophyre, leucophaea
28x Amphibolite, granophyre, leucophaea
28y Amphibolite, granophyre, leucophaea
28z Amphibolite, granophyre, leucophaea

EDEN LAKE PLUTONS

27 Unsubdivided
27a Amphibolite, minor quartz monzonite, granodiorite, siltstone
27b Gabbro

GRENVILLE FRONT PLUTONS

(Migmatitic and felsic plutons)

26 Unsubdivided
26a Quartz monzonite, quartz diorite, granodiorite and minor orthopyroxene-bearing
26b Amphibolite, quartz monzonite, quartz diorite, granodiorite
26c Amphibolite, quartz monzonite, quartz diorite, granodiorite
26d Amphibolite, quartz monzonite, quartz diorite, granodiorite
26e Amphibolite, quartz monzonite, quartz diorite, granodiorite
26f Amphibolite, quartz monzonite, quartz diorite, granodiorite
26g Amphibolite, quartz monzonite, quartz diorite, granodiorite
26h Amphibolite, quartz monzonite, quartz diorite, granodiorite
26i Amphibolite, quartz monzonite, quartz diorite, granodiorite
26j Amphibolite, quartz monzonite, quartz diorite, granodiorite
26k Amphibolite, quartz monzonite, quartz diorite, granodiorite
26l Amphibolite, quartz monzonite, quartz diorite, granodiorite
26m Amphibolite, quartz monzonite, quartz diorite, granodiorite
26n Amphibolite, quartz monzonite, quartz diorite, granodiorite
26o Amphibolite, quartz monzonite, quartz diorite, granodiorite
26p Amphibolite, quartz monzonite, quartz diorite, granodiorite
26q Amphibolite, quartz monzonite, quartz diorite, granodiorite
26r Amphibolite, quartz monzonite, quartz diorite, granodiorite
26s Amphibolite, quartz monzonite, quartz diorite, granodiorite
26t Amphibolite, quartz monzonite, quartz diorite, granodiorite
26u Amphibolite, quartz monzonite, quartz diorite, granodiorite
26v Amphibolite, quartz monzonite, quartz diorite, granodiorite
26w Amphibolite, quartz monzonite, quartz diorite, granodiorite
26x Amphibolite, quartz monzonite, quartz diorite, granodiorite
26y Amphibolite, quartz monzonite, quartz diorite, granodiorite
26z Amphibolite, quartz monzonite, quartz diorite, granodiorite

MIDDLE PRECAMBRIAN

SUDBURY NICKEL IRRUPTIVE

25 Unsubdivided
25a Magnetite
25b Magnetite
25c Magnetite
25d Magnetite
25e Magnetite
25f Magnetite
25g Magnetite
25h Magnetite
25i Magnetite
25j Magnetite
25k Magnetite
25l Magnetite
25m Magnetite
25n Magnetite
25o Magnetite
25p Magnetite
25q Magnetite
25r Magnetite
25s Magnetite
25t Magnetite
25u Magnetite
25v Magnetite
25w Magnetite
25x Magnetite
25y Magnetite
25z Magnetite

INTRUSIVE CONTACT

WHELEWATER GROUP

24 Unsubdivided
24a Quartz monzonite, quartz diorite, granodiorite
24b Quartz monzonite, quartz diorite, granodiorite
24c Quartz monzonite, quartz diorite, granodiorite
24d Quartz monzonite, quartz diorite, granodiorite
24e Quartz monzonite, quartz diorite, granodiorite
24f Quartz monzonite, quartz diorite, granodiorite
24g Quartz monzonite, quartz diorite, granodiorite
24h Quartz monzonite, quartz diorite, granodiorite
24i Quartz monzonite, quartz diorite, granodiorite
24j Quartz monzonite, quartz diorite, granodiorite
24k Quartz monzonite, quartz diorite, granodiorite
24l Quartz monzonite, quartz diorite, granodiorite
24m Quartz monzonite, quartz diorite, granodiorite
24n Quartz monzonite, quartz diorite, granodiorite
24o Quartz monzonite, quartz diorite, granodiorite
24p Quartz monzonite, quartz diorite, granodiorite
24q Quartz monzonite, quartz diorite, granodiorite
24r Quartz monzonite, quartz diorite, granodiorite
24s Quartz monzonite, quartz diorite, granodiorite
24t Quartz monzonite, quartz diorite, granodiorite
24u Quartz monzonite, quartz diorite, granodiorite
24v Quartz monzonite, quartz diorite, granodiorite
24w Quartz monzonite, quartz diorite, granodiorite
24x Quartz monzonite, quartz diorite, granodiorite
24y Quartz monzonite, quartz diorite, granodiorite
24z Quartz monzonite, quartz diorite, granodiorite

MISSISSIPPI DIABASE

23 Unsubdivided
23a Amphibolite, metagabbro
23b Amphibolite, metagabbro
23c Amphibolite, metagabbro
23d Amphibolite, metagabbro
23e Amphibolite, metagabbro
23f Amphibolite, metagabbro
23g Amphibolite, metagabbro
23h Amphibolite, metagabbro
23i Amphibolite, metagabbro
23j Amphibolite, metagabbro
23k Amphibolite, metagabbro
23l Amphibolite, metagabbro
23m Amphibolite, metagabbro
23n Amphibolite, metagabbro
23o Amphibolite, metagabbro
23p Amphibolite, metagabbro
23q Amphibolite, metagabbro
23r Amphibolite, metagabbro
23s Amphibolite, metagabbro
23t Amphibolite, metagabbro
23u Amphibolite, metagabbro
23v Amphibolite, metagabbro
23w Amphibolite, metagabbro
23x Amphibolite, metagabbro
23y Amphibolite, metagabbro
23z Amphibolite, metagabbro

INTRUSIVE CONTACT

CREIGHTON PLUTON

22 Unsubdivided
22a Quartz monzonite, hybrid granitic rocks
22b Granite

INTRUSIVE CONTACT

HURONAN SUPERGROUP

COBALT GROUP

21 Unsubdivided
21a Quartz monzonite, minor granodiorite and gabbro, and gneiss
21b Amphibolite, quartz diorite
21c Amphibolite, quartz diorite
21d Amphibolite, quartz diorite
21e Amphibolite, quartz diorite
21f Amphibolite, quartz diorite
21g Amphibolite, quartz diorite
21h Amphibolite, quartz diorite
21i Amphibolite, quartz diorite
21j Amphibolite, quartz diorite
21k Amphibolite, quartz diorite
21l Amphibolite, quartz diorite
21m Amphibolite, quartz diorite
21n Amphibolite, quartz diorite
21o Amphibolite, quartz diorite
21p Amphibolite, quartz diorite
21q Amphibolite, quartz diorite
21r Amphibolite, quartz diorite
21s Amphibolite, quartz diorite
21t Amphibolite, quartz diorite
21u Amphibolite, quartz diorite
21v Amphibolite, quartz diorite
21w Amphibolite, quartz diorite
21x Amphibolite, quartz diorite
21y Amphibolite, quartz diorite
21z Amphibolite, quartz diorite

INTRUSIVE CONTACT

LORRAIN FORMATION

20 Unsubdivided
20a Amphibolite, quartz diorite
20b Amphibolite, quartz diorite
20c Amphibolite, quartz diorite
20d Amphibolite, quartz diorite
20e Amphibolite, quartz diorite
20f Amphibolite, quartz diorite
20g Amphibolite, quartz diorite
20h Amphibolite, quartz diorite
20i Amphibolite, quartz diorite
20j Amphibolite, quartz diorite
20k Amphibolite, quartz diorite
20l Amphibolite, quartz diorite
20m Amphibolite, quartz diorite
20n Amphibolite, quartz diorite
20o Amphibolite, quartz diorite
20p Amphibolite, quartz diorite
20q Amphibolite, quartz diorite
20r Amphibolite, quartz diorite
20s Amphibolite, quartz diorite
20t Amphibolite, quartz diorite
20u Amphibolite, quartz diorite
20v Amphibolite, quartz diorite
20w Amphibolite, quartz diorite
20x Amphibolite, quartz diorite
20y Amphibolite, quartz diorite
20z Amphibolite, quartz diorite

CONGOLESA FORMATION

19 Unsubdivided
19a Amphibolite, quartz diorite
19b Amphibolite, quartz diorite
19c Amphibolite, quartz diorite
19d Amphibolite, quartz diorite
19e Amphibolite, quartz diorite
19f Amphibolite, quartz diorite
19g Amphibolite, quartz diorite
19h Amphibolite, quartz diorite
19i Amphibolite, quartz diorite
19j Amphibolite, quartz diorite
19k Amphibolite, quartz diorite
19l Amphibolite, quartz diorite
19m Amphibolite, quartz diorite
19n Amphibolite, quartz diorite
19o Amphibolite, quartz diorite
19p Amphibolite, quartz diorite
19q Amphibolite, quartz diorite
19r Amphibolite, quartz diorite
19s Amphibolite, quartz diorite
19t Amphibolite, quartz diorite
19u Amphibolite, quartz diorite
19v Amphibolite, quartz diorite
19w Amphibolite, quartz diorite
19x Amphibolite, quartz diorite
19y Amphibolite, quartz diorite
19z Amphibolite, quartz diorite

LOCAL DISCONFORMITY

ELIOT LAKE GROUP

18 Unsubdivided
18a Amphibolite, quartz diorite
18b Amphibolite, quartz diorite
18c Amphibolite, quartz diorite
18d Amphibolite, quartz diorite
18e Amphibolite, quartz diorite
18f Amphibolite, quartz diorite
18g Amphibolite, quartz diorite
18h Amphibolite, quartz diorite
18i Amphibolite, quartz diorite
18j Amphibolite, quartz diorite
18k Amphibolite, quartz diorite
18l Amphibolite, quartz diorite
18m Amphibolite, quartz diorite
18n Amphibolite, quartz diorite
18o Amphibolite, quartz diorite
18p Amphibolite, quartz diorite
18q Amphibolite, quartz diorite
18r Amphibolite, quartz diorite
18s Amphibolite, quartz diorite
18t Amphibolite, quartz diorite
18u Amphibolite, quartz diorite
18v Amphibolite, quartz diorite
18w Amphibolite, quartz diorite
18x Amphibolite, quartz diorite
18y Amphibolite, quartz diorite
18z Amphibolite, quartz diorite

MAFIC INTRUSIVE ROCKS

GABRO AND DIKES

17 Unsubdivided
17a Amphibolite
17b Amphibolite
17c Amphibolite
17d Amphibolite
17e Amphibolite
17f Amphibolite
17g Amphibolite
17h Amphibolite
17i Amphibolite
17j Amphibolite
17k Amphibolite
17l Amphibolite
17m Amphibolite
17n Amphibolite
17o Amphibolite
17p Amphibolite
17q Amphibolite
17r Amphibolite
17s Amphibolite
17t Amphibolite
17u Amphibolite
17v Amphibolite
17w Amphibolite
17x Amphibolite
17y Amphibolite
17z Amphibolite

INTRUSIVE CONTACT

SUPERIOR PROVINCE

EARLY PRECAMBRIAN

FELSIC PLUTONIC ROCKS

BIRCH LAKE BATHOLITH

16 Unsubdivided
16a Quartz monzonite, minor granodiorite and gabbro, and gneiss
16b Amphibolite, quartz diorite
16c Amphibolite, quartz diorite
16d Amphibolite, quartz diorite
16e Amphibolite, quartz diorite
16f Amphibolite, quartz diorite
16g Amphibolite, quartz diorite
16h Amphibolite, quartz diorite
16i Amphibolite, quartz diorite
16j Amphibolite, quartz diorite
16k Amphibolite, quartz diorite
16l Amphibolite, quartz diorite
16m Amphibolite, quartz diorite
16n Amphibolite, quartz diorite
16o Amphibolite, quartz diorite
16p Amphibolite, quartz diorite
16q Amphibolite, quartz diorite
16r Amphibolite, quartz diorite
16s Amphibolite, quartz diorite
16t Amphibolite, quartz diorite
16u Amphibolite, quartz diorite
16v Amphibolite, quartz diorite
16w Amphibolite, quartz diorite
16x Amphibolite, quartz diorite
16y Amphibolite, quartz diorite
16z Amphibolite, quartz diorite

SYMBOLS

Geological boundary, position interpreted
Geological boundary, position assumed
Lineament or fault
Grenville Front Boundary Fault
Anticline, syncline with plunge
Motor road, provincial highway number enclosed where applicable
Other road
Railway with station, siding or similar facility
Aircraft landing facilities
District boundary, approximate location only
Township boundary, median or base line approximate position only
735' Altitude in feet above mean sea level
Producer
Past producer

PRODUCERS

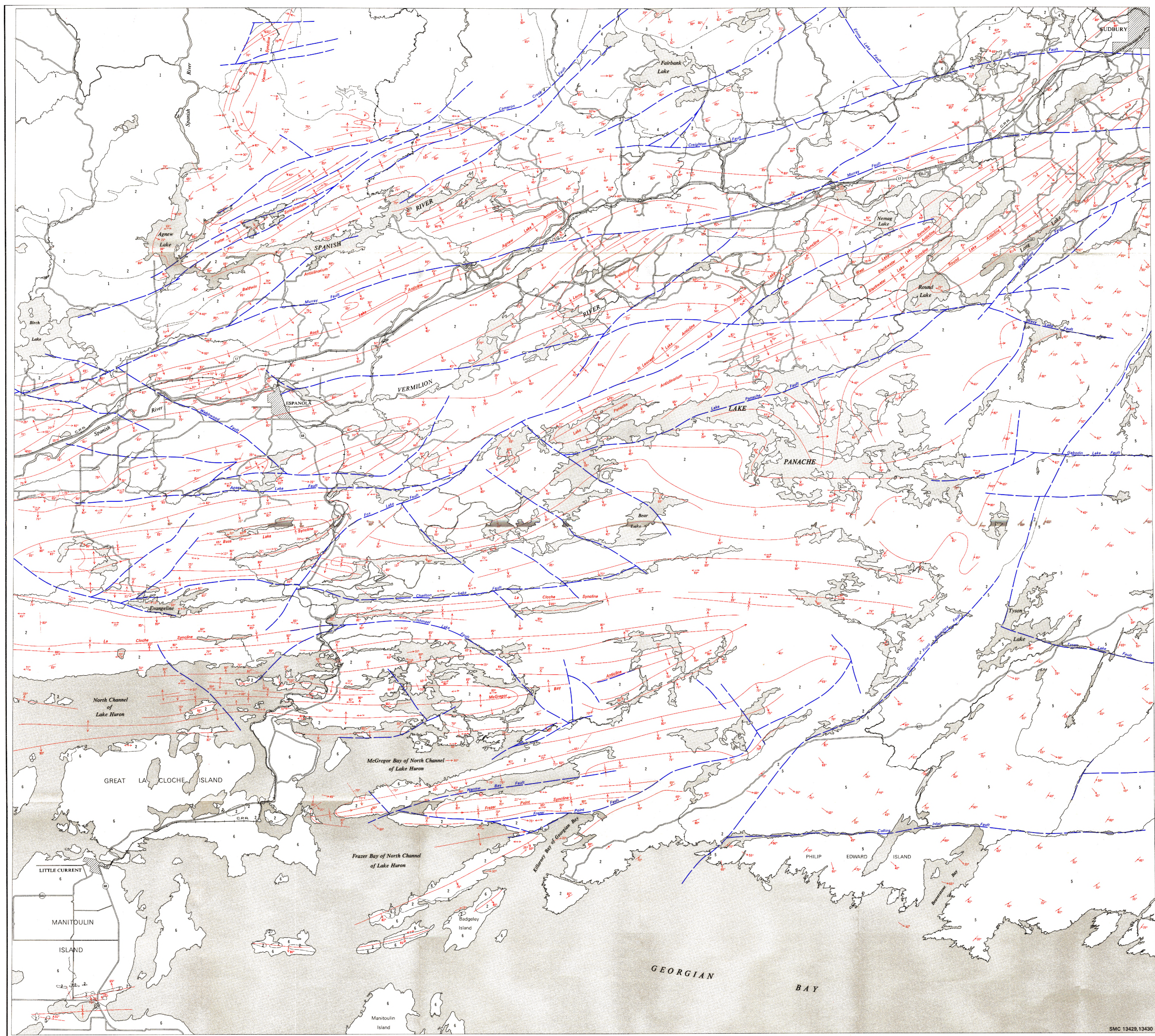
1. International Silica
2. Sudbury Island quarry
3. Silica International Nickel Co. of Canada Ltd., The
4. Carleton Place
5. Nickel, copper
6. Copper Cliff North mine
7. Nickel, copper
8. Copper Cliff South mine
9. Nickel, copper
10. Lawson quarry
11. Nickel, copper
12. Parvaneh Lake Quartz Ltd.
13. Silica International Nickel Co. of Canada Ltd., The
14. Nickel, copper
15. Nickel, copper
16. Nickel, copper
17. Nickel, copper
18. Nickel, copper
19. Nickel, copper
20. Nickel, copper
21. Nickel, copper
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SOURCES OF INFORMATION

Geology by K. D. Card, 1959-73.
Additional information from publisher maps of the Natural Resources (GNM) and unpublished maps by J. W. Chubb, 1971; 1972; 1973; and GOM-555; 1975; 1976; 1977; 1978; 1979; 1980; 1981; 1982; 1983; 1984; 1985; 1986; 1987; 1988; 1989; 1990; 1991; 1992; 1993; 1994; 1995; 1996; 1997; 1998; 1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021; 2022; 2023; 2024; 2025; 2026; 2027; 2028; 2029; 2030; 2031; 2032; 2033; 2034; 2035; 2036; 2037; 2038; 2039; 2040; 2041; 2042; 2043; 2044; 2045; 2046; 2047; 2048; 2049; 2050; 2051; 2052; 2053; 2054; 2055; 2056; 2057; 2058; 2059; 2060; 2061; 2062; 2063; 2064; 2065; 2066; 2067; 2068; 2069; 2070; 2071; 2072; 2073; 2074; 2075; 2076; 2077; 2078; 2079; 2080; 2081; 2082; 2083; 2084; 2085; 2086; 2087; 2088; 2089; 2090; 2091; 2092; 2093; 2094; 2095; 2096; 2097; 2098; 2099; 2100; 2101; 2102; 2103; 2104; 2105; 2106; 2107; 2108; 2109; 2110; 2111; 2112; 2113; 2114; 2115; 2116; 2117; 2118; 2119; 2120; 2121; 2122; 2123; 2124; 2125; 2126; 2127; 2128; 2129; 2130; 2131; 2132; 2133; 2134; 2135; 2136; 2137; 2138; 2139; 2140; 2141; 2142; 2143; 2144; 2145; 2146; 2147; 2148; 2149; 2150; 2151; 2152; 2153; 2154; 2155; 2156; 2157; 2158; 2159; 2160; 2161; 2162; 2163; 2164; 2165; 2166; 2167; 2168; 2169; 2170; 2171; 2172; 2173; 2174; 2175; 2176; 2177; 2178; 2179; 2180; 2181; 2182; 2183; 2184; 2185; 2186; 2187; 2188; 2189; 2190; 2191; 2192; 2193; 2194; 2195; 2196; 2197; 2198; 2199; 2200; 2201; 2202; 2203; 2204; 2205; 2206; 2207; 2208; 2209; 2210; 2211; 2212; 2213; 2214; 2215; 2216; 2217; 2218; 2219; 2220; 2221; 2222; 2223; 2224; 2225; 2226; 2227; 2228; 2229; 2230; 2231; 2232; 2233; 2234; 2235; 2236; 2237; 2238; 2239; 2240; 2241; 2242; 2243; 2244; 2245; 2246; 2247; 2248; 2249; 2250; 2251; 2252; 2253; 2254; 2255; 2256; 2257; 2258; 2259; 2260; 2261; 2262; 2263; 2264; 2265; 2266; 2267; 2268; 2269; 2270; 2271; 2272; 2273; 2274; 2275; 2276; 2277; 2278; 2279; 2280; 2281; 2282; 2283; 2284; 2285; 2286; 2287; 2288; 2289; 2290; 2291; 2292; 2293; 2294; 2295; 2296; 2297; 2298; 2299; 2300; 2301; 2302; 2303; 2304; 2305; 2306; 2307; 2308; 2309; 2310; 2311; 2312; 2313; 2314; 2315; 2316; 2317; 2318; 2319; 2320; 2321; 2322; 2323; 2324; 2325; 2326; 2327; 2328; 2329; 2330; 2331; 2332; 2333; 2334; 2335; 2336; 2337; 2338; 2339; 2340; 2341; 2342; 2343; 2344; 2345; 2346; 2347; 2348; 2349; 2350; 2351; 2352; 2353; 2354; 2355; 2356; 2357; 2358; 2359; 2360; 2361; 2362; 2363; 2364; 2365; 2366; 2367; 2368; 2369; 2370; 2371; 2372; 2373; 2374; 2375; 2376; 2377; 2378; 2379; 2380; 2381; 2382; 2383; 2384; 2385; 2386; 2387; 2388; 2389; 2390; 2391; 2392; 2393; 2394; 2395; 2396; 2397; 2398; 2399; 2400; 2401; 2402; 2403; 2404; 2405; 2406; 2407; 2408; 2409; 2410; 2411; 2412; 2413; 2414; 2415; 2416; 2417; 2418; 2419; 2420; 2421; 2422; 2423; 2424; 2425; 2426; 2427; 2428; 2429; 2430; 2431; 2432; 2433; 2434; 2435; 2436; 2437; 2438; 2439; 2440; 2441; 2442; 2443; 2444; 2445; 2446; 2447; 2448; 2449; 2450; 2451; 2452; 2453; 2454; 2455; 2456; 2457; 2458; 2459; 2460; 2461; 2462; 2463; 2464; 2465; 2466; 2467; 2468; 2469; 2470; 2471; 2472; 2473; 2474; 2475; 2476; 2477; 2478; 2479; 2480; 2481; 2482; 2483; 2484; 2485; 2486; 2487; 2488; 2489; 2490; 2491; 2492; 2493; 2494; 2495; 2496; 2497; 2498; 2499; 2500; 2501; 2502; 2503; 2504; 2505; 2506; 2507; 2508; 2509; 2510; 2511; 2512; 2513; 2514; 2515; 2516; 2517; 2518; 2519; 2520; 2521; 2522; 2523; 2524; 2525; 2526; 2527; 2528; 2529; 2530; 2531; 2532; 2533; 2534; 2535; 2536; 2537; 2538; 2539; 2540; 2541; 2542; 2543; 2544; 2545; 2546; 2547; 2548; 2549; 2550; 2551; 2552; 2553; 2554; 2555; 2556; 2557; 2558; 2559; 2560; 2561; 2562; 2563; 2564; 2565; 2566; 2567; 2568; 2569; 2570; 2571; 2572; 2573; 2574; 2575; 2576; 2577; 2578; 2579; 2580; 2581; 2582; 2583; 2584; 2585; 2586; 2587; 2588; 2589; 2590; 2591; 2592; 2593; 2594; 2595; 2596; 2597; 2598; 2599; 2600; 2601; 2602; 2603; 2604; 2605; 2606; 2607; 2608; 2609; 2610; 2611; 2612; 2613; 2614; 2615; 2616; 2617; 2618; 2619; 2620; 2621; 2622; 2623; 2624; 2625; 2626; 2627; 2628; 2629; 2630; 2631; 2632; 2633; 2634; 2635; 2636; 2637; 2638; 2639; 2640; 2641; 2642; 2643; 2644; 2645; 2646; 2647; 2648; 2649; 2650; 2651; 2652; 2653; 2654; 2655; 2656; 2657; 2658; 2659; 2660; 2661; 2662; 2663; 2664; 2665; 2666; 2667; 2668; 2669; 2670; 2671; 2672; 2673; 2674; 2675; 2676; 2677; 2678; 2679; 2680; 2681; 2682; 2683; 2684; 2685; 2686; 2687; 2688; 2689; 2690; 2691; 2692; 2693; 2694; 2695; 2696; 2697; 2698; 2699; 2700; 2701; 2702; 2703; 2704; 2705; 2706; 2707; 2708; 2709; 2710; 2711; 2712; 2713; 2714; 2715; 2716; 2717; 271



LEGEND

- PALEOZOIC**
- 6 Paleozoic rocks.
- MIDDLE AND LATE PRECAMBRIAN - GRENVILLE PROVINCE**
- 5 Felsic plutonic rocks and high rank metamorphic gneiss.
- MIDDLE PRECAMBRIAN - SOUTHERN PROVINCE**
- 4 Sudbury Nickel Intrusive.
 - 3 Whitewater Group.
 - 2 Huronian Supergroup and related mafic and felsic intrusions.
- EARLY PRECAMBRIAN - SUPERIOR PROVINCE**
- 1 Felsic plutonic rocks and migmatitic gneiss.

SYMBOLS

- Strike and dip of bedding, dipping and vertical. Arrow indicates direction of top.
- East-west foliations, dipping and vertical; early bedding plane foliations; early and late cataclastic mylonitic foliations.
- East-northeast foliation, dipping and vertical; staly-type cleavage.
- Grenville Front Tectonic Zone, cataclastic mylonitic foliation, dipping and vertical.
- Late strain-slip cleavage and kink bands, dipping and vertical.
- Lineations: rodding, mineral, and intersection lineations, and minor fold axes.
- Axial trace of anticline with plunge.
- Axial trace of syncline with plunge.
- Fault.
- Geological contact.

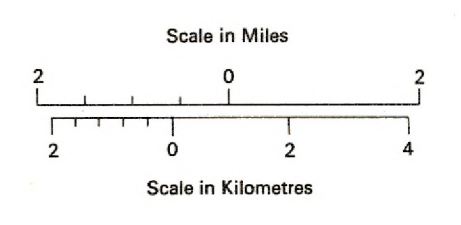


Fig. 32—Generalized trends of bedding, foliation, and lineation with major faults and folds.

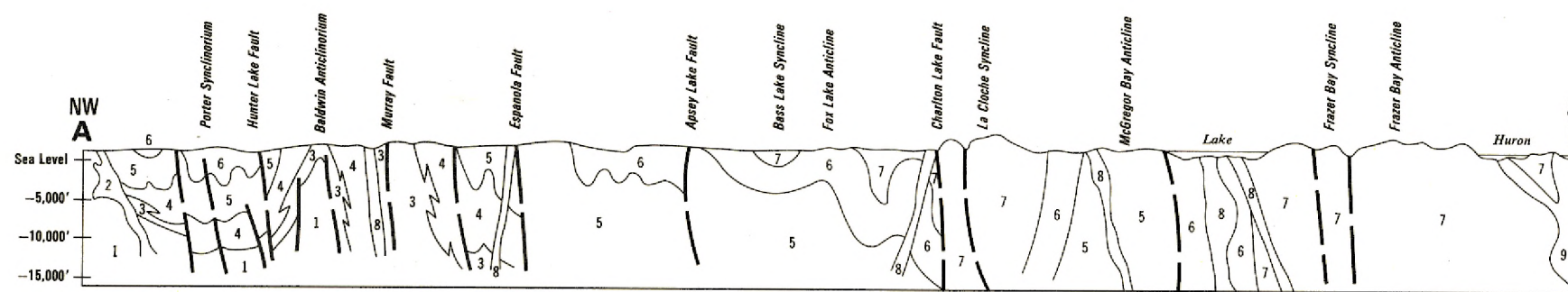
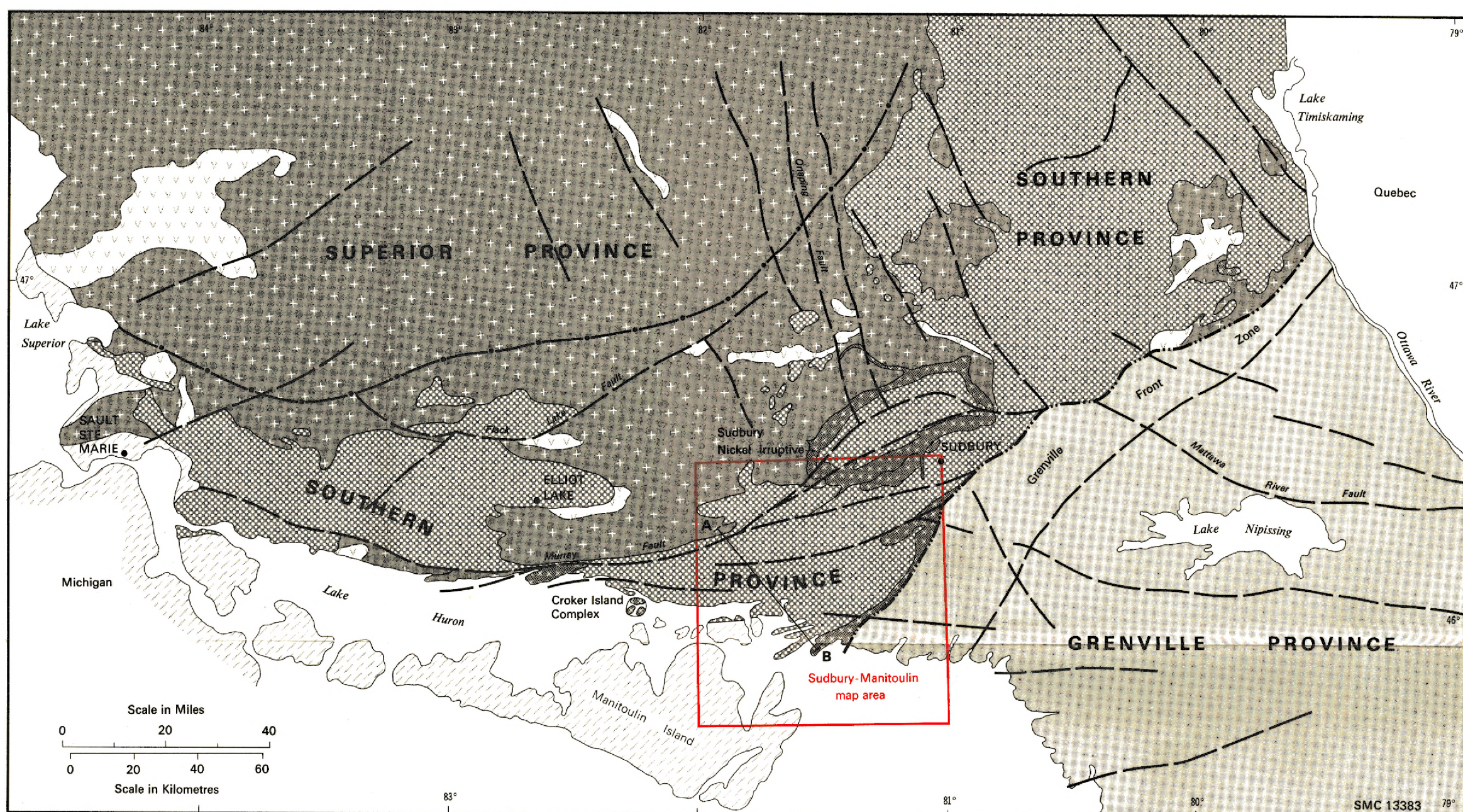


Fig. 2—Geological subdivisions and tectonic elements of the North Shore of Lake Huron

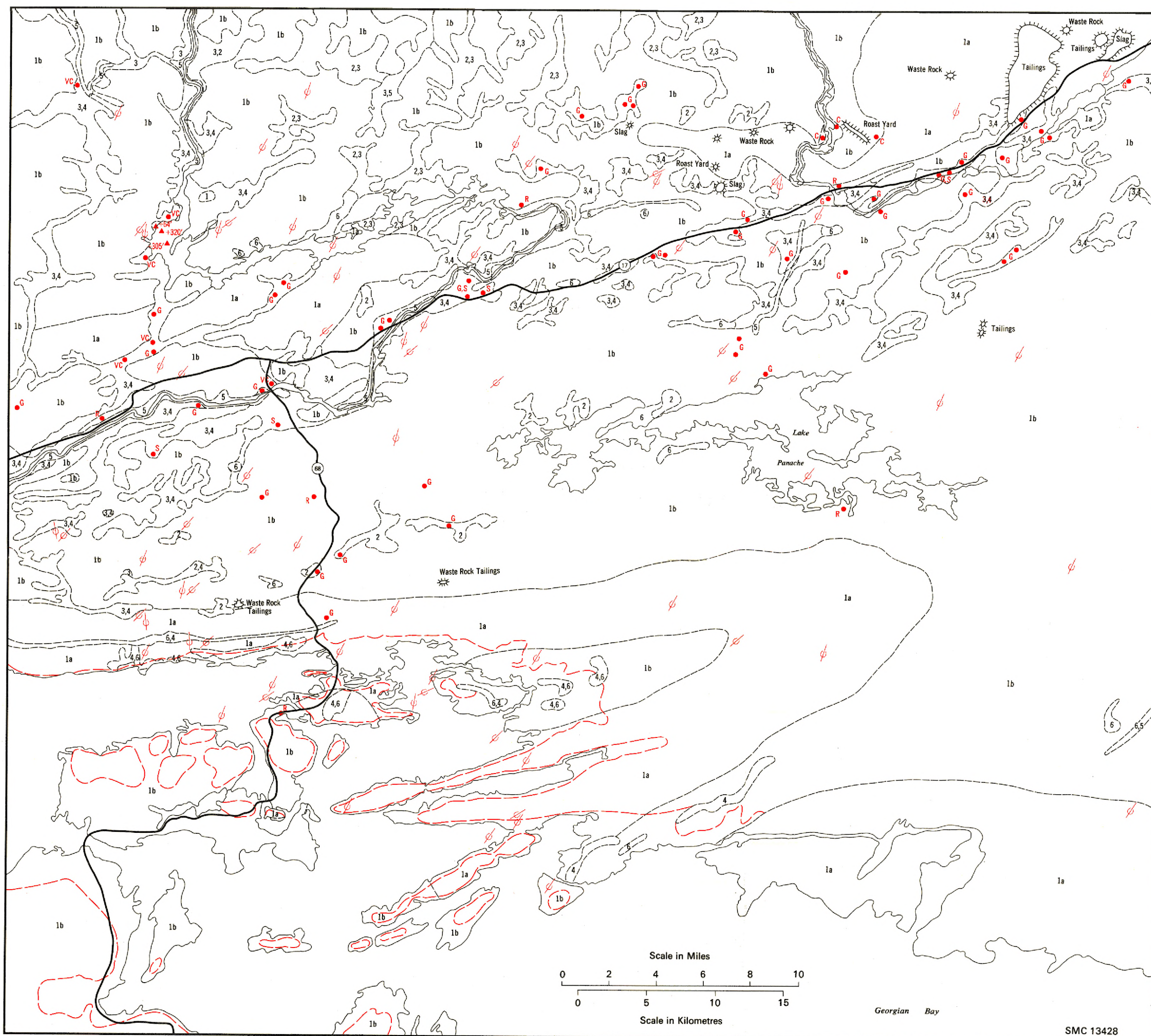


Fig. 31—Surficial geology-Sudbury Manitoulin area

TABLE 4 CHEMICAL ANALYSES, NORMS, AND MODAL ANALYSES OF ROCKS OF THE ELSIE MOUNTAIN, STOBIE, COPPER CLIFF, AND SALMAY LAKE FORMATIONS, SUDBURY-MANITOULIN AREA. CHEMICAL ANALYSES BY MINERAL RESEARCH BRANCH, DIVISION OF MINES.

Chemical Analyses, Major Components in Weight Percent																																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
SiO ₂	51.20	49.00	57.38	59.40	59.30	61.48	54.40	47.00	54.20	49.90	53.00	54.40	67.60	57.40	64.00	58.40	58.40	56.60	56.10	71.10	83.50	78.30	72.50	76.80	70.10	75.90	71.60	73.20	72.60	78.80	77.80	51.90	96.50	48.60	53.90	48.00	
Al ₂ O ₃	14.10	19.00	25.33	23.10	21.80	21.77	16.30	16.60	13.00	15.90	12.80	13.70	9.75	23.80	20.00	12.40	15.70	19.80	24.50	12.10	8.61	12.42	15.40	13.20	14.30	15.10	14.00	14.70	14.70	12.20	9.37	15.80	0.66	14.70	13.40	17.60	
Fe ₂ O ₃	0.70	1.50	1.13	1.10	0.46	2.64	2.77	1.27	0.73	0.46	0.93	1.53	0.58	1.60	0.29	2.92	3.71	3.17	1.95	1.30	-	-	0.45	0.37	0.77	0.50	0.70	0.76	0.35	0.34	0.60	2.90	0.10	3.22	2.55	2.80	
FeO	11.50	7.92	4.86	4.19	5.42	4.10	7.89	14.70	12.20	9.45	12.90	9.28	7.85	3.89	4.32	8.39	2.97	5.42	3.96	0.31	0.55	4.59	1.03	0.77	3.83	1.03	3.78	1.18	0.81	0.88	3.32	10.80	0.40	10.40	10.20	8.83	
MgO	6.22	4.32	2.48	1.58	2.05	2.74	4.83	5.10	4.29	7.81	4.05	4.33	2.00	1.58	1.58	3.10	1.37	2.50	1.42	0.22	0.07	0.36	0.28	0.09	0.09	0.75	0.50	0.62	0.11	0.30	2.21	1.44	0.40	4.67	4.31	6.70	
CaO	10.50	12.40	0.34	0.59	0.90	1.39	2.19	5.59	9.55	10.30	11.00	8.27	6.33	0.38	1.15	6.53	4.77	1.18	0.88	2.71	0.14	0.46	2.21	1.97	1.43	0.10	1.35	0.60	0.30	1.33	1.80	9.02	0.16	10.10	8.55	7.84	
Na ₂ O	1.97	1.37	2.08	1.30	1.56	1.32	3.04	2.73	1.20	2.37	1.06	2.51	1.94	1.43	2.19	1.85	4.25	2.07	2.20	1.39	3.06	4.05	2.50	4.93	3.58	0.38	4.04	0.92	2.10	3.18	1.46	2.88	0.09	2.22	2.91	2.76	
K ₂ O	0.61	0.47	2.01	4.59	4.13	2.20	1.34	0.80	0.27	0.53	0.24	1.14	0.66	5.43	3.21	1.04	1.98	3.69	5.29	6.57	2.96	1.63	4.24	1.45	3.62	3.91	2.75	4.85	7.67	1.38	1.13	1.11	0.14	0.91	1.49	0.38	
H ₂ O ⁺	1.04	1.51	3.60	2.17	2.52	1.23	3.48	2.18	1.05	1.55	0.92	0.91	0.59	1.72	1.29	1.83	0.23	3.02	1.59	1.76	0.07	-	0.47	0.34	0.59	1.49	0.24	0.93	0.34	0.39	1.21	1.17	0.21	1.54	1.45	3.37	
H ₂ O ⁻	0.09	0.11	0.07	0.55	0.13	0.07	0.03	0.03	0.04	0.07	0.07	0.32	0.07	0.11	0.03	0.12	0.30	0.23	0.10	0.24	0.02	-	-	0.09	0.05	0.03	0.07	0.10	0.08	0.05	0.04	0.06	0.04	0.02	0.09	0.08	0.11
CO ₂	0.14	0.12	0.64	1.06	0.08	0.53	0.05	0.36	0.21	0.17	0.45	1.11	0.38	0.01	0.21	0.10	0.15	-	0.10	-	0.05	-	-	0.10	0.15	0.10	0.10	0.10	0.10	0.10	0.10	0.18	0.26	0.35	0.33	0.10	
TiO ₂	1.10	1.05	1.00	1.17	1.25	0.88	1.21	2.02	1.56	0.84	1.59	1.35	1.11	1.19	0.82	1.52	1.40	1.27	1.39	0.28	0.05	0.04	0.19	0.06	0.49	0.16	0.46	0.19	0.13	0.13	0.54	1.75	<0.01	1.60	1.03	0.42	
P ₂ O ₅	0.08	0.11	0.11	0.10	0.10	0.12	0.14	0.15	0.11	0.09	0.17	0.18	0.14	0.01	0.07	0.17	0.05	0.12	0.10	-	0.01	0.01	<0.02	<0.02	0.09	<0.02	0.10	0.03	<0.02	<0.02	0.07	0.28	<0.01	0.07	0.05	0.06	
MnO	0.24	0.18	0.05	0.04	0.06	0.06	0.13	0.26	0.23	0.19	0.22	0.18	0.16	0.03	0.05	0.15	0.15	0.06	0.03	0.10	0.01	-	-	0.03	0.07	0.01	0.09	0.02	0.01	0.01	0.06	0.25	0.01	0.23	0.29	0.20	
FeS ₂	0.01	0.01	-	-	-	-	1.36	1.77	0.11	0.01	0.03	0.13	0.22	0.94	0.38	1.63	3.92	1.85	0.95	0.02	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Total	99.50	99.07	101.08	100.94	99.76	100.53	99.16	100.56	98.75	99.64	99.43	98.34	99.38	99.52	99.59	100.15	99.35	100.98	100.36	97.10	99.11	101.86	99.52	100.19	99.15	99.53	99.82	98.20	99.30	99.11	99.78	99.61	98.98	98.71	100.55	99.19	
Specific Gravity	3.04	3.08	2.83	2.72	2.78	2.88	2.80	2.96	3.08	2.98	3.12	2.92	2.91	2.72	2.74	2.94	2.75	2.82	2.78	2.69	2.62	N.D.	2.68	2.66	2.72	2.78	2.70	2.70	2.61	2.68	2.70	3.09	2.64	3.06	2.93	N.D.	
Trace Elements in ppm																																					
As	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Ba	150	-	600	1200	1000	900	400	-	-	150	-	500	150	600	1500	400	300	1200	800	150	-	-	4	<3	<3	<3	<3	<3	4	<3	<3	<3	<3	<3	<3	<3	<3
Cr	150	70	250	300	200	150	200	80	100	300	60	20	15	30	100	10	100	150	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Co	50	40	20	20	20	20	10	50	40	50	40	40	10	20	30	20	30	30	30	7	-	-	<5	<5	6	<5	<5	<5	<5	<5	15	35	-	40	50	-	
Cu	20	80	10	100	30	300	100	200	40	110	50	100	100	20	40	100	150	150	90	6	-	-	15	20	20	10	10	10	20	15	45	45	4	50	90	10	
Ga	30	30	-	-	-	-	-	40	30	15	40	-	20	20	30	20	60	70	90	15	-	-	20	20	25	25	20	25	20	15	15	15	15	15	20	20	40
Ni	130	70	80	60	80	80	80	70	90	200	70	20	50	30	70	15	30	15	10	10	-	-	15	15	25	10	10	10	10	9	40	25	<5	100	100	-	
Pb	10	10	20	15	10	20	15	10	10	10	10	15	15	15	15	30	10	30	30	15	-	-	40	40	50	25	20	40	40	40	15	20	10	40	10	10	
Sc	30	20	20	20	30	10	150	40	30	30	30	40	20	20	20	200	150	150	200	200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Sr	130	150	200	150	100	200	-	150	80	250	100	200	200	100	100	250	50	200	-	50	-	-	70	30	400	50	70	50	50	100	100	300	-	200	200	1000	
V	200	130	150	250	200	150	250	200	150	120	150	250	200	50	150	30	10	15	30	-	-	-	10	10	10	-	-	-	-	-	-	-	-	-	-		
Y	15	20	10	10	20	10	10	40	20	20	20	10	40	30	15	200	100	150	150	-	-	-	100	100	100	50	50	20	20	50	-	50	-	30	50	-	
Zr	60	60	80	150	150	150	120	120	120	80	120	100	300	150	150	-	-	-	70	-	-	-	100	130	100	700	150	500	150	150	130	150	400	<20	150	150	
Zn	130	110	-	-	60	-	-	190	150	110	140	-	100	80	80	-	-	-	-	-	-	-	10	70	45	120	35	110	35	40	45	70	150	4	120	120	100
Li	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	20	35	35	50	35	25	30	35	-	-	-	-		
Be	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	5	3	3	3	5	3	5	-	3	-	-	-		
Sn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15	20	10	10	10	15	10	10	-	-	-	-	-		
Rb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	170	60	170	200	150	360	340	100	40	20	-				