FIELD TRIP GUIDEBOOK FOR THE ARCHEAN AND PROTEROZOIC STRATIGRAPHY OF THE GREAT LAKES AREA, UNITED STATES AND CANADA

PREPARED FOR THE FIFTH ANNUAL MEETING OF THE
INTERNATIONAL UNION OF GEOLOGICAL SCIENCES
SUBCOMMISSION ON PRECAMBRIAN STRATIGRAPHY
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FIELD TRIP GUIDEBOOK FOR

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G.B. Morey, Editor

Prepared for the Fifth Annual Meeting of the
International Union of Geological Sciences
Subcommission on Precambrian Stratigraphy

September 4-19, 1979

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FOREWORD

This guidebook is prepared for the field excursion accompanying the Fifth Meeting of the International Union of Geological Sciences Subcommission on Precambrian Stratigraphy, to be held September 4-19, 1979, in the Great Lakes area, United States and Canada. Separate segments of the guidebook were prepared by the various field trip leaders and assembled by G. B. Morey, editor. M. J. Frarey coordinated the separate contributions for the Canadian part of the field excursion. This is to acknowledge financial assistance for the meetings by the Geological Survey of Canada, the Minnesota Geological survey, the National Science Foundation (United States), and the U.S. Geological Survey. The Geological Survey of Canada, Minnesota Geological Survey, Ontario Division of Mines, Royal Ontario Museum, University of Minnesota, Duluth, and U.S. Geological Survey provided guides for the field excursion and contributed time and facilities toward preparation of the guidebook.

The main purpose of the field excursion is to examine classic Precambrian sequences in the Lake Huron and Lake Superior regions, as a background for discussions on possible subdivision of the Archean and Proterozoic. The field excusion will be followed by technical sessions held in the Duluth, Minnesota, area.

P.K. Sims

P. K. Sims
Secretary
Subcommission on Precambrian
Stratigraphy

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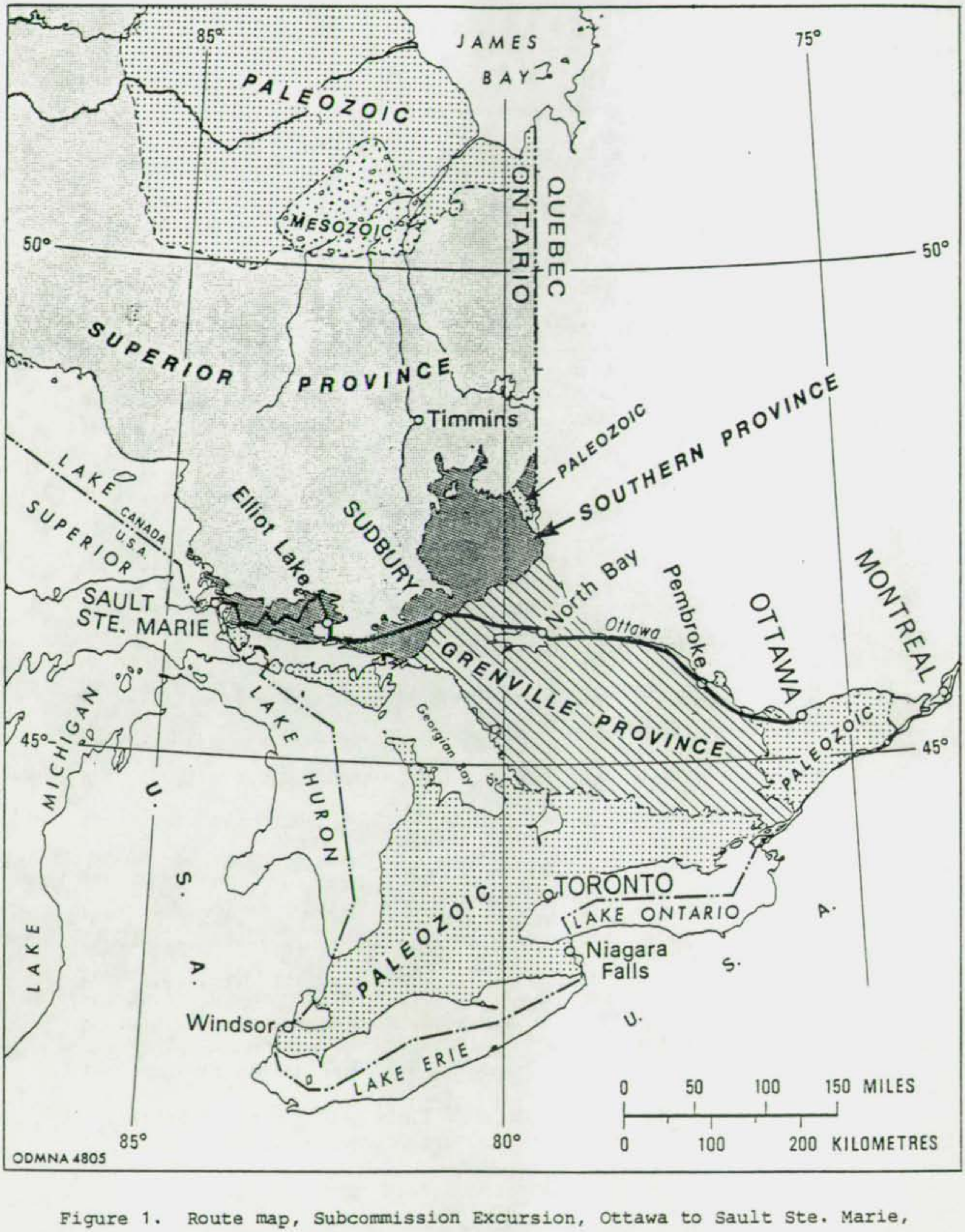

Figure 1. Route map, Subcommission Excursion, Ottawa to Sault Ste. Marie, Ontario, 1979.

THE GRENVILLE PROVINCE OF ONTARIO

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GEOLOGIC SUMMARY

The Grenville Province, the most southerly of the three structural provinces of the Canadian Shield in Ontario (fig. 1), is underlain by a variety of supracrustal and intrusive rocks that reflect a long, complex geological history spanning more than 2000 Ma. Interpretation of this history is difficult because most of the rocks were subjected to a Late Precambrian high-rank regional metamorphism which culminated between about 1300 and 1000 Ma ago, and which converted nearly all the rocks into markedly recrystallized and deformed gneisses. This metamorphism, which is commonly referred to as the "Grenvillian Orogeny", affected the entire Grenville Province of the Canadian Shield and allows the Grenville Province to be recognized as a unique, primary subdivision of the Shield. Some of the major geologic features of the Grenville Province in Ontario are shown in Figure 2.

In Ontario and for an unknown distance northeastward across the Interprovincial Boundary into Quebec, high-metamorphic-rank gneisses of the Grenville Province are separated from relatively low metamorphic-rank rocks of the Superior and Southern Provinces by a fault zone, the Grenville Front Boundary Fault, which defines the northwestern boundary of the Grenville Province in Ontario (Lumbers, 1978, and fig. 2). This fault is near the northwestern margin of the Grenville Front Tectonic Zone; details of which are discussed in Lumbers (1978; copies accompany this excursion guide).

The Grenville Province of Ontario contains two major supracrustal accumulations of contrasting age and lithology. The older accumulation, deposited during the Middle Precambrian between 2500 and 1800 Ma ago, is confined to the northern two thirds of the Province and consists mainly of clastic siliceous metasediments deposited in deep water below wave-base (fig. 2). Near the northwestern margin of the Grenville Province, the older accumulation rests unconformably upon Archean rocks extending across the Grenville Front Boundary Fault into the Grenville Province from the Superior Province (fig. 2 and Lumbers, 1978). The base of this accumulation is marked by a coarse clastic sequence (fig. 2) deposited largely in deep water below wave-base, probably in a submarine fan environment (Lumbers, 1978). This coarse facies gradually changes into thinly bedded, medium-grained metagreywacke and meta-argillite which could represent a facies change to outer fan turbidites. These rocks were deposited in a linear depression or trough along the northwestern margin of the Grenville Province and are correlative with the lower part of the Huronian Supergroup in the Southern Province (Lumbers, 1978). South of the trough metasediments, the supracrustal rocks contain several major units of moderately to well-sorted arkose, subarkose, orthoquartzite, aluminous

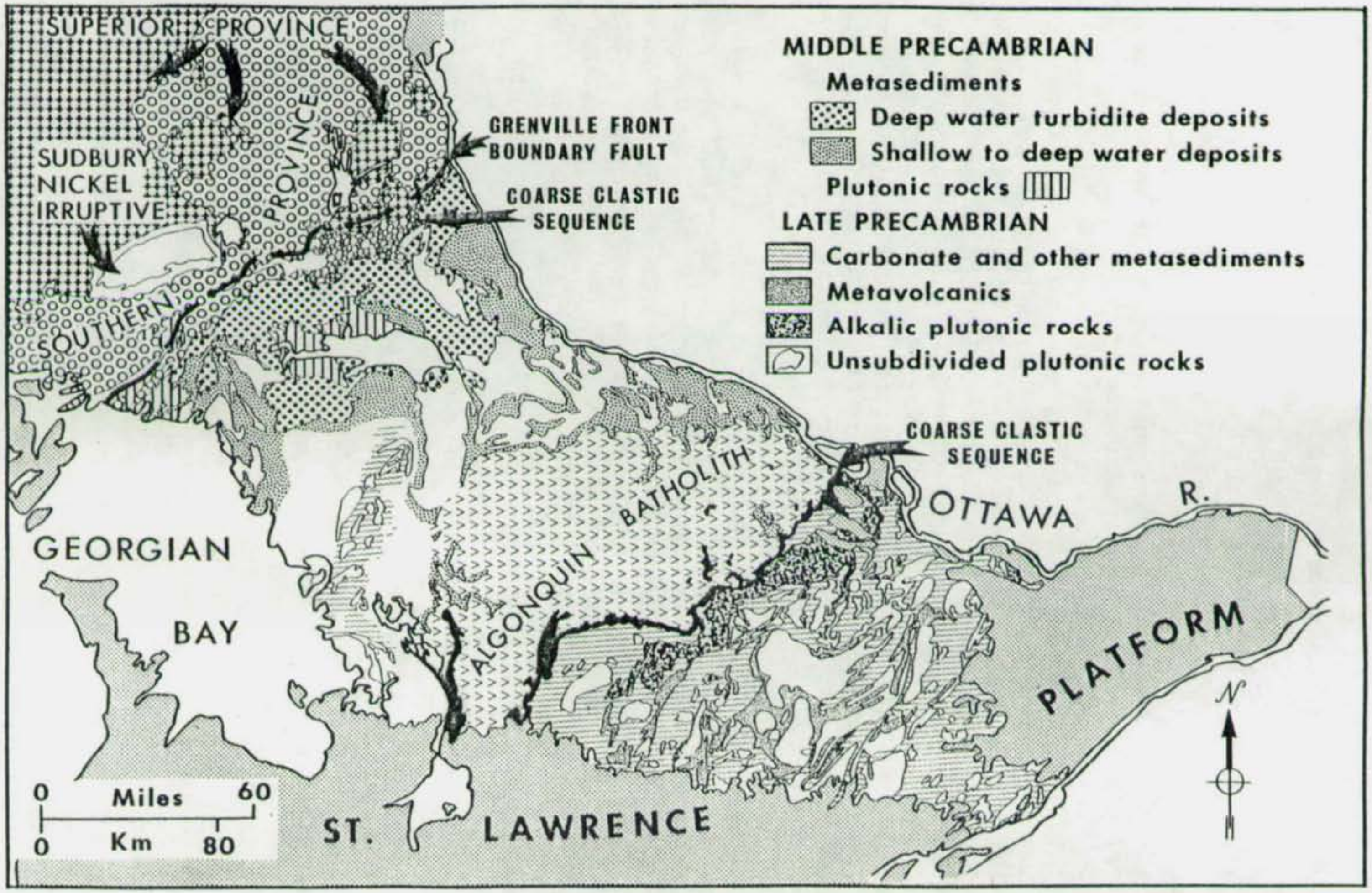

Figure 2. Sketch-map showing some major geologic features of the Grenville Province of Ontario.

clay-rich material, and rare iron-formation that were deposited in a nearshore environment under the influence of wave action and are intercalated with thick sequences of impure sandstone. These rocks mark an important change in the paleogeography of the Middle Precambrian geosynclinal accumulation, and they could represent a younger Middle Precambrian sequence deposited upon the deep-water facies of the trough.

The younger accumulation, which includes rocks commonly referred to as the "Grenville Supergroup", is present mainly in the southern third of the Grenville Province (fig. 2) and consists mainly of carbonate metasediments, subordinate clastic siliceous metasediments, and locally thick sequences of metavolcanics. The older accumulation was intruded by the Algonquin batholith (fig. 2), composed of anorthosite suite rocks consisting mainly of quartz monzonite and syenitic rocks, and containing only local concentrations of anorthositic and tonalitic rocks. The batholith underlies the central portion of the Grenville Province of Ontario and appears to be part of a major magmatic event of continental proportions, about 1400 to 1500 Ma old, that has been recognized throughout a broad area extending from Labrador to southern California (Silver et al., 1977).

Supracrustal rocks of the younger accumulation rest unconformably upon the southern and at least part of the western flanks of the batholith, and the base of the accumulation is marked by a basal arkose and coarse clastic sequence (fig. 2) containing local thin units of marble, calcareous and siliceous shaly metasediments, and orthoquartzite. This basal sequence undergoes a facies change across strike into a carbonate-rich sequence deposited in a marine basin that can be traced continuously across strike for over 240 km southeast into the Adirondack region of New York State. Major volcanism occurred within the carbonate basin about 1300 Ma ago (Lumbers, 1967), but the volcanism appears to be restricted to the northwestern part. The base of the volcanic sequence is not exposed, but the earliest recognizable volcanism was basaltic and formed shield volcanic complexes which later evolved into stratovolcanoes (Lumbers, 1967). Volcanic highlands were eroded supplying volcaniclastic detritus that formed aprons of turbidite deposits about the eroded highlands. The carbonate facies was deposited both during and after the volcanism, so that this facies is intercalated with most of the volcanic and volcaniclastic rocks (Lumbers, 1967). The thickest accumulation of exposed volcanic rocks is near the southern edge of the Canadian Shield (fig. 2), and this portion coincides with the only region of low-rank metamorphism so far identified in the Grenville Province of the Shield (Lumbers, 1967). No basement rocks have been identified within the basin, and it appears that the Algonquin batholith was emplaced near the margin of a Middle Precambrian continental mass. A second basin of supracrustal rocks possibly correlative with those of the younger accumulation extends northward from southeastern Georgian Bay to south of Lake Nipissing (fig. 2). These supracrustal rocks have been only partly mapped on a reconnaissance scale, but they appear to be characterized by abundant shaly metasediments and intercalated thin marble units, together with minor metavolcanic units. The oldest plutonic rocks identified within the younger accumulation are about 1280 Ma old, and this age provides an upper limit for the interval involved in deposition of the accumulation.

Most of the plutonic rocks cutting the older accumulation belong to the anorthosite suite and are Late Precambrian, ranging in age from about 1500 to 1100 Ma old (Lumbers, 1975; Lumbers and Krogh, 1977). The only plutonic bodies older than those of the anorthosite suite consist mainly of quartz monzonite and minor granodiorite emplaced mainly within the deep-water turbidite facies during the Middle Precambrian, about 1800 Ma ago (fig. 2). A large variety of plutonic rocks were emplaced within the carbonate-rich basin of the younger accumulation between about 1300 and 1000 Ma ago. About five major igneous rock suites can be recognized (Lumbers, 1967; in press a), and in approximate order of decreasing age these are: (1) biotite diorite suite closely associated in space and time with the volcanism and characterized by the abundance of dioritic and sodic granitic rocks; (2) anorthosite suite; (3) quartz monzonite suite; (4) alkalic suite dominated by alkalic syenite and granite, but containing minor mafic alkalic rocks and nepheline syenite; and (5) syenite-monzonite suite characterized by abundant calc-alkalic syenite and minor monzonite, quartz monzonite, and mafic rocks. The alkalic suite is probably the most renowned of the five suites because of the nepheline syenites and deposits of corundum associated with the suite. The suite is mainly concentrated in a major complex near the northern margin of the carbonate basin (fig. 2). Recent work (Lumbers, 1976; in press) suggests that a genetic link may exist between this suite and the anorthosite suite. Emplacement of pegmatite dikes throughout the gneisses between about 1100 and 900 Ma ago during the waning of the high-rank regional metamorphism ended major plutonic activity within the Grenville Province of Ontario. Most of the pegmatite is granitic in composition, but syenite pegmatite is abundant in the alkalic complex near the northern margin of the carbonate basin. The pegmatites and related skarns are the hosts for most of the uranium mineralization known in the Grenville Province.

The metamorphic history of the Grenville Province is difficult to determine in detail because the late high-rank regional metamorphism effectively obliterated evidence of any earlier metamorphic events. Nevertheless, some evidence suggests that the older supracrustal accumulation near the northwestern margin of the Grenville Province was affected by the Penokean event that regionally metamorphosed rocks of the Southern Province near Sudbury and to the west between 2160 and 1800 Ma ago (Lumbers, 1978). This metamorphism varied in intensity but rarely exceeded the temperature and pressure conditions of the lower almandine amphibolite facies. Mineral assemblages developed in the Grenville gneisses during the late high-rank regional metamorphism are most indicative of temperature and pressure conditions existing in the middle to upper almandine amphibolite facies. Locally within some highly strained granitic intrusions in the younger accumulation south of the Algonquin batholith, mineral assemblages suggestive of granulite-facies temperature and pressure conditions exist. During the late metamorphism, the Algonquin batholith was reactivated and became diapiric toward the overlying rocks, causing most of the tectonic deformation not only of rocks of the batholith, but also of rocks of the two supracrustal accumulations (Schwerdtner and Lumbers, in prep.). Numerous local diapiric structures replete with subhorizontal flattening gneissosity have been identified within the batholith. The long diameter of the batholith parallels the overall trend of the folded unconformity that marks the base of the younger supracrustal accumulation (fig. 2). This diapirism accounts for subhorizontal gneissic foliation and recumbent folding dominant in the supracrustal rocks for tens of kilometres around the batholith.

The latest tectonism recognizable in the Grenville Province is late activity along the Ottawa-Bonnechere Graben (fig. 3) which crosses the Grenville Province westward along the Ottawa and Mattawa Valleys and continues westward across the Grenville Front Tectonic Zone to join the Murray Fault System south of Sudbury. The graben, which is part of the St. Lawrence Rift System (Kumarapeli and Saull, 1966) was probably initiated early in Archean time (Lumbers, in press b) and has remained active to the present eastward from Lake Nipissing. The graben is marked by prominent fault systems on the north (Mattawa River Fault and Ottawa System, fig. 3), by swarms of diabase dikes and a prominent zone of normal faulting and subsidiary grabens on the south, and widely scattered zones of localized fenitization. Most of the diabase dikes postdate the late high-rank regional metamorphism in the Grenville Province, but some were intruded while this metamorphism was on the wane. Lamprophyre dikes, small peridotite bodies, one late gabbro body, and a few alkalic rock-carbonatite complexes and cryptoexplosion structures, all ranging in age from Late Precambrian to Early Cambrian, are localized within the graben.

CURRENT RESEARCH

There are numerous problems to be resolved before an adequate understanding of the Grenville Province is attained. Chief among these is the need for more complete geologic mapping than is now available. Although over half of the Grenville of Ontario is covered by reconnaissance and more detailed geologic maps at scales of 1:126,720, 1:63,360, and 1:31,680, much of the Grenville in Quebec to the east of Ontario is either unmapped, or covered by reconnaissance mapping at scales of 1:253,440 or even less detail. This scanty mapping coverage in Quebec is particularly serious because most of the Grenville Province of the Canadian Shield lies in this region. Nevertheless, major advances in our knowledge of Grenville geology have been made in the last 15 years, aided greatly by the application of modern isotopic age dating.

Current research in the Grenville of Ontario is focused upon regional mapping, structural and metamorphic studies, and petrology of the plutonic rocks in order to determine the general stratigraphy and metamorphic and plutonic histories. Geochronology is an essential element in this research, and much has been learned in interpreting the primary lithology and origin of the high-rank metamorphic gneisses. Without this capability, advances in our understanding of Grenville geology would be limited severely.

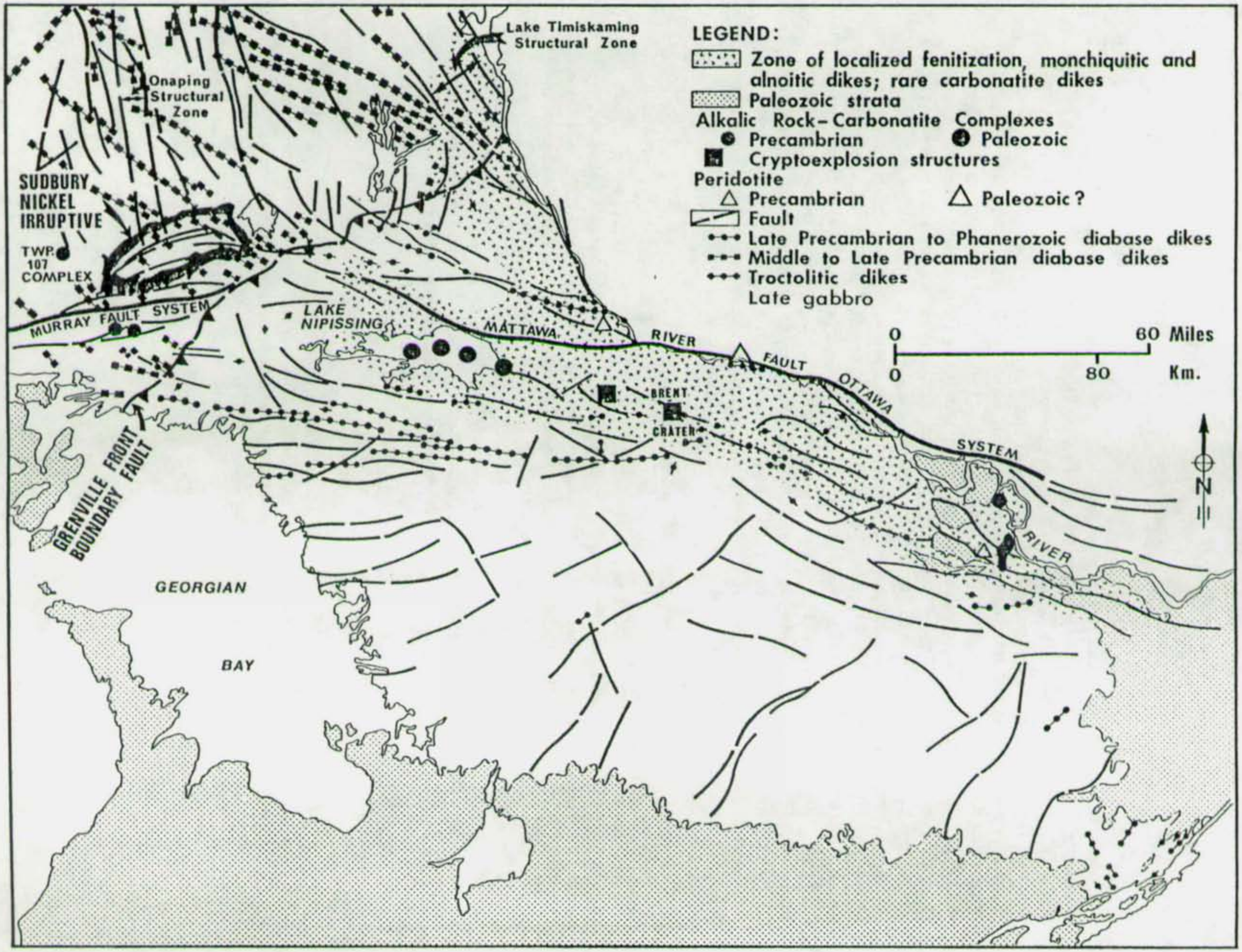

Figure 3. Sketch-map showing some major geologic features of the Ottawa-Bonnechere Graben in Ontario.

GEOLOGY OF THE SUDBUY-SAULT STE. MARIE AREA, ONTARIO[1]

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INTRODUCTION

The Sudbury-Sault Ste. Marie area comprises much of the eastern part of the Southern Province, a tectonic subdivision of the Canadian Shield that extends eastward from Minnesota through Lake Superior, along the north shore of Lake Huron to the Grenville Front near Sudbury, and northeastward to the Cobalt and Kirkland Lake areas (fig. 4). The Southern Province adjoins the Superior Province to the north and the Grrenville Province to the southeast. To the south and west it is bounded by undeformed Phanerozoic rocks. The major deformation within the Southern Province occurred during the early Proterozoic (Aphebian)* tectonic events and is consequently younger than that of the Archean Kenoran Orogeny of the Superior Province and older than that of the late Proterozoic Grenvillian Orogeny of the Grenville Province.

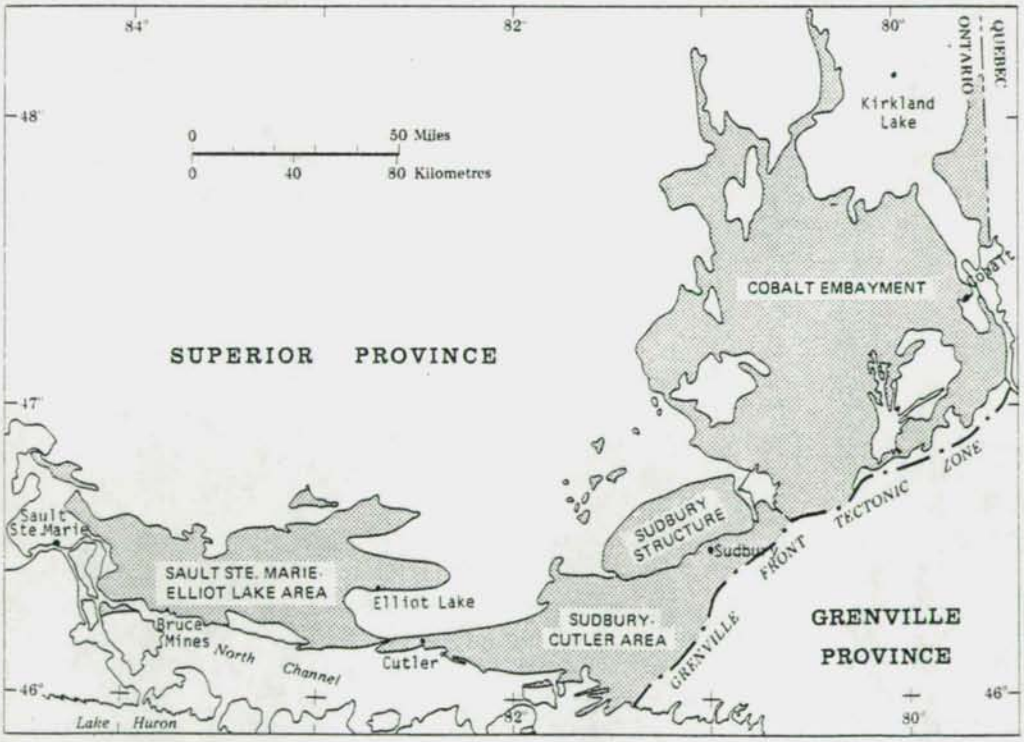

Figure 4. Major tectonic subdivisions of the Canadian Shield in the Lake Huron region.

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[1] This section is a combined, expanded version of previous guidebook descriptions by Baer et al. (1972), Card et al. (1972b), Card et al. (1978), and Robertson (1978).

*Stockwell (1961) time nomenclature is given in parentheses.

The eastern part of the Southern Province, i.e., from Lake Superior eastward, consists mainly of early Proterozoic (Aphebian) sedimentary and volcanic rocks of the Huronian Supergroup, which, together with their basement of Archean granites, metasediments and metavolcanics, were variably deformed, metamorphosed, and invaded by mafic and felsic intrusions during early Proterozoic (Aphebian) time. The Huronian sequence was deposited between 2500 million years ago, the approximate age of the Archean granitic basement rocks, and 2115 million years ago, the age of the post-Huronian Nipissing Diabase intrusions (Van Schmus, 1965; Fairbairn, et al., 1969). After the widespread intrusion of the Nipissing Diabase, there followed, successively, deformation and metamorphism, an explosive event of great magnitude in the Sudbury area creating the Sudbury Structure, deposition of the Whitewater Group within it, intrusion of the Nickel Irruptive, and further deformation and mafic to felsic intrusion, all within the early Proterozoic (Aphebian). Later events recorded in various parts of the region include the intrusion of relatively small differentiated circular complexes, local fenitization, emplacement of mafic dyke swarms, Keweenawan volcanism near Lake Superior, and tectonism close to the Grenville Front, all in the middle Proterozoic (Helikian). The record is closed by deposition of late Proterozoic (Hadrynian) sandstone in the extreme west near Lake Superior. The geological record of the eastern Southern Province spans approximately 1500 million years of Proterozoic time.

The Sudbury Structure, which here refers to the Nickel Irruptive and its world-famous nickel-copper sulphide ores, the Whitewater Group within the Sudbury Basin, and the brecciated and shatter-coned zones in the surrounding country rocks, is the foremost geological feature of the eastern Southern Province, scientifically and economically. Over $12,000,000,000 worth of nickel, copper, cobalt, selenium, tellurium, platinum metals, gold, silver, iron ore, and sulphur have been produced from the Sudbury ore deposits over the past 90 years. Since the first production of nickel at Sudbury in 1890 until 1975, an estimated 6.5 million metric tons of nickel and 6.4 million metric tons of copper have been produced. Metals have been produced from over 40 mines in this period, and some 21 mines are in production. In spite of continuous study for almost a century, however, questions about the ore deposits and the origin of the structure remain.

Ranking not far behind the Sudbury district in economic and scientific interest is the uranium mineralization mainly concentrated in the Elliot Lake Camp about 100 miles (160 km) to the west. Uranium and thorium mineralization is present in several of the Huronian formations throughout the eastern Southern Province, but deposits of major importance occur in pyritic quartz-pebble conglomerates of the basal Matinenda Formation in that area. These deposits are directly related to stratigraphy and sedimentology, as they are generally considered to be syngenetic placer deposits, possibly formed under anoxygenic conditions. To the end of 1978, a total of 81,854 metric tons of uranium metal has been produced, or 106,410 short tons of U_3O_8. In addition, relatively minor amounts of thorium and yttrium production followed, during which up to 12 mines operated, but then a protracted period of sharply reduced tonnage set in extending into the seventies. Then, because of large new sales contracts lasting well into the next century, production returned to capacity and substantial expansion programs were undertaken by the two remaining producing companies, Denison Mines Limited and Rio Algom Mines Limited. The combined mining rate of approximately 13,000 metric tons per day will be sharply increased by 1982.

General Geology

The general geology of the Lake Huron region is shown in Map No. 2, Guidebook No. 4, Ontario Division of Mines, part of your excursion kit, and the table of formations is given in Table 1, this account. The Archean rocks of the Superior Province in the north comprise abundant felsic plutons of quartz monzonite composition, remnant metavolcanic-metasedimentary belts and hybrid migmatitic gneisses. A large window of these rocks occurs within the Southern Province along the shore of Lake Huron southwest of Elliot Lake (fig. 5), showing that much of the Proterozoic belt, at least, was intracratonic and not deposited on a continental margin. The metavolcanic sequences of Superior Province commonly yield radiometric ages of about 2700 Ma, the felsic plutons 2500 to 2700 Ma. The Archean rocks represent the major source of detritus for the Proterozoic clastic sediments. Subsidence of cratonic blocks,, presumably controlled by faulting, was accompanied by mafic intrusion and volcanism during the initiation of the Proterozoic trough.

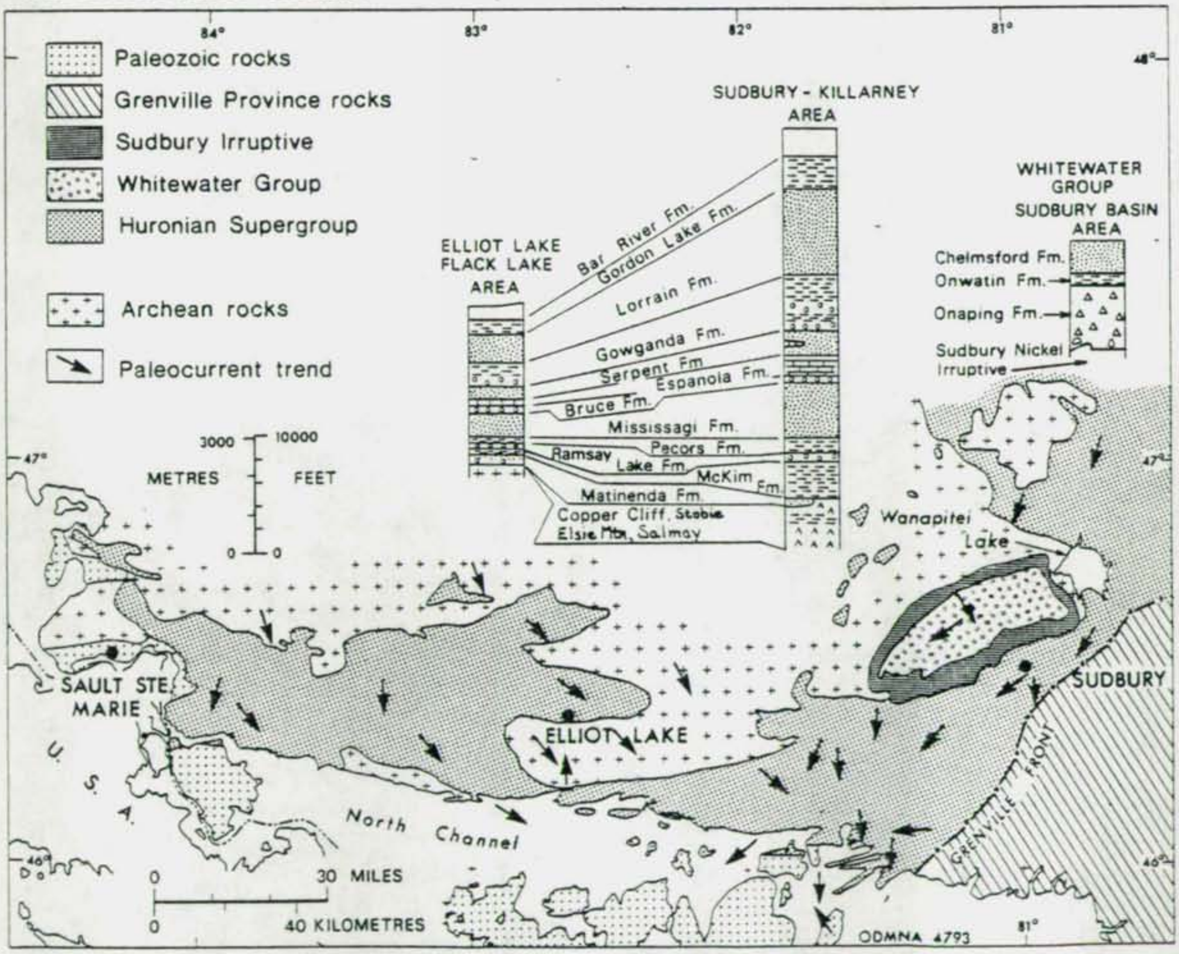

Figure 5. Distribution, stratigraphy, and paleocurrents of the Huronian Supergroup.

Table 1. Table of Precambrian formations -- north shore of Lake Huron.

EON	ERA	PERIOD OR SUB-ERA	SUPERGROUP	GROUP	FORMATION, LITHOLOGY AND ESTIMATED MAXIMUM THICKNESS (METRES)	Rb/Sr Age (Ma) (λ-1.42) (Zr-U/Pb) age	TECTONIC EVENTS
PROTEROZOIC	HADRYNIAN				JACOBSVILLE 200+ (ss)		
	Unconformity						GRENVILLIAN OROGENY (local effects near Grenville Front)
	HELIKIAN	NEO-HELIKIAN		KEWEENAWAN	MAMAINSE POINT (basalt, rhyol.)	ca 1100	
			Unconformity				
					MAFIC DYKES oliv. diabase lamprophyre	 1250 1385	
			Intrusive contact				
		PALEO-HELIKIAN			CROKER COMPLEX gran. to dior.)	1460	
			Intrusive contact				
					MONGOWIN COMPLEX (dior. to perid.)		
	Intrusive contact						HUDSONIAN OROGENY (limited to southern part of belt)
					CUTLER PLUTON (gran. to monz.)	ca 1750	
			Intrusive contact				
					NICKEL IRRUPTIVE (norite, gabbro, granophyre) 4000	1845 (Zr)	
			Intrusive contact				
				WHITE-WATER	CHELMSFORD (gw.) 850 ONWATIN ' (slate) 300 ONAPING (tuff-breccia) 1800	ca 1900(?) (no direct dates)	PENOKEAN OROGENY (Main Huronian folding and meta-morphism)
			Unconformity				
					NIPISSING DIABASE (qrtz. diab., gb., gnphyre) CREIGHTON AND MURRAY PLUTONS (gran., qtz., monz.)	2115 ca 2165	"BLEZARDIAN EVENTS" (Intrusion, Sudbury district, early Huronian folds)
			Intrusive contact				

PROTEROZOIC	APHEBIAN		HURONIAN	COBALT	BAR RIVER (o'qzite.) 900				
					GORDON LAKE (slst., ch., ss.) 550				
					LORRAIN (qzite., ark.) 2150				
					GOWGANDA 1500 (cgl., slst., ss., arg.)				
				Gradation to disconformity					
				QUIRKE LAKE	SERPENT (qzite., ark.) 2000				
					ESPANOLA 540 (ls., slst., dol., ss.)				
					BRUCE (cgl.) 300				
				Conformity					
				HOUGH LAKE	MISSISSAGI (qzite., ark.) 2000(?)				
					AWERES (ark., cgl.)	(Probable Mississagi equivalent at Sault Ste. Marie			
					PECORS (arg., ss.) 600				
					RAMSAY LAKE (cgl.) 200(?)				
				Conformity - Disconformity					
				ELLIOT LAKE	WEST	ELLIOT LAKE	EAST		
					Thessalon (basalt) 1000	McKim (arg.) 900	McKim (slst., gw., arg.) 2000		
					Matinenda (sub-arkose) 600	Matinenda (sub-arkose) 225	Copper Cliff (rhyol.) 750		
							Stobie (volc.-wacke) 1500		
						Mafic volcanics	Elsie Mountain-Salmay Lake (basalt) 1000(?)		
Unconformity (Regolith)									
ARCHEAN					Massive granite, granodiorite			ca 2600	KENORAN OROGENY
					Intrusive contact				
					Gneissic to massive granite, syenite, granodiorite, quartz monzonite, migm.				
					Intrusive contact				
					Mafic and felsic metavolcanics, metasediments; paragneiss and amphibolite				

The Grenville Province adjacent to the southeast comprises a variety of Proterozoic felsic and mafic intrusions and highly metamorphosed supracrustal rocks that are broadly correlative with those of the Southern Province. The metasediments were originally mainly thin-bedded wacke and chert, now metamorphosed to a variety of biotitic gneisses. There are subordinate amounts of arkose, orthoquartzite, and clay-rich sediments now represented by quartzofeldspathic gneisses, and lesser amounts of calcareous rocks, now calc-silicate gneiss and marble. Major metamorphism and deformation of the Grenville Province last occurred during the Grenvillian Orogeny 1000 to 1200 Ma ago.

The region along Lake Huron visited on this excursion is underlain mainly by Huronian rocks, and has been informally referred to as the "Huronian fold belt", but it has long been formally classified tectonically (Stockwell, 1961) as a part of the Penokean fold belt, a subdivision of the Southern Province that lies largely in the United States south of Lake Superior. As mentioned, these rocks have been moderately to severely deformed, regionally metamorphosed, and intruded by mafic and felsic plutons during several Proterozoic tectono-thermal events.

HURONIAN SUPERGROUP

The Huronian Supergroup is the dominant supracrustal sequence in the region, as well as the oldest of the Proterozoic rocks (tbl. 1). Preserved strata of the supergroup occupy a northerly-concave arcuate belt some 320 km long along the north shore of Lake Huron from Sault Ste. Marie in the west to the Grenville Front in the east, and also continue northeastward to Cobalt and beyond as far as the vicinity of Noranda, Quebec, for a further 250 km. Strata correlative for the most part with upper Huronian rocks occur farther northeast in Quebec in the Chibougamau area and perhaps in the Otish Mountain area as well, extending the possible length for the Huronian depository to over 1000 km. The succession is most completely preserved in the Bruce Mines area in the western part (the "original Huronian area", having been first studied 130 years ago by Wm. Logan and A. Murray), in the Elliot Lake-Flack Lake area in the central part, and in the Sudbury-Lake Huron section in the eastern part of the fold belt. In general, the succession and most of its formations thicken southward and eastward; at Bruce Mines the supergroup attains a thickness of about 7000 m compared with 10,000-12,000 m in the Sudbury-Lake Huron section.

The Huronian Supergroup consists mainly of coarse clastic sediments, with local basal volcanics and minor chemical sediments, divided into the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt Groups, in order upward (tbl. 1). Volumetrically it is dominated by quartz-feldspar and quartz-arenites of the Matinenda, Mississagi, Serpent, Lorrain and Bar River Formations (fig. 5). Quartzose and feldspathic siltstones, wackes, and conglomerates are important in other formations, but shaly rocks are rare. The clastic sediments were derived mainly from the Archean craton to the north (fig. 5), and were deposited under very shallow to deep water conditions in the epicratonic basin superimposed on the Archean basement.

The basal part of the Huronian sequence, the Elliot Lake Group, comprises an interfingering sequence of feldspathic quartzite and conglomerates of various types including uraniferous quartz-pebble conglomerate

(Matinenda Formation), a westward-thinning wedge of siltstone, argillite, and greywacke (McKim Formation), and local accumulations of volcanic rocks, mainly basaltic, that have local names. This group varies considerably from west to east. West of Elliot Lake, it comprises essentially only the Matinenda and its equivalents and important volcanic units that in some cases exceed 1000 m in thickness. The McKim is absent or negligible. At Elliot Lake the Matinenda is dominant, volcanics are thin, and the west edge of the McKim wedge appears in the section. In the Sudbury area, a marked change appears, and the group consists of a thick basal sequence of tholeiitic metabasalt and greywacke (Elsie Mountain and Stobie Formations), felsic metavolcanics, largely pyroclastic (Copper Cliff Formation), and voluminous turbiditic greywacke and siltstone of the McKim Formation. The Matinenda wedges out a short distance west of Sudbury.

The two succeeding groups, the Hough Lake and the Quirke Lake, constitute two major sedimentary cycles, each consisting of a lower conglomerate (paraconglomerate) unit, a middle, largely silty unit, and an upper thick sandstone unit (tbl. 1). The conglomeratic units, the Ramsay Lake and Bruce Formations, are relatively thin, massive or crudely bedded sheets of pebbly to bouldery wacke. The middle units consist of thin-bedded siltstone, fine-grained greywacke or "impure" quartzite, and thick-bedded greywacke turbidite, grading upward into non-turbidite protoquartzite. One, the Espanola Formation of the Quirke Group, is noteworthy for its content of carbonate-rich beds. The sandstone units, the Mississagi and Serpent Formations, consist of coarse-grained, crossbedded immature to submature arenites rich in quartz and feldspar.

Roughly the upper half of the Huronian Supergroup, the Cobalt Group, transgresses far to the north of the lower groups and overlies them with varying relationship ranging from gradational to nongradational conformity, to disconformity, to local angular discordance. Over a large area west of Elliot Lake, the Cobalt lies on an eroded surface in the Espanola Formation, and in the extreme west near Sault Ste. Marie it rests directly on still older units, but this may be due to original westward thinning of the Quirke Lake Group as well as erosion. The Cobalt Group, in order upward, consists of: a heterogeneous assemblage of conglomerate, siltstone, paraconglomerate, greywacke, and arkose (Gowganda Formation); a thick sequence of arkose, feldspathic quartzite, and orthoquartzite (Lorrain Formation); a distinctive sequence of thin-bedded, varicoloured siltstone and fine-grained sandstone (Gordon Lake Formation); and an uppermost orthoquarzite with hematitic siltstone (Bar River Formation).

Sedimentary structures commonly found in clastic sequences are abundant in the Huronian strata. Crossbedding is by far the most prevalent, occurring throughout the thick quartzite formations and in the sandstone and siltstone of other formations in all four groups. It is commonly rather obscure in the orthoquartzite units bcause of the monomineralic character of the rock. The scale of crossbeds and the thickness of foresets is usually proportional to grain size. Graded greywacke sequences, sole marks, portions of Bouma cycles, and other criteria for turbidite sedimentation are well documented in the argillite-siltstone-greywacke sequences of the McKim, Pecors, and upper Gowganda Formations near Sudbury, but are rare elsewhere in the belt. Slump structures in fine-grained units and clastic intrusions and breccias in pre-Cobalt formations, particularly the Espanola Formation, suggest that some form of syn-sedimentary tectonic activity took place (Collins, 1925; Eisbacher, 1970; Young, 1973a)

The available paleocurrent data indicate that the Huronian sediments were deposited by generally south-flowing currents. Regional data indicate a Y-shaped pattern with currents from the northwest in westerly areas and from the north to northeast in central and easterly areas (fig. 5). Bimodal to polymodal patterns have been observed in many formations in various parts of the Sudbury-Lake Huron district (Young, 1968; Casshyap, 1968; Card, 1976). However, nearly all major percentage modes in the coarse clastic quartzite formations point southeasterly, southerly or southwesterly. It is not certain if the observed bimodality or polymodality is due to sample bias, as suggested by Pettijohn (1957) and Young (1968), or if it is real, resulting from original changes in stream current regimes or, as favoured by Palonen (1973) and Card (1978), from redistribution by long-shore marine currents.

Although its formations are remarkably continuous and lithologically similar throughout the belt, the Huronian displays variations in thickness and facies related to the tectonic development of the depository. This is most apparent in the east, where, as mentioned, there are rapid facies changes in the basal Elliot Lake Group, especially around the main centre of volcanism at Sudbury. The entire sequence, particularly the lower half, thickens southerly and southeasterly; the pre-Cobalt sequence thickens from approximately 2000 m in the north and west to 6000 m in the south and east. Much of this thickening occurs abruptly across zones now marked by major faults of the Murray System, indicating that the ancestors of these structures actively controlled Huronian depositional patterns. There are also notable, if inconsistent, variations in thickness of some Huronian formations as the Grenville Front is approached. For example, the McKim and Mississagi Formations thicken toward the front near Sudbury whereas the Espanola, Bruce, and Serpent thin markedly in this direction. The Grenville Front has been described as marking an important paleogeographic boundary in the development of a basin that extended well into the Grenville Province from the Lake Huron regions (Lumbers, 1975).

The Huronian sediments have been interpreted as the products of fluvial, littoral, and continental to marine glacial processes (Frarey and Roscoe, 1970; Young, 1970; Roscoe, 1973). In contrast, Pettijohn (1970) and Card (1978) have interpreted the Huronian groups, including the coarse arenites, as products of regressive marine cycles, although Pettijohn retained a glacial or glaciomarine origin for the conglomeratic greywackes. In the interpretation of Card (1978), the regressive cycles probably began with normal faulting, subsidence, and sudden increase in paleoslope that triggered submarine debris flows and deposition of the conglomeratic units. This was followed by deposition of the silty rocks under relatively deep water conditions by turbidity currents. Then, with infilling and return to shallow-water conditions, the crossbedded sandstones were deposited.

In summary, the lower half of the Huronian Supergroup and strata considered to be of similar age in the adjacent Grenville Province constitute a southeastward-thickening ensialic clastic wedge deposited over a rapidly subsiding basin superimposed on the Archean craton. In the north and west, these deposits were floored by a relatively stable, gently sloping platform, although disconformities caused by periodic vertical movements occur in the sequence. In the south and east, they thicken rapidly, and the incoming of thick subaqueous volcanics and turbidites lend miogeosynclinal attributes to the lower part of the succession. Lumbers (1975) and Card (1978) suggest that a miogeosynclinal facies continued into the Grenville Province and was rapidly replaced there by a deep-water greywacke facies, now represented by biotitic paragneisses. The lower Huronian was variously followed by important uplift and erosion in the north and west, by local mild tectonism, and in the southeast without interruption by deposition of the Cobalt Group, which along the entire belt far overlapped the lower half onto the craton. The four thick formations of the upper group record four distinct, abruptly grading environmental regimes in Cobalt time: first the heterogeneous, disordered clastic debris including tillite-like beds and dropstone-bearing silts presumably indicating a glacial or frigid regime; next the shallow-water coarse arenite succession of the Lorrain Formation ranging upward from arkose to orthoquartzite, whose upper part has been interpreted as the product of a warm humid environment because diaspore, kaolinite, and their metamorphic equivalents occur in the orthoquartzite (Church, 1967; Chandler, et al., 1969); thirdly the thin-bedded fine clastics and cherty beds (Gordon Lake Formation) of littoral, lagoonal, or tidal-flat origin; and finally the reversion to high-energy orthoquartzite of the Bar River Formation, variously interpreted as fluvial, beach, or shallow marine. This great four-part clastic sequence of the Cobalt Group, 4 to 6 km thick, was laid down throughout the entire region from Sault Ste. Marie to Cobalt and probably far beyond; it was everywhere deposited uninterruptedly, indicating regular, continuous, and protracted subsidence of the Archean floor.

WHITEWATER GROUP

The Whitewater Group, comprising the Onaping, Onwatin, and Chelmsford Formations, is confined to the Sudbury Basin, the area bounded by the Sudbury Nickel Irruptive (fig. 6). The lowermost formation, the Onaping, is intruded by the granophyre of the Sudbury Nickel Irruptive.

The Onaping consists of approximately 1800 m of tuff-breccia composed of angular fragments of pumice, granite, gneiss, and quartzite, and large bodies of devitrified glass in a fine-grained carbonaceous matrix characterized by numerous shard-like fragments of devitrified glass. The Onaping is poorly sorted and only grossly stratified. A discontinuous zone of coarse breccia as much as 90 m thick at the base of the formation consists of metasedimentary (notably quartzite), granitic and gneissic fragments as large as 90 m in maximum dimension in an igneous or annealed matrix. This is succeeded by 150 m of interstratified coarse and fine breccias, 900 m of breccia lacking the coarse blocks of the unit below, and 600 m of fine and medium breccia and finally by about 150 m of massive and bedded fine-grained clastic material (Stevenson, 1972). The Onaping has been interpreted as a pyroclastic deposit formed by explosive volcanism (Williams, 1957; Stevenson, 1972) and as a "fallback breccia" produced by meteorite impact (Dietz, 1964; French, 1970). In either interpretation it is a remarkable deposit. Entirely fragmental, its preserved volume is crudely estimated at between 2000 and 4000 cubic kilometres, using a geometric configuration similar to that in Figure 8D.

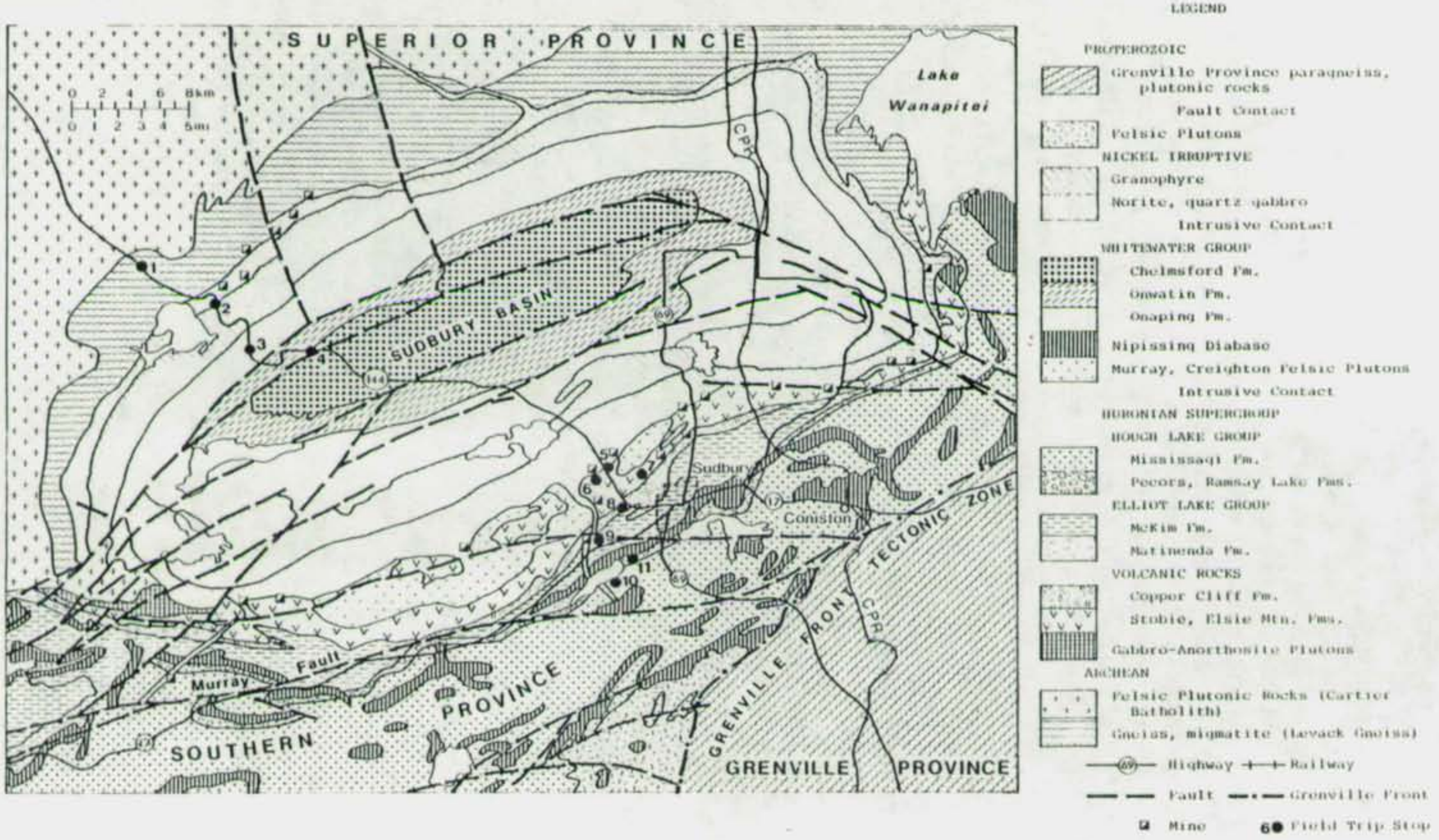

Figure 6. Geology of the Sudbury area, with field stops for Day 2.

The Onwatin Formation consists of about 300 m of carbonaceous, pyritic slate. The contact with the underlying Onaping Formation is conformable and gradational through a sequence of interbedded tuff and slate, or, at the southwest end of the basin, through a thin sequence of carbonate- and chert-rich rocks with concentrations of copper, zinc, and lead-bearing sulphides. This carbonate-chart unit has been informally termed the "Vermilion formation".

The uppermost unit, the Chelmsford Formation, comprises about 850 m of feldspathic greywacke with the thick differentiated bedding, graded 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 to the north or northeast and were transported by turbidity currents flowing southwest parallel to the present major axis of the Sudbury Basin (Cantin and Walker, 1972; Rousell, 1972).

The rocks of the Sudbury Structure have been deformed and mildly metamorphosed and the intensity of this deformation and metamorphism increases from north to south. The Whitewater Group strata have been thrown into a series of en echelon doubly plunging open synclines and anticlines. The axial surfaces of these structures are approximately vertical and the folds display a nonpenetrative axial plane cleavage. In the southern part of the basin there is a pronounced southeast-plunging rodding lineation developed in the rocks of the Whitewater Group. The rocks of the northern part of the Structure are essentially unmetamorphosed, whereas those of the southern part display metamorphic mineral assemblages indicative of low greenschist conditions. Several major faults of the Murray System traverse the length of the Structure, and post-Irruptive vertical movements on these faults (south side up) of several kilometres have been postulated (Souch, et al., 1969). The deformation of the Sudbury Structure and the Whitewater Group was accomplished by compressive forces acting from the south in a direction normal to the major axis of the Basin (Rousell, 1975). This thermotectonic event occurred during the Proterozoic, probably some 1750 ± 50 Ma ago.

THE SUDBURY STRUCTURE

The Sudbury Structure is an elliptical structure some 56 km long and 24 km wide, elongated in an east-northeast direction and outlined by the Sudbury Nickel Irruptive (fig. 6). The Irruptive is a differentiated, funnel-shaped, tholeiitic intrusion 1.5 to 4.8 km thick that intrudes the Archean rocks on the north and Huronian metavolcanics and metasediments, the Nipissing Diabase, and granitic rocks on the south. The area inside the Irruptive, the Sudbury Basin, is, as mentioned, occupied by rocks of the Whitewater Group, and the older country rocks surrounding the Irruptive are extensively brecciated and contain shatter cones.

The Sudbury Structure was formed in a relatively brief interval beginning with an explosive event of great magnitude that resulted in brecciation, shatter coning, and shock metamorphism of the country rocks, formation of a large crater or caldera within which the Whitewater Group was deposited, followed by emplacement of the Nickel Irruptive and its sulphide ores, presumably by rising along fractures that extended to the lower crust or mantle. Chronometrically, the explosive event occured between 2115 Ma, the age of Nipissing Diabase, and 1840 Ma, the age of the Nickel Irruptive. It has been variously ascribed to explosive volcanism (Speers, 1957; Williams, 1957; Stevenson, 1972) or to meteorite impact (Dietz, 1964; French, 1970; Dence, 1972).

The Sudbury Structure is located in an area that is unique in a number of respects, including its depositional and tectonic history (Card and Hutchinson, 1972). It is located near the common junction of three tectonic provinces of the Canadian Shield, the Superior, Southern, and Grenville Provinces. The Sudbury Structure straddles the contact between the Superior Province and the Southern Province. It lies along the juncture of two major fault systems, the Murray and Onaping Systems, and is located near the intersection of regional antiformal arches. The Sudbury Structure is situated in an area in which the Huronian sequence not only reaches its greatest thickness but also contains appreciable amounts of volcanics and turbidites. The Sudbury Structure is probably located along a major crustal structure that extends the length of the Southern Province. This structure apparently originated during the Archean Eon, possibly as a suture or major fault between two contrasting cratonic domains, and to a large extent controlled Proterozoic depositional, tectonic, and igneous patterns in the Southern Province.

The foregoing relationships indicate that the Sudbury Structure is uniquely related to its regional setting and thus probably owes its origin to endogenic, explosive processes, rather than to fortuitous meteorite impact.

There still remains, however, the abundant evidence of shock metamorphism, phenomena which, as far as we know, can only be produced by hypervelocity shock waves generated by meteorite impact or nuclear explosion. For further information and discussion of the pros and cons of Sudbury as an astrobleme, the reader is referred to "New Developments in Sudbury Geology", especially the introductory paper by the editor of the volume, J.V. Guy-Bray (1972).

SUDBURY BRECCIA, SHATTER CONES, AND MICROSCOPIC SHOCK FEATURES

In an area some 15 to 30 km wide about the Sudbury Structure, the country rocks older than the Nickel Irruptive have been extensively brecciated and display numerous shatter cones. In addition, in these rocks and in the Onaping Formation of the Sudbury Basin there are microscopic features ascribed to shock metamorphism. The breccia zone outside the Irruptive, however, is much larger than that of the shatter cones, probably extending southward to Lake Huron about 50 km away (Frarey and Cannon, 1968); the outer limit of shock-metamorphic features in the breccia zone is not known.

The Sudbury Breccia consists of rounded country rock fragments ranging from a few millimetres to several metres in maximum dimension in a generally dark-coloured rock flour matrix. The breccia bodies range in width from thousands of metres to hairline seams, and form ramifying swarms that transect structural trends and lithologic contacts in the country rocks. Massive rock units such as the Creighton granite and the thick

Huronian quartzite formations are extensively brecciated. Regional mapping indicates that the Sudbury Breccia forms belts that are both radially and concentrically disposed about the Sudbury Structure (Card, 1978). Numerous examples exist of both monomict and polymict breccia. Chemical analysis of fragments and matrix of monomict breccias shows that there is no significant difference in composition between the fragments and the matrix except for the addition of water and carbon to the matrix (Card, 1968). Country rock structures and lithostratigraphic units can be traced through the breccia zones, demonstrating that, although there has been extensive milling in place, the breccia materials have not been moved great distances.

Shatter cones are prevalent in the country rocks in a zone approximately 15 km wide surrounding the Sudbury Structure and have also been noted in rock fragments in the Onaping Formation (French, 1972). They are present in all rock types older than the Nickel Irruptive but are best developed in micaceous Huronian quartzites. The shatter cones are cone-shaped parting surfaces in the rocks on which there are numerous lineations or striations that radiate out from a common apex. They are presumably the result of uniaxial compression resulting from a "hammer-blow" type stress. Commonly the cones or cone segments occur together in complex overlapping patterns (horsetail effect) and it is not uncommon to see cones in close proximity that "point" in opposite directions. Studies of the orientation of shatter cones with respect to the Sudbury Structure by Guy-Bray, et al. (1966) and French (1972) have given conflicting results, primarily because of uncertainties regarding the attitude of the Huronian strata at the time of shatter cone formation. In general, the shatter cones point toward the centre of the Sudbury Basin.

The microscopic features ascribed to shock metamorphism include kink bands in micas, planar features (shock lamellae) in quartz and feldspar, recrystallization and plastic deformation of quartz and feldspars, and melting of individual minerals and rock fragments. These features are abundant in the clasts of the Onaping Formation and in the older country rocks adjacent to the Irruptive. They have been documented by French (1972) and by Dence (1972).

SUDBURY NICKEL IRRUPTIVE

The Sudbury Nickel Irruptive, a differentiated tholeiitic intrusion some 1.5 to 6 km in outcrop width, forms an elliptical ring 56 km long and 24 km across with its long axis oriented east-southeast. It consists of two parts: the main Irruptive consisting of concentric gradational rings of granophyre, quartz gabbro, quartz-hypersthene gabbro, and quartz-augite norite, and a discontinuous ore-bearing basal unit, the "sub-layer", which also constitutes the dykes extending out from the main Irruptive that are known as "offsets" (Stevenson and Colgrove, 1968). The Irruptive was emplaced between the Whitewater Group and the underlying basement rocks. Both the inner and outer contacts of the Irruptive dip, for the most part, toward the centre, defining a funnel- or bowl-shaped structure. The age of the Nickel Irruptive, as given by a U-Pb zircon isochron age of the norite, is 1844 ± 4 Ma (Krogh and Davis, 1974).

Main Irruptive

The early view that the Nickel Irruptive was a simple differentiated sill, folded into a basin shape (Coleman, 1905), was disputed by later geologists (Knight, 1917) who claimed it was a ring-dyke complex. Others (Wilson, 1956) have interpreted it as a funnel-shaped intrusion.

Naldrett, et al. (1970) have shown that cryptic variation in the compositions of hypersthene, augite, and plagioclase is present in the Irruptive and that this supports the view that the body is gravity differentiated. In agreement with Stevenson and Colgrove's (1968) earlier observation, they showed that although the North and South Ranges are petrographically quite similar, the South Range is different (fig. 7).

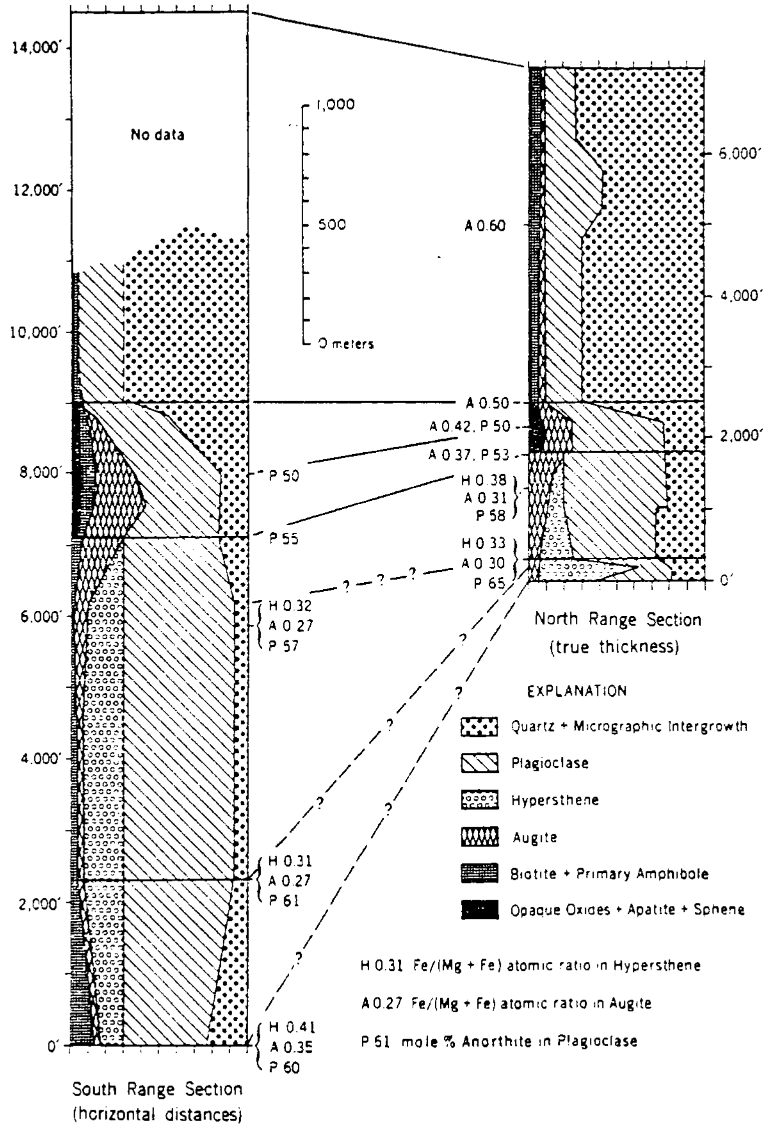

Figure 7. Comparison and correlation of partially idealized modal analysis plots through the North and South Ranges, Sudbury Nickel Irruptive (from Naldrett et al., 1970).

It can be seen that whereas the granophyre ("micro-pegmatite") and the immediately underlying gabbros are petrologically similar on the North and South Ranges, the orthocumulus felsic norite of the North Range corresponds only to the extreme upper part of the South Range norite. The bulk of the South Range norite is a mesocumulate, which is absent on the North Range.

It is suggested that the main Irruptive started to recrystallize as an essentially funnel-shaped body beneath a thin cover of breccia and sediments (fig. 8). After a portion of the magma had crystallized as the South Range norite (fig. 8A), some of the remaining liquid was squeezed out farther beneath the cover to crystallize as a thinner peripheral sill of felsic norite, quartz gabbro, and granophyre (fig. 8B and fig. 8C). Subsequent faulting (as proposed by Souch, et al., 1969) has resulted in the peripheral sill being preserved on the North Range and a deeper section through the funnel-shaped portion of the intrusion being exposed on the South Range (fig. 8D). The dimensions of the funnel and the volume of rock units are shown only schematically in Figure 8. A recent gravity interpretation by Popelar (1972) suggests that the funnel is less steep and has a more rounded bottom than is shown here.

Naldrett, et al. (1970) remarked that the quartz-rich norite of the South Range, which they interpret as a marginal facies, is not present on the North Range. However, Hewings (1971) has subsequently shown that a unit known as the mafic norite, developed intermittently along the outer margin of the North Range, has a number of features in common with the quartz-rich norite.

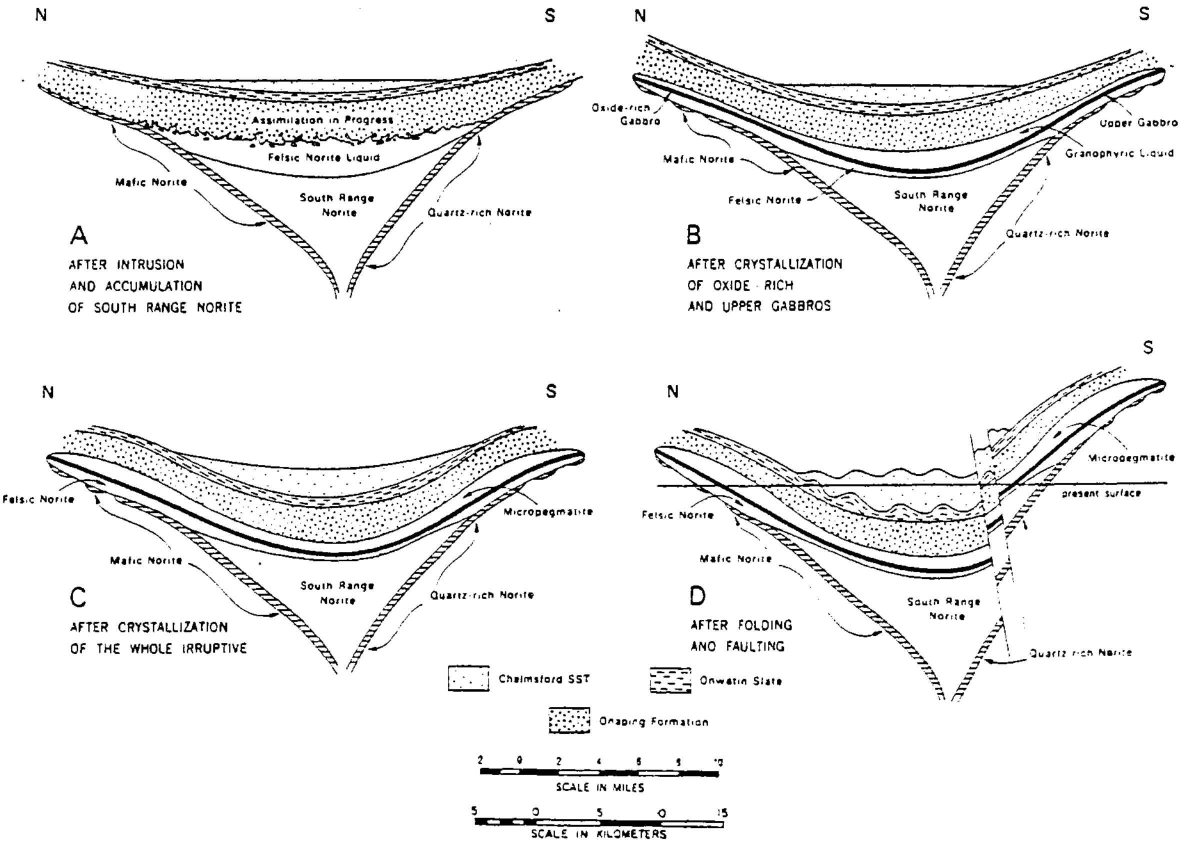

Figure 8. A model for crystallization and deformation of the Nickel Irruptive (Naldrett et al., 1970).

Sublayer and Sudbury Ore Deposits

The nickel-copper ore bodies of the Sudbury area are associated with a distinct and separately intruded group of breccias and igneous rocks collectively termed the sublayer, which occurs as lensoid sheets at the base of the main Irruptive and as steeply dipping dykes, locally known as offsets, that project into the footwall from the base of the Irruptive. The sublayer consists of inclusion- and sulphide-rich silicate rocks whose separate emplacement went unrecognized for many years. The sublayer concept of Souch, et al. (1969) replaces the long-held gravity differentiate origin of the ore bodies, a theory which no longer explains all the available data.

The close association of the sublayer with the ore deposits is illustrated in Figures 6 and 10, where mineral deposits are shown to be confined to the outer rim of the Irruptive and along the offset dykes.

The sublayer occurs as a thin, discontinuous layer concentrated in embayments or depressions along the footwall contact. It is characteristically composed of three phases: sulphides, inclusions, and a silicate matrix of varying gabbro-norite-tonalite composition and igneous to metamorphic texture. The ore minerals are consistently pyrrhotite, chalcopyrite, and pentlandite with minor amounts of other Cu, Ni, and Fe sulphides and arsenides (Hawley, 1962). Three sublayer ore environments or associations are distinguished on the basis of the silicate rock matrix; sulphides and inclusions are common to all. These three are: (1) mafic igneous sublayer which is typical of embayment and contact ore bodies, (2) leucocratic, tonalitic breccia (commonly known as granite breccia) restricted to the North Range, including the deposits between Levack West and Longvack Mines (fig. 6), and (3) the offset dyke environment where the host rock is quartz diorite.

(1) The mafic igneous sublayer rocks range from augite norite to hypersthene gabbro. Texturally and modally these rocks are quite distinct from the mafic and felsic norites forming the lower part of the main Irruptive along the North Range. On the South Range, the sublayer silicate matrix in part closely resembles the overlying main mass norite both texturally and mineralogically, but some variants are distinctly different. Some noritic rocks of these types occur within the dykes, although the dominant rock type there is hornblende-biotite quartz diorite.

Gabbro-norite environment is characterized by several distinctive ore types. The ores are composed of sulphides, varying proportions of inclusions and silicate matrix (fig. 9). A typical section from footwall to hanging wall of a South Range mine (fig. 10) consists of the following ore types: (1) massive sulphide followed by (2) inclusions and massive sulphide, i.e., massive sulphide enclosing scattered fragments of footwall rock, grading by an increase in proportion and change in type of inclusions into (3) the gabbro-peridotite inclusion-sulphide variety. Sulphide and inclusions occur in approximately equal proportions and silicate matrix may be minor. There are no known counterparts of the gabbroic and ultramafic inclusions in the footwall or main Irruptive rocks. For this reason, they are considered to have been carried up from depth with the intruding sulphide-rich magma. The inclusions range in diameter from a few centimetres to 100 m but are commonly about 0.5 m in size. Increase in inclusion content and decrease in sulphide result in an ore type (4) called ragged disseminated sulphide in which the sulphide occurs interstitially between closely packed, subrounded, and generally small inclusions. This ore type is succeeded upward by a variety of norite with sulphide interstitial to the silicate crystals, which is ore type (5), interstitial sulphide. The noritic host for this type is similar to the overlying main mass norite.

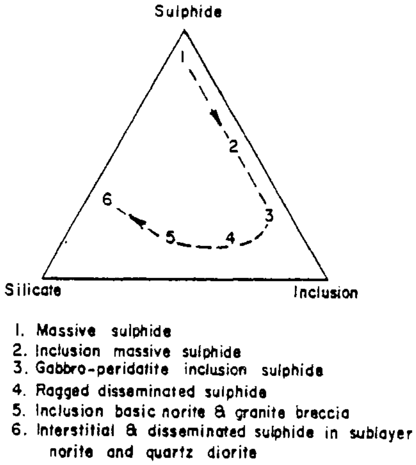

Figure 9. Schematic composition diagram for Sudbury ore types.

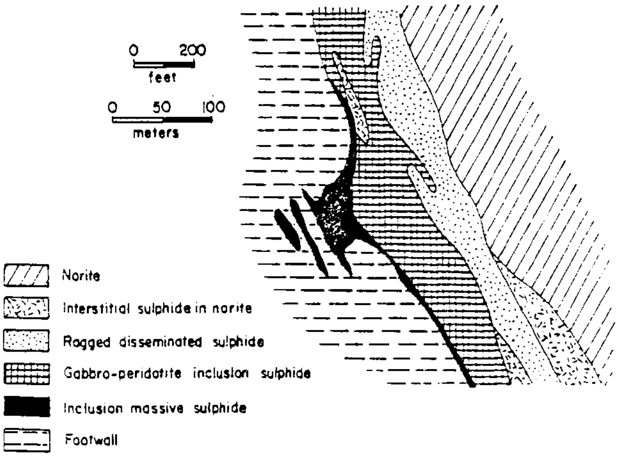

Figure 10. Diagrammatic cross-section through a typical South Range deposit.

(2) A variety of breccias occurs between the Nickel Irruptive and the footwall rocks. A group of these breccias, referred to locally by such terms as "granite breccia", "late granite breccia", "grey breccia" and "footwall breccia", are classed as the leucocratic sublayer. They have been studied in detail by Greenman (1970) at the Strathcona Mine. They are characterized by abundant footwall inclusions and, in places, by abundant inclusions of ultramafic and mafic rocks in a granoblastic to igneous matrix composed largely of quartz and plagioclase. They are host to much of the ore in the large deposits along the North Range. Since field relationships are ambiguous, some controversy exists over the origin of the breccias and whether they are pre- or post-Irruptive. It is very likely that a pre-Irruptive breccia with many of the characteristics of this group was formed at the time of origin of the Sudbury Structure, later marking the boundary between the Whitewater Group and the footwall rocks, and that this breccia served to localize intrusion of the main Irruptive and sublayer. Subsequent explosion and fluidization due to heating of water in the breccia zone by intrusion of the overlying Irruptive may have caused further brecciation along the contact, affecting the Irruptive rocks and giving rise to the ore-bearing breccias.

Granite breccia ore of the North Range consists of blebby sulphides in an igneous tonalitic matrix with abundant inclusions of the footwall gneiss of the Levack complex, as the terrane north of the Structure is called, often grading into massive sulphides. Above the granite breccia there commonly occurs a sublayer variant known as xenolithic norite. This gabbroic to noritic rock also contains abundant and varied inclusions but generally lacks the economic sulphide content of the granite breccia.

(3) In the offset dyke environment, the ore bodies occur as steeply plunging sheet-like and pipe-like bodies elongated along the strike of the offset. The ore zones generally consist of an inner core of inclusion- and sulphide-rich quartz diorite grading outward into barren or weakly mineralized, inclusion-free quartz diorite. The most common ore type consists of disseminated sulphides in quartz diorite, but inclusion-bearing ore types (gabbro-peridotite inclusion sulphide and inclusion massive sulphide) are also found in the dykes.

Ore deposits at the east end of the South Range between Kirkwood and Falconbridge mines are located on a faulted contact between the Irruptive and the footwall. Shearing of sublayer and possible remobilization of sulphide into the fault zone has produced these deposits. The typical ore type here is contorted schist-inclusion sulphide. Sheared and bent fragments of footwall rocks are included in a sheared sulphide matrix. This ore type is also found at many other mines where the sublayer is cut by faults.

Nearly all of the sublayer rocks are exceptionally rich in sulphides in comparison with the main body of the Irruptive. The proportion of sulphide, which is generally restricted to the matrix, ranges from a few per cent to almost one hundred per cent. Although most Sudbury geologists believe that the emplacement of the ores was in conjunction with the sublayer rather than the main body, the relative ages of the two are uncertain. On the North Range, contact relations are sharp between them, but no chilling is evident, and clear evidence of one type crosscutting the other has not been observed. On the South Range, it is difficult to recognize the exact contact between sublayer and main Irruptive.

REGIONAL DEFORMATION, METAMORPHISM, AND IGNEOUS ACTIVITY

Following stabilization of the Archean craton at the close of the Kenoran Orogeny some 2500 Ma ago, there was extensional tectonic activity leading to the emplacement of mafic dyke swarms and plutons. Large-scale subsidence controlled or accompanied by faulting took place in what is now the eastern Southern Province, and the Huronian Supergroup was deposited. Mild tectonism continued sporadically throughout sedimentation. Major compressional tectonism began about 2200 Ma ago with folding of the Huronian strata, approximately synchronous with emplacement of the Murray and Creighton felsic plutons and the much more extensive Nipissing Diabase, according to the radiometric dating of Van Schmus (1965) and Gibbins, et al. (1972). The deformation and felsic igneous activity at this time in the Sudbury area has recently been termed "Blezardian" by Stockwell, who has also employed it as a means of subdividing the Aphebian Era. Important deformation and regional metamorphism later occurred, culminating approximately 1900 Ma ago (Fairbairn, et al., 1969), presumably as a manifestation of the Penokean Orogeny (Van Schmus, 1976). The regional metamorphism was of the low-pressure - intermediate type of Miyashiro (1961) and metamorphic grade ranges from subgreenschist facies in the west, north, and northeast to amphibolite facies in the south. The higher grade metamorphic zones in the south display a nodal pattern (fig. 11) similar to the Penokean metamorphism of Michigan (James, 1955).

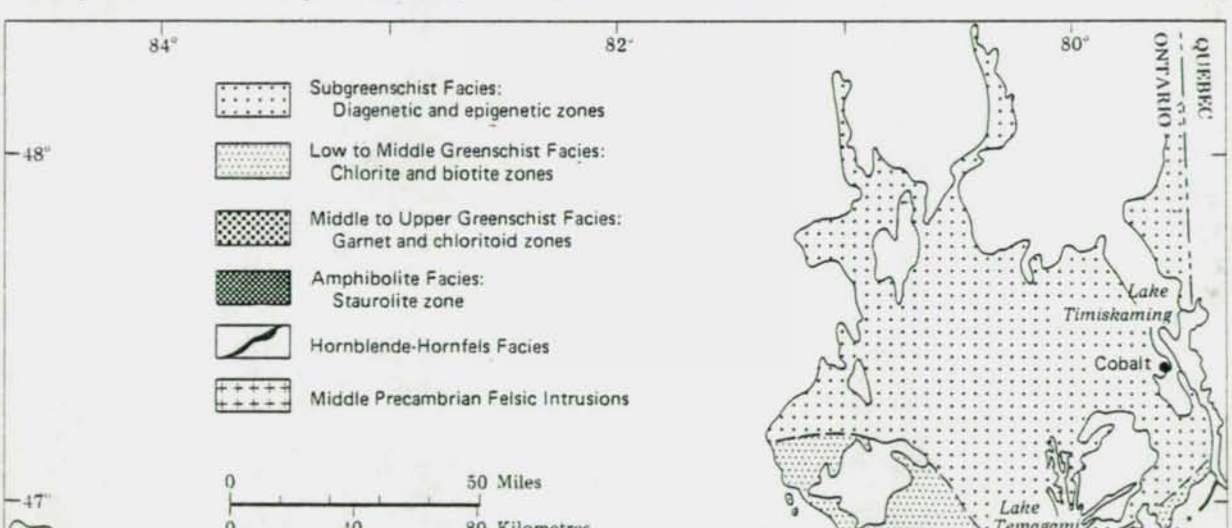

Figure 11. Pattern of regional metamorphism in the eastern Southern Province.

Subsequent to the regional metamorphism, there was a protracted period of intermittent igneous intrusive activity, deformation and low-grade regional metamorphism. During this, the Sudbury Nickel Irruptive (1840 Ma), the Cutler batholith (1750 Ma) and the Grenville Front felsic plutons (1730 to 1500 Ma) were emplaced. Deformation and low-rank metamorphism of the rocks of the Sudbury Structure and of the Cutler area occurred about 1750 Ma ago and may be correlated with the Hudsonian Orogeny. Later events include the intrusion of anorogenic felsic plutons approximately 1500 Ma ago, of northwest-trending olivine diabase dyke swarms about 1250 Ma ago, and deformation and high-rank metamorphism in the Grenville Province (Grenvillian Orogeny) about 1000 to 1200 Ma ago.

The foregoing deformational events have resulted in gentle to tight folding and extensive faulting of the rocks of the Southern Province (figs. 12 and 13). The intensity of deformation increases from north to south and from west to east. Huronian rocks along the northern edge of the Lake Huron region are virtually flat-lying and unmetamorphosed. Major folds are open to flattened subisoclinal concentric buckles with upright to slightly northward-overturned, commonly curved axial surfaces. In areas south of Sudbury, and in the western part of the Huronian belt between Sault Ste. Marie and Elliot Lake, major fold axes are regular and axial traces of individual folds extend many kilometres. Near Sudbury, where secondary (Hudsonian) deformation was especially intense, fold axes generally display abrupt culminations and the resulting fold pattern is one of doubly plunging, en echelon synclines and anticlines.

Fault sets strike east, northeast, and northwest. The major east-west faults of the Murray System, and others including the north-northwest faults of the Onaping System north of Sudbury were initiated prior to Huronian deposition but were periodically reactivated during subsequent orogenic events. Foliations in the west, weak to locally intense near faults, appear to be of one generation; in the east, foliations of several ages are present, including early penetrative schistosity, later non-penetrative crenulation cleavages, and still later strain-slip cleavages. As mentioned, breccias and shatter cones formed during the "Sudbury Event" are widespread in the rocks surrounding the Sudbury Structure.

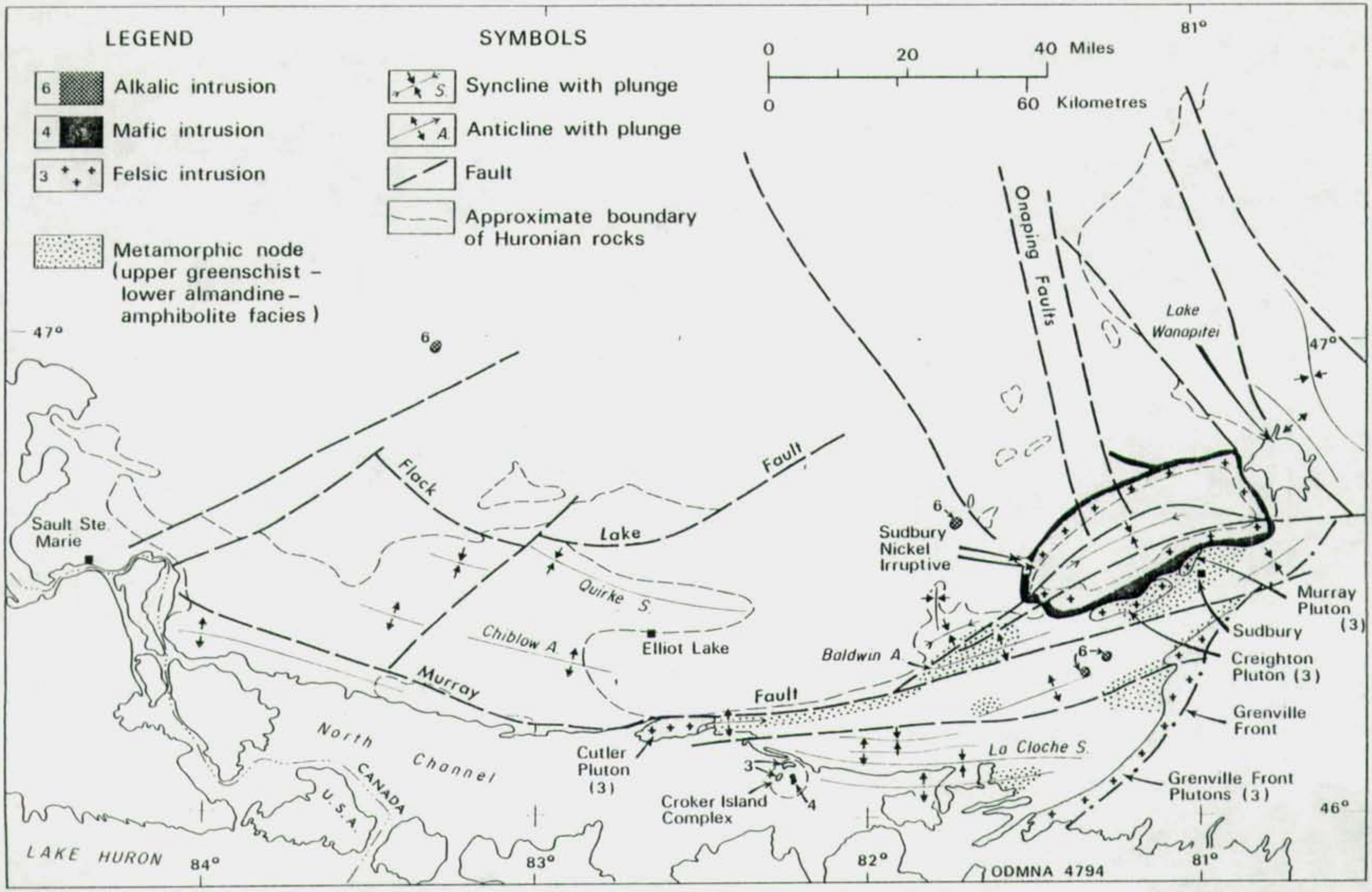

Figure 12. Major structural elements of the Lake Huron region.

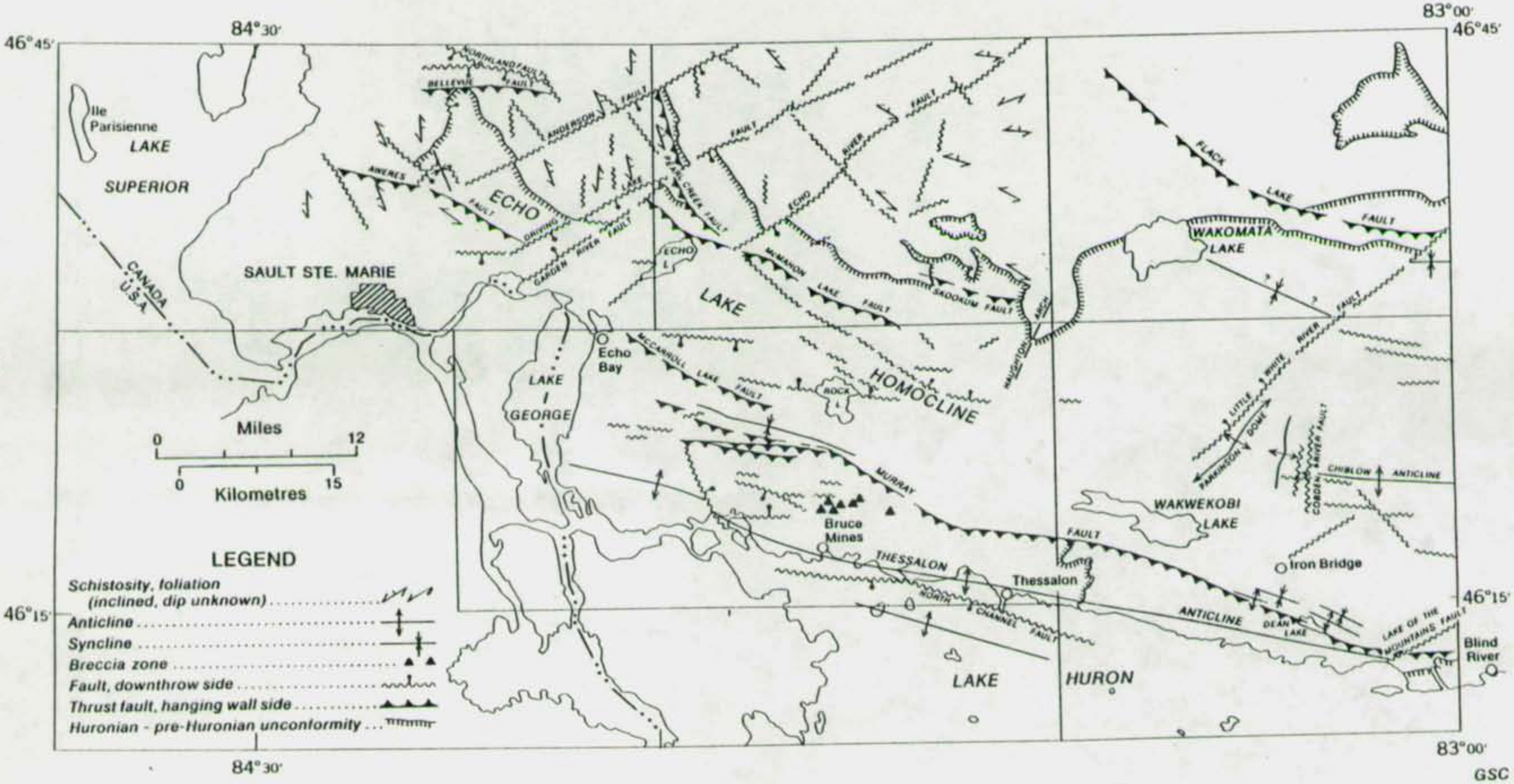

Figure 13. Principal structural features, Sault Ste. Marie - Blind River.

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DAY 1 -- THE GRENVILLE PROVINCE OF ONTARIO

Leader: S.B. Lumbers

The field excursion will travel along Highway 17 from Ottawa to Sudbury during the first day. This route follows the Ottawa Valley to Mattawa, and then west to Sudbury along the northern shore of Lake Nipissing (figs. 2 and 3). Much of the route lies within or near the Algonquin batholith so that opportunities to examine supracrustal rocks are limited, and time does not permit side trips to rectify this situation. Four formal stops are outlined below, and time and weather allowing, other stops may be made.

STOP 1.1

MARBLE WITHIN THE CARBONATE BASIN OF THE LATE PRECAMBRIAN SUCCESSION about 4 km west of Arnprior on Highway 17. The outcrops at this locality are in a marble-rich portion of the Late Precambrian supracrustal accumulation and are not as highly deformed and recrystallized as marble in proximity to the Algonquin batholith where all the rocks show recumbent folding and subhorizontal gneissic foliation. Gneissic foliation in the marble is subparallel to original bedding and dips subvertically. The marble is calcitic and contains variable amounts of siliceous impurities, mainly tremolite, quartz, feldspar and phlogopite. Beds of siliceous marble and calcareous shales (now largely calc-silicate rocks and amphibole-rich gneiss) are intercalcated with the calcitic marble. A thin unit of siliceous shaly metasediments is present near the east end of the outcrop. Note the variable recrystallization of the calcitic marble accentuated by light- to dark-grey hues.

From Stop 1, the excursion will travel northwestward along Highway 17 toward the Algonquin batholith.

STOP 1.2

ALKALIC ROCKS OF THE ALKALIC COMPLEX, at Cobden. At the northwestern limit of the town of Cobden a flat exposure of gneissic alkalic syenite and granite on the east side of the road illustrates some of the common lithology present in the complex. Petrographically the outcrop is highly variable with respect to mineralogy and textures. Pegmatitic phases rich in altered alkalic pyroxene are common. The leucocratic phases consist mainly of perthite, albite and locally abundant quartz, with iron-titanium oxide minerals, titanite, carbonate and apatite as common accessory constituents. A few large crystals of apatite are visible in parts of the outcrop.

From Stop 2, the excursion will continue northwest along Highway 17 to within 2.5 km of Pembroke. At this point we will travel westward to Highway 41, skirting the town in order to examine some exposures of basal arkose forming part of the coarse clastic sequence marking the base of the Late Precambrian acccumulation.

STOP 1.3

BASAL ARKOSE OF THE COARSE CLASTIC SEQUENCE on a concession road 0.4 km east of Highway 41 and 4 km south of Pembroke. Outcrops along the concession road consist of medium- to coarse-grained meta-arkose composed mainly of quartz, potassic feldspar, and minor sodic oligoclase. The quartz content is variable, but most of the rocks contain 40 to 50 per cent quartz. Relic detrital zircon is also common. The rocks show subhorizontal gneissic foliation due to recumbent folding, and are within about 0.4 km of the Algonquin batholith. In places a gradation in grain size is visible on faces perpendicular to the foliation and thin beds of quartz-rich metasandstone and calc-silicate rocks are present locally.

From Stop 3, the excursion will continue northwestward past Pembroke and rejoin Highway 17 south of Petawawa. Road-cuts along the route expose gneissic quartz monozonite and tonalite phases of the Algonquin batholith. Between Pembroke and Petawawa, the Algonquin batholith narrows greatly (fig. 2) and we pass into the older supracrustal accumulation that was intruded by the batholith.

STOP 1.4

IMPURE METASANDSTONE AND CALC-SILICATE ROCKS OF THE OLDER ACCUMULATION, about 6 km west of Stonecliffe. These metasediments are on the northern side of the Algonquin batholith and are recumbently folded with the gneissic foliation dipping shallowly eastward. The metasediments consist mainly of intercalated impure sandstone (biotite-K-feldspar-quartz-plagioclase gneiss) and biotite-rich meta-argillite (fine-grained, garnetiferous, biotite-feldspar-quartz gneiss and schist) locally with intercalated units derived from calcareous shaly metasediments and rich in biotite, amphibole, and diopside. Locally the metasediments show the development of alkalic feldspar porphyroblasts and veinlets of quartz-feldspathic material.

From Stop 1.4, the excursion will continue westward along Highway 17 to Sudbury. Time permitting, a few additional stops may be made to examine anorthosite suite rocks and other facies of the older Middle Precambrian supracrustal accumulation.

End of Day 1

DAY 2 -- THE SUDBURY STRUCTURE

Leaders: M.J. Frarey, K.D. Card, and J.A. Robertson

A north-south section across the Sudbury Structure will be examined and will include examples of the Early Precambrian rocks to the north of the Sudbury Basin, part of the North Range of the Irruptive, the Whitewater Group, the ore-bearing sublayer, and shatter cones and breccia in the Huronian rocks in the south. Stop locations are shown on Figure 6.

We will travel directly to Stop 2.1, a distance of some 53 km (33 miles), crossing the Sudbury Structure from southeast to northwest. The city of Sudbury is built mainly upon ridges of the McKim Formation and Nipissing Diabase. Highway 144 leads out of the city between bare hills of Copper Cliff rhyolite on the right and slag heaps from the Copper Cliff smelter on the left. The road climbs northeastward through the basal Huronian metavolcanics and metasediments, past the Clarabelle concentrator and the Copper Cliff North mine shaft.

The lower contact of the Sudbury Nickel Irruptive is marked by gossan and concrete structures of the original Murray Mine. From this point, we drive more than 1.5 km (1 mile) over the subdued plateau topography of the South Range of the Irruptive, then down into the interior lowland of the Sudbury Basin. The hills of the North Range are visible 15 km to the northwest. The southern part of the Basin is mainly flat farmland established on Pleistocene glaciolacustrine deposits. In the central part of the Basin, low, wooded, east-northeast trending hills are formed by open folds in the Chelmsford sandstone. Beyond Dowling the highway climbs into the North Range: the massive, erosion-resistant Onaping Formation is marked by the cataract of High Falls on the Onaping River; above the falls the road winds through rugged hills of granophyre and norite of the North Range of the Irruptive. The north contact of the Irruptive is marked by a valley and from here the route transverses the topographically subdued Early Precambrian granite terrane of the Superior Province.

STOP 2.1 - 53 km (33 miles)

SUDBURY BRECCIA. Exposures of migmatitic gneiss and mafic dykes are pervaded by irregular tongues of pseudotachylitic breccia. The blocks are rounded to angular disoriented fragments of country rock, in a matrix of finely comminuted rock flour. No foreign igneous component is present; the breccia has been formed by attrition in situ without apparent melting. In thin section the larger fragments may show weak shock features.

The Sudbury Basin is surrounded by a zone of such brecciated rocks, extending at least 20 km beyond the Irruptive contact and probably much farther in the south. This zone includes the zone containing shatter cones. Together with the presence of shock metamorphism in the wall rocks, this suggests that the breccias formed as a consequence of explosive meteorite impact.

Stop 2.1 to Stop 2.2: Closer to the Nickel Irruptive contact the gneiss structure of the country rock becomes quite irregular and brecciation is pervasive. The Irruptive contact is not exposed, but as is usual on the North Range, it is marked by a topographic depression.

STOP 2.2 - 5.6 km (3.5 miles)

QUARTZ GABBRO AND TRANSITION INTO MICROPEGMATITE. We will stop at an outcrop on Highway 144 showing most of the quartz gabbro. The most northerly outcrop is oxide-rich gabbro with a south-dipping igneous lamination. Walking south, up the hill, we cross the transitional contact between quartz gabbro and micropegmatite which is arbitrarily placed at the point where granophyre content exceeds plagioclase content. The basal micropegmatite here is a rather dark pink rock richer in mafic minerals and plagioclase than it is higher in the sequence. Modal compositions of rocks from a section similar to this one are shown in the North Range section of Figure 7.

STOP 2.3 - 11.5 km (7.2 miles)

ONAPING FORMATION. The Onaping is one of the most interesting, and most enigmatic, rock units in the district. It has been classified as a conglomerate, as a pyroclastic deposit, and as a tectonic breccia. According to the meteorite impact theory, the Onaping represents a "fallback" breccia composed of broken target rock fragments and glassy and crystalline impact melt. The Onaping contains abundant evidence of shock metamorphism. The rocks of the Onaping Formation exposed at High Falls belong to the "black Onaping" unit and contain several percent of carbonaceous material which locally forms black rims around glass and rock fragments. These and other features have led to the suggestion that it is water laid, and that whereas the lower grey Onaping represents fallback, the components of the black might have slumped or been washed into a sedimentary basin. The heterogeneous, fragmental nature and complete lack of bedding are well displayed in the rock-cut. In a general way the size of glass and rock fragments decreases upwards through the Onaping; here bodies of glass as much as 30 cm across with the flow structure and small rock inclusions are apparent. Most of the basement rock fragments over a few centimetres in size are unrecrystallized and show shock features; petrographic evidence of shock metamorphism at Sudbury was first discovered in specimens from this location. Some of the basement fragments are partly or completely rimmed by glass. Ubiquitous pyrrhotite imparts the characteristic rusty weathering colour. At the south end of the rock-cut a narrow spherulitic dyke cuts the Onaping; it may represent an apophysis from an underlying melt body.

STOP 2.4 - 23.5 km (14.7 miles)

ONWATIN AND CHELMSFORD FORMATIONS. On the southwest side of Highway 144 at the first hill south of Dowling, rocks of the upper part of the Onwatin Formation and the lower part of the Chelmsford Formation are exposed. The Onwatin outcrops comprise thin-bedded black carbonaceous pyritic siltstone with an excellent slaty cleavage that transects the bedding at a high angle.

The outcrops at the top of the hill comprise thick-bedded arkosic wacke and siltstone of the Chelmsford Formation. The Chelmsford displays a rhythmic sequence of beds and bed divisions known as Bouma cycles. These cycles typically consist of a lower graded sequence, a middle parallel-laminated sequence, and an upper ripple cross-laminated sequence. In addition, the Chelmsford contains carbonate concretions, convolute lamination, flute casts, load structures, erosion channels and siltstone chips. These features, and the thick bedding, indicate that the Chelmsford is a proximal (near source) turbiditic deposit.

STOP 2.5 - 39.5 km (24.7 miles)

DISCOVERY SITE. At the base of the norite is the sublayer, the heterogeneous marginal phase of the Irruptive, which contains all the orebodies. Its outcrop is delineated by a line of gossans, old pits and mine buildings. The discovery gossan is high-grade nickel-copper ore, comprising rounded inclusions of exotic basic and ultrabasic rocks in a copious matrix of nearly massive pyrrhotite, chalcopyrite and pentlandite, with little if any Irruptive silicate matrix. Similar material is being mined from the open pit across the road.

The sublayer, dipping northwards beneath the norite, in places is a few hundred metres thick. Note the interstitial sulphides present in the coarse-grained, quartz-rich basal main mass norite lying above the sublayer.

The footwall hills southeast of the discovery site are of Murray granite; the hill on the southeast consists of mafic metavolcanics of the Elsie Mountain Formation. Just south of the discovery site, small outcrops display the agmatitic contact between granite and metavolcanics. On the west side is the Irruptive's contact aureole, a hornblende-plagioclase-magnetite hornfels.

STOP 2.6 - 40.3 km (25.2 miles)

ELSIE MOUNTAIN FORMATION. Outcrop of pillowed tholeiitic metabasalt of the Elsie Mountain Formation south of the Murray Mine and the Nickel Irruptive. The Elsie Mountain Formation is intruded by the Nickel Irruptive, is approximately 900 m thick, and represents the lowermost Huronian formation preserved in this area.

STOP 2.7 - 44.0 km (27.5 miles)

STOBIE FORMATION. Pelitic metasediments of the Stobie Formation with spectacular development of metamorphic porphyroblasts including staurolite, chloritoid and garnet (largely retrograded). The Stobie conformably overlies the Elsie Mountain and comprises some 700 m of metabasalt flows and intercalated metasediments.

STOP 2.8 - 47.7 km (30.0 miles)

COPPER CLIFF FORMATION. Flow-banded rhyolite of the Copper Cliff Formation. The Copper Cliff is the uppermost member of the Huronian volcanic sequence of the Sudbury area. It comprises as much as 750 m of metamorphosed rhyolite and dacite flows and pyroclastics.

STOP 2.9 - 53.8 km (33.5 miles), Hwy 17 and Balsam St. in Copper Cliff

McKIM FORMATION. Thick-bedded wacke and thin-bedded siltstone of the McKim Formation. The McKim interfingers with and conformably overlies the

Huronian volcanics in the Sudbury area; farther west it displays similar relationships toward the Matinenda Formation which comprises quartz-feldspar sandstone and uranium-bearing quartz-pebble conglomerate. The McKim is as thick as 1500 m and displays well-developed graded bedding, ripple-drift cross-lamination, and Bouma cycles typical of turbidity current deposits.

STOP 2.10 - 55.7 km (34.8 miles)

SHATTER CONES, MISSISSAGI FORMATION. This outcrop, which has the most abundant and conspicuous development of shatter cones known in the Sudbury district, is on the south side of the road, facing bare ground southeast of Kelley Lake. When obliquely illuminated by the late afternoon sun, the many striated conical surfaces are spectacular.

The rock is a coarse subarkose, pervaded by swarms of shatter cones as much as several feet in size.

The distinctive rock fractures called shatter cones are known to form by the passage of shock waves through rocks; they are found at a number of astroblemes and "cryptoexplosion" structures. Reconnaissance has shown that the Irruptive is surrounded by a belt, at least 15 km wide, of rocks containing shatter cones, the apices of which point generally inward to an explosion centre within the Basin.

STOP 2.11 - 51.4 km (32.1 miles)

SUDBURY BRECCIA; RAMSAY LAKE AND PECORS FORMATIONS. The road passes between Robinson Lake and Kelley Lake, which extends southwest along the strike of the Huronian rocks. The south side of the outcrop consists of argillaceous, feldspathic quartzites, siltstones and argillites of the Pecors Formation; the north side is conglomeratic greywacke of the Ramsay Lake Formation. The Pecors contains a well-exposed zone of Sudbury breccia. This South Range variety of the breccia is analogous to that seen at Stop 2.1, but the inclusions are much larger. As before, they are disoriented and well rounded by attrition. The matrix material, which is metamorphically recrystallized, intrudes the wall rocks in fine, pseudo-igneous tongues, separating blocks by what appears to have been a stoping process.

End of Day 2

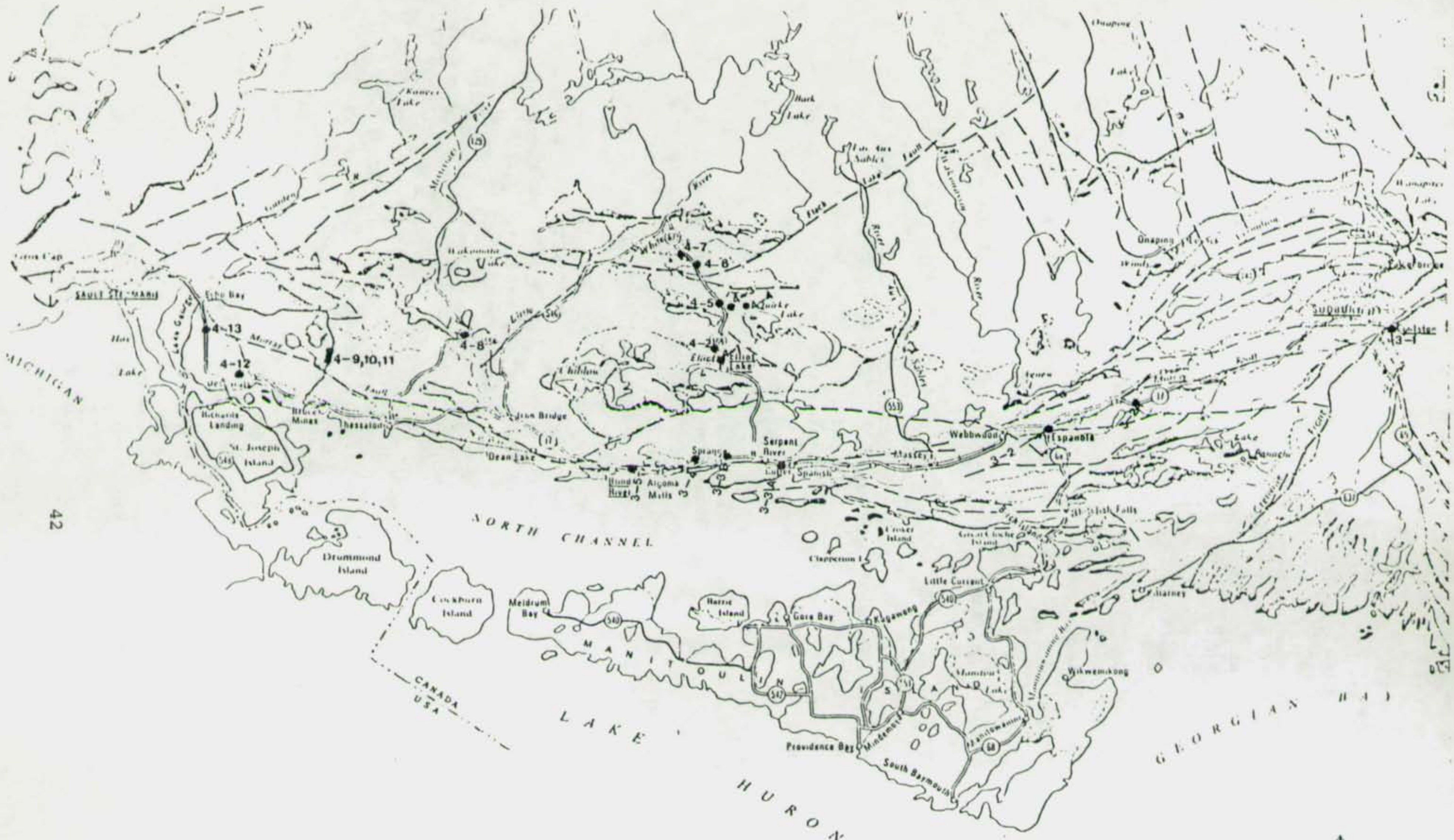

Figure 14. Location of field stops, Days 3 and 4.

DAY 3 -- SUDBURY, ONTARIO TO BLIND RIVER, ONTARIO

Leaders: S.B. Lumbers, M.J. Frarey, K.D. Card and J.A. Robertson

STOP 3.1

GRENVILLE FRONT TRAVERSE. During the morning, a north-south section beginning in the southeastern margin of the Southern Province and crossing the boundary with the Grenville Province into the Grenville rocks will be examined on foot. The section lies along the Canadian Pacific Railway south of the former Coniston smelter of INCO Limited. The total walking distance is about 4.8 km (3 miles), and the rock exposure ranges from 80 to 100 per cent. The section begins near Baby Lake, abouat 0.5 km (0.3 miles) northwest of the Grenville Front Boundary Fault, in intercalated arkose and subarkose of the Huronian Mississagi Formation. These rocks are cataclastic and tightly folded about northeasterly trending axes that for the most part dip steeply southeast. Toward the Boundary Fault, units of intercalated argillite, greywacke, and pebbly greywacke become increasingly abundant, reflecting a facies change in the formation at the northwestern margin of the Grenville Province to deeper water deposits. Sill-like bodies of cataclastic Nipissing Diabase and dykes of Late Precambrian (Neohelikian) diabase intrude the metasediments. Near the Boundary Fault, Middle Precambrian (Aphebian) cataclastic granitic rocks of the Killarney batholithic complex that extends southwestward along the Grenville Front Tectonic Zone to Georgian Bay intrude both Nipissing Diabase and the metasediments. For the most part, outcrops within the Boundary Fault are rare, and the fault is marked by linear swampy depressions. In places, almost continuous exposure is present across the Fault and indicates that the Fault is a zone of extreme cataclasis and mylonitization as much as 30 m wide. Quartz vein networks and brecciated zones are found locally within and near the Fault zone, and rocks immediately adjacent to the Fault are generally more intensely cataclastic than elsewhere. Rocks in the Grenville Province consist mainly of intercalated gneisses derived from greywacke, argillite, arkose, quartz-rich sandstone and muscovite-rich siltstone cut by gneissic gabbroic bodies equivalent to the Nipissing Diabase.

Locations of field stops for Days 3 and 4 are shown on Figure 14. After Stop 3.1 we shall drive approximately 87 km (55 miles) west on Highway 17 to the junction of Highway 68 and go a short distance south on Highway 68 to Stop 3.2. Depending on available time, an optional stop is scheduled en route, at the junction of the Wabagishik Lake road, where a paraconglomerate dyke cutting subgreywacke beds of the Pecors Formation is shown in vertical section.

STOP 3.2A (Optional) - 75 km (46 miles)

CONGLOMERATE DYKE IN PECORS FORMATION, HOUGH LAKE GROUP. Junction of Highway 17 and Wabagishik Lake road. The rock-cut on the north side of the highway is composed of well-bedded subgreywacke of the Pecors Formation close to the contact with the underlying Ramsay Lake Formation, which is largely paraconglomerate. Halfway along the face is a 3-m-wide conglomeratic dyke presumably injected up into the Pecors prior to consolidation of the Ramsay Lake. At the southeast end of the cut is a small olivine diabase dyke, and at the other end parts of shatter cones may be seen.

Proceed 11.3 km (7 miles) to junction of Highways 17 and 68, and then south on Highway 68 for 2.4 km (1.5 miles) to Stop 3.2.

STOP 3.2 - 13.7 km (8.5 miles)

ESPANOLA ROAD-CUT. Folded siltstone and wacke of the McKim Formation, Elliot Lake Group, Sudbury breccia, and mafic intrusions. Features of interest include:

(1) Bedding and ripple cross-laminations in the McKim. Note that the bedding, on average, is much thinner than at Stop 2.9. This characterizes the general facies trend in this formation from a thick-bedded proximal turbidite near Sudbury to a thin-bedded more distal facies to the west and north.

(2) Sudbury breccia consisting of rounded fragments of McKim and metagabbro (note altered, biotite-rich margins) in a rock-flour matrix. The breccia is sharply transgressive across bedding and folding in the McKim strata.

(3) Folds, a variety of minor tectonic structures, and metamorphic porphyroblasts (altered chloritoid) in the McKim.

Return to Highway 17 and resume travel westward. Several kilometres to the west, Highway 17 enters an elongate zone where metamorphism of the Huronian rocks increases to lower almandine-amphibolite grade. This zone, which might be termed the "Cutler node", extends eastward from the Cutler batholith for approximately 40 km (25 miles), south of the Murray Fault (see Figures 11 and 12).

STOP 3.3A (Optional) 10 km (6.2 miles west of the town of Spanish)

CUTLER GRANITE, HURONIAN METASEDIMENTS, EPIDIORITE. The main body of the Cutler batholith is some 16 km (10 miles) long and as much as 6 km (3.7 miles) wide, and a toungue or "tail" of the granite extends eastward, progressively thinning and anastomosing, for a further 21 km (13 miles) to the vicinity of the village of Walford. The invaded strata in this zone are metamorphic equivalents of the McKim Formation that contain micas, garnet, staurolite and cordierite, and occupy a major anticline (Robertson, 1970, 1977). Primary sedimentary textures and structures are obliterated except for bedding, and the rocks were once considered Archean.

At Stop 3.3A, there are good exposures of late pegmatite of the Cutler batholith cutting the metasediments as well as "epidiorite" or metadiabase correlative with the Nipissing Diabase.

There may be some uncertainty about the time of emplacement of the Cutler batholith relative to the time of metamorphism and deformation of the metasedimentary envelope. Cannon, who studied the area in detail, stated (1970) that "folding and metamorphism were well advanced prior to the formation of the granite" because of the nature of the fabric and mineralogy of the numerous inclusions; however, biotite foliation in the granite is symmetrical with the surrounding fabric, and the granite is also cataclastic in places, suggesting syn- or late-kinematic emplacement with respect to the major deformation and metamorphism. Cannon envisaged one long-continuing process that produced the folding and metamorphism, culminating with the intrusion of the batholith approximately 1750 Ma ago, a date obtained by the Rb-Sr method from minerals in the late pegmatite (Wetherill, et al., 1960). However, Cannon (op. cit.) also reported that muscovite had been driven out of the metasediments in the border zone of the batholith, and Robertson (1970) found that the batholith "was intruded after the sedimentary rocks had been folded and metamorphosed", suggesting a significant time interval between metamorphism and granite intrusion. As presently interpreted, the "Cutler node", which may be reasonably considered synchronous with the metamorphic nodes to the east that are assigned an age of about 1900 Ma (Card, et al., 1978), is a Penokean metamorphic effect, and the batholith is considered to be Hudsonian, as shown in the Table of Formations.

Proceed west on Highway 17. 18.4 km (11.4 miles) west of Spanish is the junction of Highway 108 which leads to Elliot Lake. Continue on Highway 17.

STOP 3.3B (Optional) - 22.4 km. 13.9 miles

MURRAY FAULT. At this point the highway coincides with the Murray Fault, which separates the Gowganda Formation of the Cobalt Group from the McKim metasediments and Pater volcanics (local name) of the Elliot Lake Group on the south. Strata on either side of the fault are steeply dipping to vertical and face south. From evidence here and elsewhere, the Murray Fault, which is traced through the entire Huronian belt, is known to be a steep, south-dipping thrust of great magnitude. Here it has eliminated all of the Hough Lake and Quirke Lake Groups. Stratigraphic displacement of as much as 2000 m (6000 feet) has been estimated by Collins (1925) and Robertson (1964) and net vertical and horizontal displacements of 2000 m (6000 feet) or more have been estimated by various workers. At this stop, shattered and sheared beds of Gowganda quartzite and conglomeratic greywacke lie north of the road, strongly sheared chlorite schist is exposed on the road-cut, and sericitic schist and metaquartzite of the McKim Formation lie south of the road.

At 11.7 km (7.3 miles) west of the junction of Highway 17 and Highway 108 (Elliot Lake Road), turn right onto Pronto Mine access road. Proceed for 2.9 km (1.8 miles) to the minesite.

STOP 3.4

PRONTO MINE. The Pronto uranium orebody was discovered in 1953 and was the first uranium orebody found in the Huronian rocks of the Blind River-Elliot Lake area. It operated from 1955 to 1960 and produced uranium valued at $47,638,000 from 2,054,800 tonnes of ore whose average grade was 0.115% U_3O_8. The geology of the Pronto Mine and surrounding area has been described by Robertson (1968). The Pronto orebody lies on the south limb of the regional Chiblow Anticline; all other uranium orebodies of the camp lie on the south and north sides of the complementary Quirke Syncline to the north (fig. 12). The orebodies are all essentially similar: they consist of pyritic, radioactive, oligomictic quartz-pebble conglomerate at or near the base of the Matinenda Formation, which lies with great unconformity on the largely granitic Archean basement. The economic deposits of the Quirke Syncline occupy two northwesterly trending zones, termed the Nordic, to the south, and the Quirke, to the north (fig. 15). The deposition of the uraniferous conglomerates, as first noted by Hart et al. (1955) and later by others including Pienaar (1963), Robertson (1966) and Roscoe (1969), was controlled by basement topography, due at least in part to differential erosion of greenstone remnant areas in the felsic igneous basement rocks (fig. 15). A probable further control was the distribution of volcanic piles in the lowermost Huronian. The main ore minerals are uraninite and brannerite, along with monazite. These are accompanied in the matrix of the conglomerate by a large suite of heavy detrital minerals. Roscoe cited good evidence for the detrital nature of uraninite and some pyrite; the latter, however, is polygenetic (Roscoe, op. cit.).

Extensive alteration of ore and host rock was encountered in the Pronto Mine, and more locally in the other deposits. Albitization and chloritization are the commonest effects, with lesser hematization and carbonatization. In some places at least this alteration is clearly related spatially and genetically to diabase dyke intrusion; at the Pronto, however, it is more widespread and related to fractures presumably developed at the time of diabase intrusion. Albitite veins in the host subarkose are seen at this stop.

The Matinenda Formation and its uraniferous conglomerates were intensively studied by Pienaar (1963), who concluded that the formation was deposited by aggrading streams flowing consistently from the north and northwest. Others have favoured a deltaic, beach, or shallow marine environment.

The Pronto ore zone is a pyritic, oligomictic, single quartz-pebble conglomerate-quartzite unit directly at the base of the Matinenda Formation. The ore zone is about 2.3 m (7.5 feet) thick, 1065 m (3500 feet) long and has a downdip length of 760 m (2500 feet). The ore zone dips 15 to 20 degrees south with the remainder of the formation. The south boundary is a thrust fault (the Pronto Thrust Fault), the east and west boundaries are sedimentary facies boundaries, and the north boundary and base is the archean basement surface. Figure 16 shows the surface geology of the mine area, the relationships in vertical cross section, and the features seen at this stop. These are:

(1) Trough and crossbedding in the Matinenda, here weakly radioactive; south of the road, a gully marks the position of the Pronto Thrust Fault, beyond which is a ridge of upthrust Archean granitic rocks.

(2) Matinenda arkose cut by albite veins.

(3) Northward coarsening of grain size in the formation. Radioactivity is also increasing. Thin, moderately radioactive pebble layers appear.

(4) Glory holes where the ore was mined to surface. At the old mine workings, the ore conglomerate is exposed on Archean granite. The hanging wall shows pebble bands and crossbedding. The arkose is weakly to moderately radioactive and the ore bed strongly so.

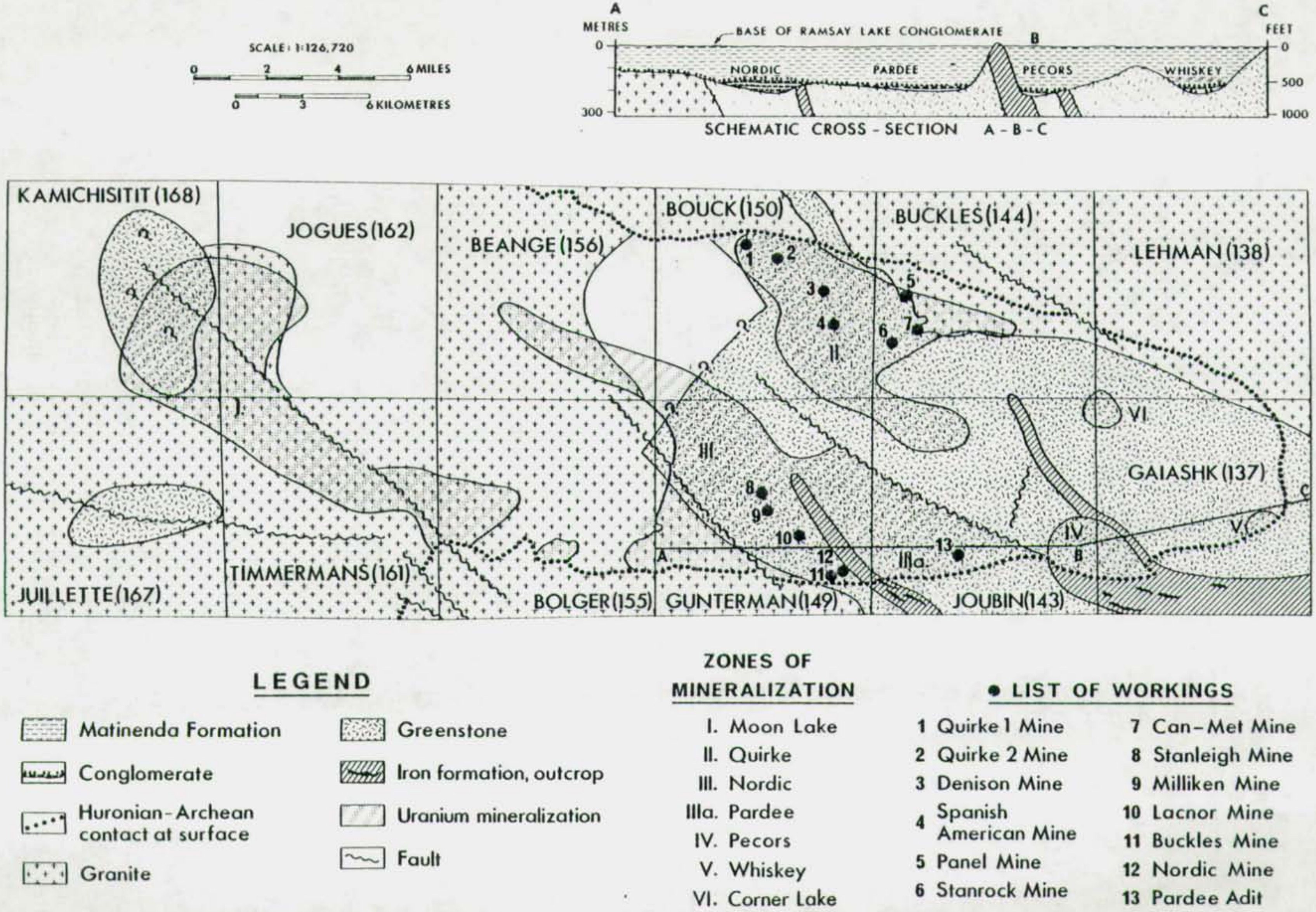

Figure 15. Uranium deposits of the Quirke Syncline related to basement lithology and topography.

(5) Archean surface showing transition to fossil soil overlain by scattered patches of pebble conglomerate. The front slope is essentially the pre-Huronian surface. The Archean rocks are cut by diabase dykes that are pre-Huronian. The formation of the regolith was characterized by a loss of iron, notably ferric iron, and soluble alkalies.

(6) The discovery locality - a number of shallow pits and trenches. The original radioactive sample resulting in the discovery of the mine came from one of these, during prospecting for base metals or gold.

Return the 365 m (1200 feet) to the bus and return to Highway 17. Proceed west approximately 19.5 km (12 miles) to motel at Blind River.

End of Day 3

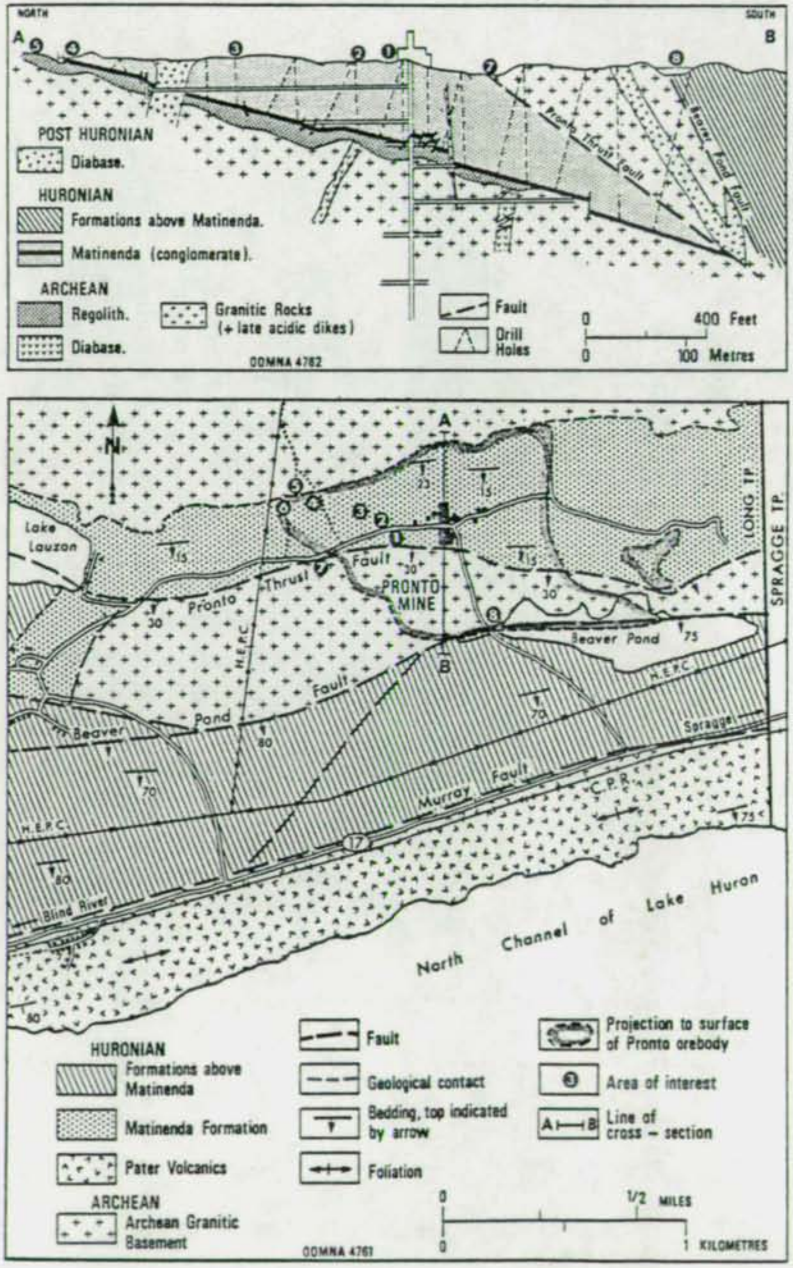

Figure 16.

Surface geology and geological section of the Pronto Mine area. Section after mine drawings.

DAY 4 -- ELLIOT LAKE, ONTARIO TO SAULT STE. MARIE, ONTARIO

Leaders: M.J. Frarey, K.D. Card, and J.A. Robertson

General Notes

Day 4 will be spent almost entirely viewing Huronian sedimentary features, near Elliot Lake, northward into the Flack Lake Area, and westward from there to Sault Ste. Marie. Time permitting, all twelve formations of the Supergroup will be seen except the Serpent Formation. To maximize the number of stops and because of highway conditions please leave and re-enter the bus quickly. We shall return eastward to the junction of Highways 17 and 108 and proceed north on 108 to Elliot Lake. Road log begins at the south entrance to Elliot Lake.

On Days 2 and 3, Huronian outcrops visited were formations of the two lower groups, mainly the basal Elliot Lake Group. Day 4 will give an opportunity to gain an appreciation of the Huronian succession that lies above them and actually forms the bulk of the supergroup. Participants are urged to review the table showing the Huronian sequence, as it will not be possible to maintain the stratigraphic order in the stops of Day 4. The general objective is to show the lithologic character of the various units, which show considerable change and variety, and to point out their various sedimentary structures; of special interest, however, are the glacial-like aspects of the paraconglomerate Ramsay Lake, Bruce, and Gowganda Formations, including varve-like deposits, and the vast, unbroken accumulation of arkose and quartzite represented by the Lorrain Formation, one of the thickest arenite formations known in the Canadian Shield.

An aspect of the Huronian sedimentary sequence that should be kept in mind in the day's tour is the upward change suggesting marked difference in the chemical environment of deposition. Thus as summarized by Roscoe (1969, 1973), the two lower Huronian groups overlie a paleosol depleted in ferric oxide, lack red beds, are generally immature, and contain widespread radioactive beds with placer concentrations of pyrite, uraninite and some gold, whereas the uppermost Cobalt Group has more mature arenites, contains red beds with hematite cement, and detrital ferric oxides in "black sand" deposits. These characteristics indicate a marked change in chemical conditions, and Roscoe (1969, 1973) has advocated a transition from a reducing atmosphere to an atmosphere beginning to accumulate free oxygen at about 2300 Ma.

The structural style in this western part of the Huronian belt is rather distinctive and simple (figs. 12 and 13). The strata are folded into broad, upright east-west structures whose gently plunging axes can be traced for tens of miles. The major folds are the Bruce Mines (also called Thessalon) Anticline, the Chiblow Anticline, and the Quirke Syncline. North of Iron Bridge, the Parkinson Dome and a complementary trough form gentle north-northeast cross flexures across the Chiblow Anticline. Throughout this terrane, the strata commonly dip between 20 and 45 degrees, except near the Murray Fault where dips locally increase to vertical. Along the northern fringe of the belt, the strata form moderately south-dipping homoclines, with local warps and folds. Near the western extremity, in the Sault Ste. Marie area, the dominant east-west trends change sharply to northwesterly. Normal and reverse faults are common throughout the area, but most faults are relatively unimportant on a regional scale. However, the Murray Fault, the Flack Lake Fault, the Aberdeen Fault, and a fourth fault in the North Channel of Lake Huron are important south-dipping thrusts, and two or three northeast-striking normal faults have appreciable displacements. Several erosional unconformities occur within the Huronian sequence, but significant angular disconformities are lacking. The most conspicuous disconformity appears below the Gowganda Formation of the Cobalt Group; in much of the area between Sault Ste. Marie and Elliot Lake, the Cobalt Group rests on, and includes angular clasts of, the lower limestone member of the Espanola Formation. A further feature emphasizing this break is a conspicuous northward transgression of the Cobalt Group beyond the paleolimits of the older groups.

As indicated, metamorphism in this terrane is slight, reaching only lower greenschist grade. Primary structures and textures are therefore commonly well preserved, and are exhibited at most stops on these days.

In addition to crossing rocks of early Proterozoic (Aphebian) age, the excursion route on Day 4 crosses, for about 25 miles east of Sault St. Marie, much younger, largely unexposed, flat-lying sandstone of the Jacobsville Formation, which occurs along the Shield margin from the Keweenaw Peninsula in the United States eastward to Lake Huron. The Jacobsville is in large part composed of red beds and is nonfossiliferous; in the past it has been classed as Precambrian and as Paleozoic. Because it unconformably overlies Keweenawan strata north of Sault Ste. Marie (McConnell, 1927) and disconformably underlies upper Cambrian beds in Michigan (Hamblin, 1961), it is currently considered to be late Proterozoic (Hadrynian). At the final scheduled stop of Day 4, the unconformity between the Jacobsville and the truncated surface of the much older Huronian is exposed.

The geology of the various townships in which Stops 4.1 to 4.7 occur has been described by our guide for the first part of the day, James Robertson, and of particular economic and sedimentological interest are his detailed descriptions of the ores and ore zones of the Quirke Syncline, including those currently producing (Robertson, 1970; summarized in Ontario Division of Mines Miscellaneous Paper No. 65, part of the excursion kit).

Stop Descriptions and Road Log, Day 4

Notes: 1. Care must be taken on highway stops. Do not loiter on pavement. 2. Quick loading and unloading of vehicles is essential. 3. Leaders reserve the right to eliminate stops or to change order in order to maintain schedule. 4. Sample taking should not deface main portions of outcrops.

South entrance to Elliot Lake (0.0 km, 0.0 miles). Elliot Lake Municipal Offices and Nuclear Museum (0.3 km, 0.2 miles), Horne Lake (0.8 km, 0.5 miles). Cliff on the east side of the lake shows Mississagi Formation (white, thick bedded) overlying Pecors Formation (grey, thin bedded). Horne Lake overlies a fault--the Horne Lake Fault. Outcrop of the Pecors Formation is displaced north on the west side of the fault and underlies Elliot Lake. Elliot Lake (2.4 km, 1.5 miles).

STOP 4.1 - 4.0 km (2.5 miles)

MISSISSAGI, BRUCE, ESPANOLA (LIMESTONE MEMBER) FORMATIONS, NIPISSING DIABASE. A sill of Nipissing Diabase, which forms a prominent ridge running east from the road, can be seen at road level. Over the next hundred metres the following units can be seen: (1) diabase, (2) Mississagi Formation showing albite (pink) and chlorite (green) introduced from the diabase, (3) contact with Bruce Formation (the Mississagi Formation was still unconsolidated when the Bruce Formation was deposited), (4) a second part of the diabase intrusion, (5) Bruce Formation, (6) transition zone to the lowermost (limestone) member of the Espanola Formation. The limestone is converted to a skarn. Grossularite (garnet), idocrase, diopside, and minor wollastonite are found. These do not show their crystal form. Drag folding, caused by differential movement of different layers during the formation of the Quirke Syncline, etched weathering, and a thin diabase sill exposed on the west side of the highway are other points of interest. The limestone outcrop is bounded on the north by a gully, north of which is (7) the Gowganda Formation; the actual contact of the Espanola limestone and the Gowganda Formation is not exposed.

4.5 km, 2.8 miles. Over the next 2 km the highway climbs through a series of road-cuts which show Gowganda conglomerate of tillite type.

STOP 4.2 - 6.4 km, 4.0 miles

GOWGANDA FORMATION. At the top of the hill is a spectacular road-cut in bedded boulder conglomerate with conglomerate-quartzite interbeds. The relay tower for the Elliot Lake T.V. satellite station is located on this ridge. The highway then runs through interbedded sparse pebble conglomerate (tillite), pink feldspathic quartzite, and greywacke.

Serpent River (12.6 km, 7.9 miles) west of the highway, is the access to Dunlop Lake. From the east end of Dunlop Lake an esker follows Highway 108 northwards past the access road to Denison Mine. Denison Mine Access Road (13.9 km, 8.7 miles). Panel Mine, Quirke #2 Mine access road (15 km, 9.4 miles). End of Highway 108. Start of Highway 639. Quirke #1 Mine and Quirke Mill (15.5 km, 9.7 miles).

Panel Mine access road - junction with Highway 108. Outcrops along Panel Road to the end of pavement at Quirke #2 Mine are in the uppermost (dolomite) member of the Espanola Formation, commonly known as the "Espanola dolomite". Over much of this distance the road is close to a fault and near-vertical dips can be seen in several of the outcrops adjacent to the road. Distances to the next two stops are measured from this junction.

STOP 4.3 - 1.6 km (1.0 miles)

ESPANOLA FORMATION. The first outcrop east of the side road to Quirke #2 Mine shows most features of the Espanola Formation dolomite member--interbedded brown-weathering dolomitic sandstone and siltstone. Sedimentary features, such as ripple marks, small-scale crossbedding, desiccation breccias, and slumpage structures such as slumpage pillows, convolute bedding flame casts, and siltstone dykes can be seen. (Eisbacher (1970) has discussed the clastic dykes at this locality.)

The road swings northeast crossing the automatic railway which transports ore from the Quirke Mill. A roadside cut (private property) shows the thin-bedded white limestone member overlain by the middle (greywacke) member of the Espanola Formation. The next outcrop on the road shows Bruce Formation conglomerate; this is more densely packed than that seen on Highway 108, indicating greater proximity to the source area. The road then swings eastward along the valley of the Serpent River. Outcrops on the south side of the road show green arkose (feldspathic sandstone) of the Mississagi Formation. Pebbly horizons are moderately radioactive.

Rocks at this stop should be contrasted with the rocks at Stop 4.1

The Serpent River Valley has resulted from the erosion of the soft argillites of the Pecors Formation, and the high ground to the north of the valley consists of red Archean granite.

SERPENT RIVER CROSSING - 3.4 km (2.1 miles)

East of the Serpent River Crossing to the Panel Mine gate the road runs along the contact between rocks of Archean and Proterozoic age just north of Quirke Lake.

STOP 4.4 - 4.3 km (2.7 miles)

RAMSAY LAKE FORMATION, PECORS FORMATION. Outcrops at the northwest corner of Quirke Lake show the boulder conglomerate of the Ramsay Lake Formation against weathered basement rocks. An outcrop just north of the road shows banded rhyolite but most outcrops are of red granite. The boulder conglomerate is overlain by greywacke showing graded bedding transitional to argillite of the Pecors Formation. This sequence shows a number of pebbles and cobbles dropped from floating ice. A cleavage intersects the bedding. Outcrops in the river bed at the entrance to Quirke Lake show shattered argillite with numerous quartz stringers.

Return to junction of Highway 108 and 639 (15.5 km, 9.7 miles) and proceed northwest on Highway 639, mileage measured from south entrance to Elliot Lake along Highway 108 and 639.

STOP 4.5 - 16.3 km (10.2 miles)

DOLLYBERRY LAKE, MISSISSAGI AND BRUCE FORMATIONS. At the foot of the hill west of the Quirke # 1 Mine there are exposures of Bruce Formation similar to that on the Panel Road. The cuts on the hill are in brownish-green arkosic Mississagi Formation and pebble bands showing weak radioactivity. The road then crosses the valley over the Pecors Formation and the Ramsay Lake Formation. Outcrops at the roadside north of the valley are of red Algoman quartz monzonite (17.8 km, 11.1 miles). On the south fringe of the outcrop west of the road massive to amygdaloidal and/or porphyritic mafic volcanic rocks can be seen resting on a regolith on granitic basement. Locally, quartz-pebble conglomerate can be seen between the volcanic rocks and the Archean rocks, and elsewhere granite inclusions can be seen in flow rocks or granite cobbles in interflow sedimentary rocks (Dollyberry Lake Formation).

The recognition of the extent and relationship of Huronian mafic volcanic rocks has been an important result of recent mapping and exploration.

Brick-red granitic rocks (23.7 km, 14.8 miles) cut by diabase dykes are exposed to Ompa Lake where the road is crossed by a fault, the Ompa Lake Fault, which is not exposed. North of this the highway-cuts and shoulders expose volcanic and sedimentary rocks of Keewatin type.

Access road to Semiwite Camp site (26.4 km, 16.5 miles), Mississagi Provincial park.

STOP 4.6 - 27.7 km (17.3 miles)

BAR RIVER FORMATION. Christman (Jimchrist) Lake and Flack Creek. Ripple-marked flaggy quartzites and iron-bearing quartzites are exposed on the highway and along the creek.

Both on the highway and on the shores of Flack Lake, ripple-marked bedding planes have sinuous structures first believed to be fossils, possibly worm casts (Hofmann, 1967), or infilled desiccated algal mats (Donaldson, 1967). Desiccation structures are also common and comparison with desiccation structures in the Gordon Lake Formation has led to the suggestion that the structures are consolidated desiccation fracture fillings transported and redeposited by later current action (Young, 1969). Hofmann later (1969) also ruled out an organic origin for these structures.

Small-scale anticline (28.8 km, 18 miles) in Bar River quartzite (best exposure east side of road).

A thin sill of Nipissing Diabase (30.9 km, 19.3 miles) crosses the road. Columnar jointing is well developed on the east side of the road. Immediately south of this lies bedded, fine-grained, pinkish quartzite marking the transitional zone between the Bar River and Gordon Lake Formations. The road descends to the Boland River Crossing through intermittent exposures of the interbedded siltstones, cherts, and fine-grained sandstones of the Gordon Lake Formation. The best outcrop is at the junction with the Laurential Lodge road 0.4 km south of the Boland River.

STOP 4.7 - 32.6 km (20.4 miles)

GORDON LAKE FORMATION. Here ripple marks, mudcracks, crossbedding, slumpage structure and a late cleavage are well displayed in a sequence of siltstones and sandstones.

This concludes the stops in the Elliot Lake-Flack Lake district. Continuing north for 6 km (3.7 miles) to the junction of Highways 546 and 639, we turn onto 639 and proceed southwest for 50.6 km (31.5 miles). Here we turn right (west) and proceed for 14.1 km (8.8 miles) to the junction of Highways 554 and 129. Stop 4.8 is 0.5 km (0.3 miles) south (left) of the junction.

STOP 4.8

GOWGANDA VARVITE. Here a 50-m (150-foot) cliff is composed of laminated clast-bearing argillite of the Gowganda Formation. The argillite consists of varve couplets ranging in thickness from 2 mm to 1.5 cm and carrying granitic ice-rafted clasts up to boulder size. Note the regularity and persistence of individual laminae, their occasional wedging out, the depression of bedding planes below dropstones, and near the centre of the examination area, a bed of slumped, broken and slurried varves. Assuming that the estimated average couplet thickness of 1 cm represents an annual deposit, a time span of about 5000 years is represented by the 150 vertical feet (50 m) of the cliff. This classic exposure shows much better couplet development than most Gowganda argillites, which are also commonly referred to as varvites. The occurrence of these fine-grained pelitic rocks with dropstones is considered to be compelling evidence of a frigid climatic regime during Gowganda deposition. Care should be taken in climbing the talus slope and moving around the cliff face. Collection of samples should be from the talus only. Suitable for photography if the day is bright.

Continue southwest on Highway 129 for 20.2 km (12.5 miles) and turn right onto secondary road. Follow secondary and forest access roads northwest and west to Highway 561 at a point 1.2 km (0.75 miles) northeast of the village of Rydal Bank. Go north on 561 from this junction for 1.6 km (1 mile) to Stop 4.9

STOP 4.9 - 3.1 km (2 miles) north of bridge at Rydal Bank

WHITE ORTHOQUARTZITE MEMBER, LORRAIN FORMATION. In this area, the Lorrain Formation is informally divided onto five members, as follows:

upper white orthoquartzite
upper pebbly pink quartzite
jasper conglomerate member
lower pebbly pink member
basal arkose member

The white uppermost member is the thickest (ca. 725 m, 2400 feet) and most conspicuous, forming prominent snow-white hills. All five members are present in this vicinity, where a Lorrain reference section has been set up (Frarey, 1977). The occurrence of the aluminous minerals diaspore, kaolinite, and pyrophyllite in the upper three members (Chandler, 1969; Chandler, et al., 1969; Frarey, 1977) led to the interpretation by Young (1973b) and Wood (1973) that deposition took place under tropical conditions, resulting in complete alteration in situ of detrital feldspar. Kaolinite-coated or talc-coated slips are visible at this stop, but diaspore and pyrophyllite are submegascopic. Note the thick lenticular bedding, crossbedding, ripple marks, and the supermaturity of the rock. This unit contains up to 99 per cent silica and has been quarried for flux and the production of ferro-silicon. In places, this member and the pebbly pink units show concentrations of detrital hematite on crossbed foresets.

STOP 4.10 - 4 km (2.5 miles) from Rydal Bank

UPPER PEBBLY PINK MEMBER, LORRAIN FORMATION. Red and white gritty quartzite and pebble conglomerate. Thick bedded, with tabular and trough crossbeds. Talc-kaolinite(?) veinlets and slips. Hematite laminae. Pebbles are dominantly chert and quartz, including sparse jasper. This unit grades by interbedding over 30 m (100 feet) into the white member of the previous stop.

STOP 4.11 - 4.6 km (2.9 miles)

JASPER CONGLOMERATE MEMBER, LORRAIN FORMATION. The member consists of jasper-rich pebble conglomerate with white quartzite interbeds. In addition to the conspicuous red jasper, the pebbles include dark and pale chert and vein quartz. The ill-sorted matrix consists mainly of rounded quartz grains. The abundant jasper and chert pebbles, many of which are angular to subangular, suggest a rapid derivation from a source that included sedimentary iron-formation. The "flood" of jasper represented by this member extends from Sault Ste. Marie eastward for about 145 km (90 miles), diminishing eastward. The nearest Archean greenstone terrane containing iron-formation in the upstream direction is the Batchawana belt some 80 km (50 miles) to the northwest, but the actual source of the jasper remains conjectural.

The jasper conglomerate is much in demand by rock collectors because of its striking appearance, and is one of the best known Precambrian rocks in Canada. Its beauty when polished makes it suitable for jewelry and ornamental purposes. Sampling is difficult at this stop.

STOP 4.12 (Optional) - 2.8 km (1.8 miles) west of Desbarats

RIPPLE ROCK. BASAL ARKOSE MEMBER, LORRAIN FORMATION. This locality is well known for its fine display of ripple-marked bedding surfaces in the arkosic sandstone. Ripple crests are relatively long and straight and spaced as much as 6 inches (15 cm) apart. One surface shows two sets of interfering ripples, the most prominent of which is at right angles to the orientation of adjacent surfaces. This locality is illustrated in Photo 134 of Guidebook No. 4, Ontario Division of Mines (Robertson and Card, 1972) and in Figure 22 of G.S.C. Memoir 383 (Frarey, 1977). The basal Lorrain beds here dip abnormally steeply for this area (roughly 60 degrees), as they have been tilted between faults that lie a short distance north and south of the exposure. Do not sample rippled surfaces.

Proceed west and north on Highway 17 for 16.8 km (10.5 miles) to Stop 4.13, at intersection of the highway and the Calabogie Road.

STOP 4.13

JACOBSVILLE-HURONIAN UNCONFORMITY. Immediately north of the intersection a road-cut exposes a low, steep rock face for about 50 m (165 feet). This locality is distant from outcrop areas and the identity of the Huronian beds is extrapolated from relations to the east. The southernmost third of the exposure consists of varicoloured siltstone correlated with the Gordon Lake Formation, and the remainder is white orthoquartzite similar to that of the upper Lorrain and of the Bar River Formation, and probably belongs to the latter. In the highest part of the cut and flanking it, red Jacobsville sandstone breccia can be seen truncating the quartzite, filling cracks, and in some spots surrounding quartzite blocks. The interval represented at this unconformity between the folded Huronian beds below and the flat-lying Jacobsville above is of the order of 1000 Ma of Precambrian time.

Proceed north and west on Highway 17 for 33.5 km (21 miles) to Sault Ste. Marie.

End of Day 4

DAY 5 -- HALF-DAY OF REST IN SAULT STE. MARIE

NOTES ON THE CITY OF SAULT STE. MARIE AND THE CITY TOUR

Sault Ste. Marie, known colloquially as "The Soo", is a city of some 75,000 with both industrial and historical significance. Industrially, it is dominated by the steel-producing complex of the Algoma Steel Corporation, Canada's third largest steel producer. This is a modern plant producing a wide variety of steel products, with a total capacity of 5 million tons of steel and pig iron per year. The iron ore is supplied by the Corporation's own and leased mines near Wawa, and additional ore purchased from the Steep Rock Mine in northwestern Ontario. The Corporation also has its own limestone and coal supplies in the United States. The excursion will not tour the steel plant, but an appreciation of its size will be gained during the city tour.

Electric power for the city and surrounding district is generated at the St. Mary's River rapids by the Great Lakes Power Corporation. Tourism is also an important industry, as the city lies on the international border, and is a major point of entry from the United States. It is connected with large centres of population to the south by a modern system of highways.

Historically, Sault Ste. Marie dates back to the earliest days of exploration of North America by the white man. Etienne Brulé visited the site in 1622 and was followed by all the French explorers going into central and western North America. The rapids of the St. Mary's River presented a barrier to water travel and a logical site for a fur-trading post and settlement. Thus the Northwest Company established a fur-trading post here in 1783 and the first canal and lock in 1787, the sites of which will be seen during the tour of the city.

In the late 18th and early 19th centuries, there was of course no formal boundary line here, and there were periodic hostilities between American and British forces in the vicinity of Sault Ste. Marie. Plaques commemorating some of these will also be seen. The growth of the settlement proceeded gradually, and eventually received stimulus from the arrival of the Canadian Pacific Railway, and later by a road connection with eastern Canada. In the nineteen twenties, power facilities were built, iron mining commenced in the ranges near Wawa, and the steel industry began. Reserves of direct-shipping iron ore at Wawa being very limited, the steel industry did not flourish, however, until a process for extraction of iron from siderite and pyrite was successfully introduced in 1939. Rapid expansion came with World War II and has continued to the present time. The half-day tour of Sault Ste. Marie will include visits to the city park and zoo, sites of the early trading post and canal, the power plant, the "Soo" locks and the Algoma Steel complex.

In the afternoon the group will go to Marquette, Michigan. No field stops are planned.

End of Day 5

MARQUETTE RANGE

William F. Cannon
U.S. Geological Survey

REGIONAL SETTING

Proterozoic sedimentary and volcanic rocks, collectively forming the Marquette Range Supergroup, are widespread in northern Michigan and Wisconsin. They lie on Archean basement rocks, the youngest of which are about 2,600 Ma old, and are intruded by granitic rocks about 1,800 Ma old. Volcanic rocks in the upper part of the supergroup are about 2,000 Ma old.

The supergroup extends for about 300 km in an east-west direction, partly beneath Paleozoic cover, and is truncated on the east, west, and north by the Keweenawan rift and associated volcanic rocks which are about 1,100 Ma old. To the south the supergroup loses its identity in a plutonic terrane in northern and central Wisconsin.

The supergroup consists of four groups, the lower three of which will be seen in the Marquette area. The fourth is mostly slate and iron-formation and is preserved only in the Iron River area, about 100 km southwest of Marquette.

STRATIGRAPHY OF THE MARQUETTE AREA

In the vicinity of Marquette, the Marquette Range Supergroup is preserved as an infold, the Marquette synclinorium, in the surrounding Archean gneiss and greenstone.

The supergroup here contains three groups that have a sharp angular unconformity with Archean rocks and are separated from each other by low-angle unconformities or disconformities.

The oldest group, the Chocolay Group, in ascending order consists of vitreous quartzite (Mesnard Quartzite), dolomite and related argillite (Kona Dolomite), and banded argillite and slate (Wewe Slate). Locally, the Mesnard is underlain by polymictic conglomerate (Enchantment Lake Formation of the Marquette range) that might be a tillite. The progression from polymictic conglomerate to vitreous quartzite is similar to the Gowganda-Lorrain sequence of the "Huronian" and some have proposed that the lower part of the Chocolay Group is correlative with the Gowganda and Lorrain. The two sequences are separated by Keweenawan volcanic rocks so there is no hope of being able to trace one into the other even in the subsurface.

On this field trip we will visit exposures of the Enchantment Lake Formation at its type locality west of Marquette, and exposures of the Mesnard and Kona just south of Marquette.

Overlying the Chocolay Group with a low-angle unconformity is the Menominee Group. Westward from Marquette the unconformity at the base of the Menominee Group gradually cuts downward through the Chocolay Group. Near the town of Negaunee, about 15 km west of Marquette, the Chocolay Group is entirely eroded and the Menominee Group rests directly on basement rock from there to the west.

The Menominee Group consists of vitreous to feldspathic quartzite with basal conglomerate (Ajibik Quartzite) overlain by slate, argillite, and graywacke of the Siamo Slate, which in turn is overlain by the Negaunee Iron-Formation. The Negaunee is the principal iron-bearing unit of the Marquette iron range. It is very thick in this area reaching a maximum thickness of more than 1000 m just south of the town of Negaunee. On the field trip we will visit the Ajibik Quartzite where it lies unconformably on the Mesnard Quartzite, a representative outcrop of the Siamo Slate, and two outcrops of the Negaunee Iron-Formation that illustrate two of the most common types of iron-formation in this area, the carbonate facies and oxide facies.

Unconformably overlying the Menominee Group is the Baraga Group. The basal conglomerate of the Baraga Group, part of the Goodrich Quartzite, contains abundant detritus eroded from the Negaunee Iron-Formation. Although angular discordance is infrequently seen in a single exposure, on a regional scale the unconformity truncates the Menominee Group to the west, and in the western part of the Marquette iron range the Baraga Group lies directly on Archean basement.

The Baraga Group was deposited during a time when the region was changing from a relatively stable platform to an unstable, rapidly subsiding "oceanic" basin. Although the Goodrich Quartzite is a relatively well-sorted, shallow-water deposit, the upper parts of the Baraga Group are a suite of deep-water turbidite and volcanic sequences with rapid lateral facies changes and great stratigraphic thickness. Volumetrically, this suite of rocks dominates the Marquette Range Supergroup accounting for more than 95 percent of the preserved Proterozoic rocks in northern Michigan.

On the field trip we will visit an exposure of Goodrich conglomerate near Palmer where we will also have a view of one of the large open-pit iron mines, and finally an outcrop of graded-bedded graywacke of the Michigamme Formation of the Baraga Group at the west end of the Marquette synclinorium.

DAY 6 -- MARQUETTE IRON DISTRICT

Leader: W.F. Cannon

STOP 6.1

MESNARD QUARTZITE. At this stop the Mesnard Quartzite, the basal orthoquartzite of the Chocolay Group, is seen in vertically dipping beds along the shore of Lake Superior south of the city of Marquette. This exposure is probably a few hundred meters stratigraphically above the base of the formation. The older Enchantment Lake Formation, although not exposed here, is believed to underlie the low area just to the north. Abundant ripple marks and cross-beds are preserved in the quartzite and indicate the shallow-water nature of the deposit.

Also seen here is the Jacobsville Sandstone. Its age is poorly known but could probably range from Proterozoic Y to Middle Cambrian. The Jacobsville is nearly flat-lying although high initial dips can be seen on the south side of the outcrop. On the north side of the outcrop, small patches of Jacobsville plastered around joint surfaces of the Mesnard indicate that during Jacobsville deposition the Mesnard formed a small topographic rib as it does today. Nearby, flat-lying Jacobsville Sandstone rests on Mesnard Quartzite more than 100 m above lake level indicating that the pre-Jacobsville topographic relief and ruggedness was as much as or greater than that adjacent to the present shore of Lake Superior.

STOP 6.2

KONA DOLOMITE. The Kona Dolomite is mostly dolomite and silicified dolomite, partly algal, but contains lesser amounts of fine- to medium-grained clastic rocks. At this stop a roadcut on the west side of the highway gives a good representation of the various rock types of the formation. Toward the north end of the cut the stratigraphically lowermost units exposed are laminated pink, green, and maroon slate with beds as much as about 1 m thick of reddish quartzite and dolomite.

Southward along the cut and upward in the stratigraphic section, dolomite beds are more common. At the south end of the roadcut a trail leads westward uphill a short distance to a cliff in which can be seen excellent examples of large dome-shaped algal structures in siliceous dolomite.

STOP 6.3

ENCHANTMENT LAKE FORMATION. The Enchantment Lake Formation is a discontinuous unit at the base of the Marquette Range Supergroup. It consists of conglomerate, graywacke, arkose, and slate and is believed to be, at least partly, of glacial origin. It is conformably below the Mesnard Quartzite.

Immediately north of the Old State Road are several exposures of basal conglomerate of the Enchantment Lake Formation, containing fragments of tonalitic gneiss and greenstone. The matrix is rich in chlorite. The conglomerate can be seen in sharp vertical contact with slaty greenstone of the underlying Mona Schist (Archean). Within 100 feet north of the contact, the Mona Schist becomes comparatively massive. Both the greenstone and the conglomerate are strongly foliated near the contact, and steeply plunging to vertical lineations are common on foliation surfaces.

The contact of Mona Schist and the Enchantment Lake is interpreted to be a fault. In addition to the highly sheared nature of the contact, the two units are "back to back"; pillows in the Mona on nearby outcrops indicate top directions to the north, whereas the Enchantment Lake and overlying units face south and are vertical. We believe the present attitude of the Enchantment Lake is a result of draping of the sediments over a vertically rising fault block of the Mona. The alternate explanation that the Mona was overturned prior to Enchantment Lake deposition and was subsequently folded back to vertical seems less likely.

STOP 6.4

MESNARD QUARTZITE AND AJIBIK QUARTZITE. At this stop, roadcuts on both sides of the highway show the Ajibik Quartzite, the basal quartzite of the Menominee Group, lying disconformably on the Mesnard Quartzite. The Ajibik forms the westernmost exposures, the contact passing through the narrow covered interval on the north side of the highway. On the south side of the highway, where exposures are more continuous, the contact is difficult to locate precisely, and no angular discordance can be seen.

Detailed mapping of this rather well-exposed area, however, has shown clearly, by tracing a marker bed near the base of the Ajibik, that the unconformity is gradually bevelling the Chocolay Group to the west. At this locality, the Wewe Slate and Kona Dolomite have been completely eroded so that only the Mesnard and a thin unit of the Enchantment Lake Formation, seen as a small exposure of greenish slate at the east end of the roadcuts, remain. About 2 km to the west, the Mesnard and Enchantment Lake are likewise eroded so that the Ajibik rests directly on Archean rocks.

STOP 6.5

SIAMO SLATE. From Stop 4 we will walk a short distance southwest along the highway to a roadcut in Siamo Slate. We will be walking upsection, the roadcut being about 150 m stratigraphically above the base of the Siamo and about 300 m below the upper contact with the Negaunee Iron-Formation.

Typical Siamo Slate is exposed here. It is gray, brown and gray-green slate and argillite with interbeds of impure quartzite, arkose, and graywacks.

Lenses of graywacke and sericitic quartzite that transect bedding in slaty rocks are a peculiar feature here. Their origin is controversial. One school contends that they are clastic dikes formed during sedimentation, and during later deformation, and were rotated so as to be nearly parallel to cleavage. The cleavage is formed by recrystallization during deformation. Another school holds that the cleavage is a prelithification, dewatering feature, and that the sandstone dikes are formed by injection of sand into the cleavage during tectonic dewatering.

STOP 6.6

CARBONATE FACIES OF NEGAUNEE IRON-FORMATION. The Negaunee Iron-Formation contains a variety of lithologic types as a result of variations in sedimentary environment, difference in diagenetic alteration, varying degrees of metamorphism, and varying degrees of weathering and secondary oxidation. Much of the formation was probably originally cherty carbonate iron-formation such as is seen at this stop.

The Negaunee here consists mainly of alternating laminae of sideritic carbonate and fine-grained quartz (chert), but some layers contain as much as 15 percent minnesotaite, which imparts a greenish color, and some layers contain a small amount of magnetite.

A few thin (less than 1 m) metadiabase sills can be seen in the iron-formation along the south side of the road.

Most of the lower ground around the town of Negaunee, and to the west, is underlain by similar carbonate iron-formation or a more oxidized derivative. The knobby hills are mostly bodies of metadiabase intruded into the iron-formation. The large expanse of iron-formation in this area is caused by the great stratigraphic thickness and gentle dips near the keel of the Marquette synclinorium.

STOP 6.7

JASPILLITE UNIT OF NEGAUNEE IRON-FORMATION. Stop 7 is at Jasper Knob in the town of Ishpeming and is one of the most famous and frequently visited geologic localities in the Lake Superior region. In addition to spectacular exposures of tightly folded hematite-jasper iron-formation, the knob offers a panoramic view of much of the Marquette mining district.

The rock here is thinly banded with interlayered specular hematite and red jasper and is representative of much of the upper unit of the Negaunee. The upper contact of the Negaunee is along the western slope of the knob. The several small abandoned mine workings on the south and west flanks of the hill are in small bodies of high-grade iron ore that are commonly localized near the upper contact. The jaspillite may either be a primary oxide facies of iron-formation or have formed by oxidation of sideritic iron-formation during the erosion interval between deposition of the Negaunee and Goodrich.

Elsewhere in the area evidence for both processes can be seen, but features diagnostic of origin are lacking here.

STOP 6.8

BASAL CONGLOMERATE OF GOODRICH QUARTZITE. At this stop, just south of the village of Palmer, coarse conglomeratic rocks at the base of Goodrich Quartzite are exposed.

Also a view to the northwest shows the mine workings and ore processing plant of the Empire Mine, the largest iron mine on the Marquette Range.

The Goodrich Quartzite, the basal unit of the Baraga Group, lies unconformably on the Negaunee Iron-Formation. Angular discordance can seldom be seen at any single exposure, but abundant detritus from the Negaunee Iron-Formation in the conglomerate and regional truncation of the Negaunee by the overlying unconformity clearly show the unconformable nature of the contact. Here, the conglomerate is usually coarse, containing clasts of iron-formation as much as half a meter in diameter. The clasts are angular and a few show internal faulting indicating that the iron-formation was hard and brittle prior to erosion and incorporation into the conglomerate. Well-rounded clasts of vein quartz are also common and must have been derived from older basement rocks. The general absence of other basement rock types in the conglomerate suggests that the basement may have been deeply weathered so that all minerals except quartz were reduced to clays.

An interesting feature in these rocks is the presence of monazite-rich placer deposits. Nearby outcrops contain, in places, more than 100 pounds of monazite per ton.

Looking northwest from this locality, the ore-processing and pelletizing plant of the Empire iron mine can be seen. The open pit, mostly out of sight, is just beyond the plant. The mine produces 8 million tons of pellets per year from about 25 million tons of crude magnetite-chert iron-formation. On the horizon, part of the pit of the Tilden Mine can be seen. The Tilden also produces 8 million tons of pellets per year, but from hematite-chert iron-formation. A third large mine, the Cascade, may soon be developed just east of this locality also in hematite-chert iron-formation.

STOP 6.9

GRAYWACKE OF THE MICHIGAMME FORMATION. The final stop, near the village of Covington, illustrates a typical graded-bedded graywacke of the Michigamme Formation. Similar rocks underlie thousands of square kilometers in the central part of northern Michigan mostly south and west of this locality, and are by far the most abundant rock types in the Marquette Range Supergroup. The graywacke is interspersed with thick volcanic units that become more abundant toward the south.

The graded bedding, great thickness, and volcanic associations indicate that the Michigamme was deposited in a rapidly subsiding basin and reflects the onset of widespread tectonic instability that persisted through the remaining phases of deposition of the Marquette Range Supergroup.

In this outcrop, the south-dipping graded beds, typically about 1 m thick, are easily seen by the diffraction of slaty cleavage. In coarser grained lower parts of beds the cleavage is steep and not strongly developed. As grain-size diminishes upward, the cleavage becomes more prominent and gradually flattens to lower dip angles. The dip then becomes abruptly steeper as the cleavage passes into the coarser grained base of the overlying bed.

End of Day 6

DAY 7 -- MARQUETTE, MICHIGAN TO IRONWOOD, MICHIGAN

Leaders: W.F. Cannon, P.K. Sims and R.W. Ojakangas

0.0 [0.0]	Proceed west on U.S. Highway 41 and Michigan Highway 28 past Negaunee and Ishpeming.
28.0 [28.0]	Junction with Michigan Highway 95 (to Iron Mountain); continue to the right (northwest) on U.S. Highway 41 and Michigan Highway 28.
3.0 [31.0]	Village of Champion; continue straight ahead on Highways 28 and 41.
8.0 [39.0]	Village of Michigamme; continue straight ahead on Highways 28 and 41.
5.0 [44.0]	Village of Three Lakes; continue straight ahead on Highways 28 and 41.
3.0 [47.0]	Village of Nestoria; continue straight ahead on Highways 28 and 41.
10.0 [57.0]	Junction with U.S. Highway 41 (to L'Anse) and Michigan Highway 28 (to Bruce Crossing); continue to the left (southwest) on U.S. Highway 141 toward Crystal Falls.
4.0 [61.0]	Junction; Michigan Highway 28 straight ahead; turn left (south) and follow U.S. Highway 141 toward Covington and Iron Mountain.
1.0 [62.0]	STOP 7.1

GRAYWACKE OF THE MICHIGAMME FORMATION. This stop illustrates a typical graded-bedded graywacke of the Michigamme Formation. Similar rocks underlie thousands of square kilometers in the central part of northern Michigan mostly south and west of this locality, and they are by far the most widespread rock type in the Marquette Range Supergroup. The graywacke is interspersed with thick volcanic units that become more abundant toward the south.

The graded bedding, great thickness, and volcanic associations indicate that the Michigamme was deposited in a rapidly subsiding basin and reflect the onset of widespread tectonic instability that persisted through the later depositional phases of the Marquette Range Supergroup.

In this outcrop, the south-dipping graded beds, typically about a meter thick are easily seen because of the diffraction of slaty cleavage. In the coarser grained lower parts of beds, the cleavage is steep and not strongly developed. As grain size diminishes upward the cleavage becomes more prominent and gradually flattens to lower dip angles. It then becomes abruptly steeper as it passes into the coarser grained base of the overlying bed.

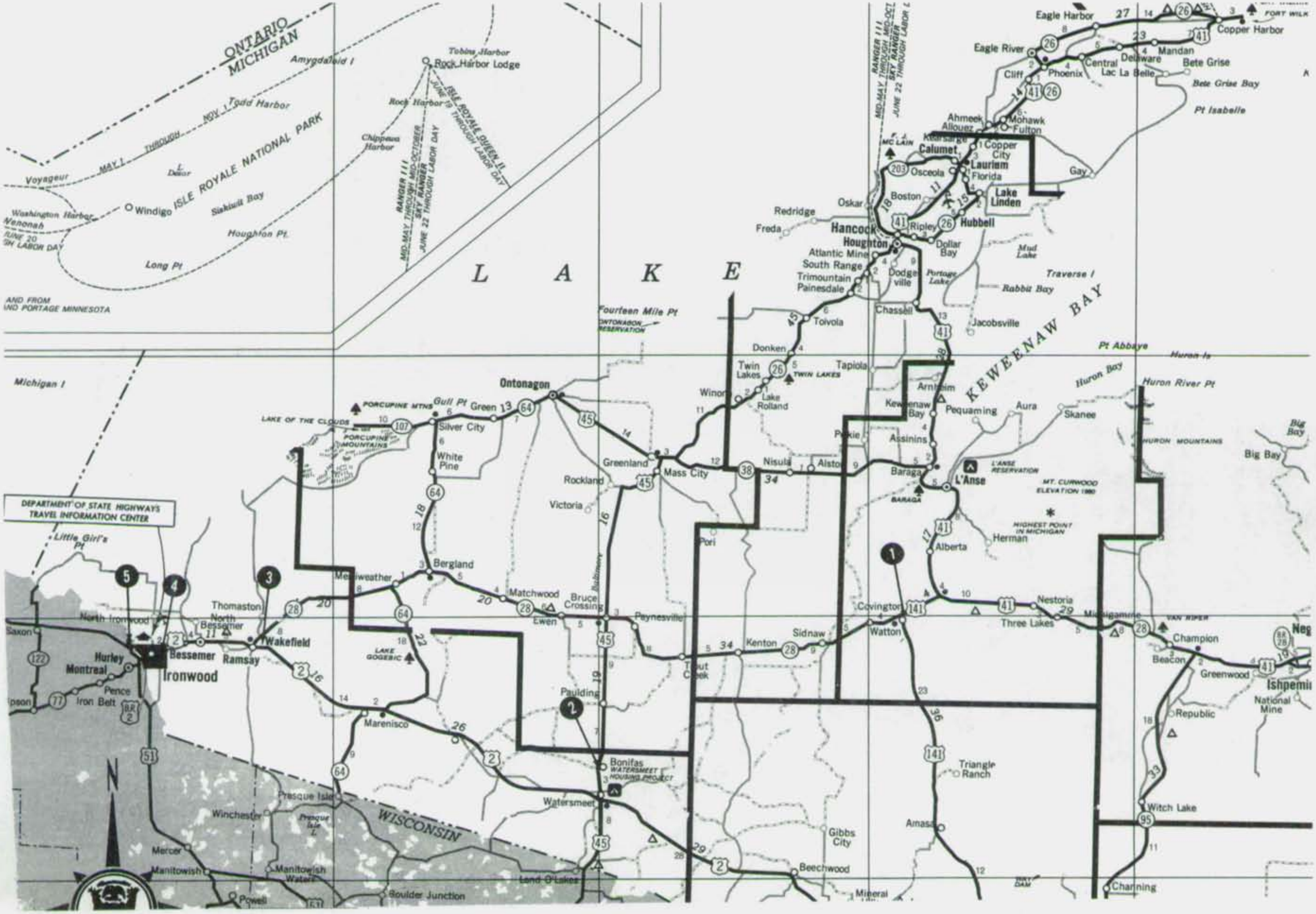

Figure 1. Highway map of a part of northern Michigan showing locations of stops for Day 7.

Return over same route to junction with Michigan Highway 28.

1.0 [63.0] Junction, turn left (west) and follow Michigan Highway 28 toward Watton.

4.0 [67.0] Village of Watton; continue straight ahead on Highway 28.

5.0 [72.0] Village of Sidnaw; continue straight ahead on Highway 28.

9.0 [81.0] Village of Kenton; continue straight ahead on Highway 28.

5.0 [86.0] Village of Trout Creek; continue straight ahead on Highway 28.

8.0 [94.0] Village of Paynesville; continue straight ahead on Highway 28.

3.0 [106.0] Village of Bruce Crossing; junction, turn left (south) on U.S. Highway 45 toward Watersmeet.

9.0 [106.0] Village of Poulding; continue straight ahead on U.S. Highway 45.

6.3 [112.3] STOP 7.2

EARLY ARCHEAN TONALITIC GNEISS. Roadcuts on both sides of the highway provide excellent fresh exposures of early Archean tonalitic gneiss cut by dikes of leucogranite. These and nearby exposures are along the northern margin of a gneiss dome that is mantled in this area by graywacke-slate of the lower Proterozoic Michigamme Formation. Radiometric data indicate that the gneiss dome developed about 1,750 m.y. ago, during the latter part of the Penokean orogeny.

The tonalitic gneiss is a strongly foliated rock containing irregular, discontinuous biotite-rich layers and local plagioclase augen. In the outcrops, several thin mylonite zones that cut the gneissic structure are clearly visible. It should be noted that the gneissic structure in the tonalitic gneiss is older than emplacement of the leucogranite dikes.

U-Pb zircon data on the leucogranite give an age of about 2,600 m.y. The tonalitic gneiss has a minimum U-Pb zircon age of 3,400 m.y. (radiometric data by Z.E. Peterman and R.E. Zartman). The Rb-Sr isotopic systems in both rock types were severely disturbed during reactivation of the gneiss dome about 1,750 m.y. ago, and samples of both from this outcrop give secondary isochron ages of about 1,750 m.y. Although the Rb-Sr systematics suggest a primary age for the gneiss of at least 2,600 m.y., there is no indication in the Rb-Sr data that the gneiss is of early Archean age. It is interesting that the gneiss has a Sm-Nd model age of 3,600 m.y.

(determined by M.T. McCulloch and G.J. Wasserburg, California Institute of Technology), which supports the old U-Pb zircon age.

Continue straight ahead on U.S Highway 45.

0.7 [113.0] Village of Bonifas; continue straight ahead on U.S. Highway 45.

3.0 [116.0] Village of Watersmeet; turn right (west) and follow U.S. Highway 2 toward Wakefield.

26.0 [142.0] Village of Marenisco; continue straight ahead on U.S. Highway 2.

16.0 [158.0] City of Wakefield; turn right (north) on Bedell Avenue; continue straight ahead for 3 blocks; turn right (east) one block to steep dirt road on the left (north). Park and walk up this road to the top of Radio Tower Hill.

STOP 7.3

PALMS QUARTZITE OF MARQUETTE RANGE SUPERGROUP. The principal purposes of this stop are to (1) examine an excellent exposure of the Palms Quartzite and (2) obtain a view of this part of the Gogebic iron range.

This area is in the eastern part of the Gogebic iron range, which is one of the major iron ranges in the Lake Superior region, now entirely inactive. All mining on the Gogebic was done underground from vertical shafts.

At top of hill, several abandoned mines can be seen in the lowland immediately to the north; the ridges in the intermediate distance are underlain by basalt of early Keweenawan (late Proterozoic) age. The lowland in the far distance is underlain by the Keweenawan Jacobsville Sandstone.

The view to the south overlooks Archean terrane consisting of the Ramsay Formation (mafic and felsic metavolcanic rocks) and the Puritan Quartz Monzonite and related rocks (∼2,700 m.y.), which constitute a major batholith more than 150 km long.

At this locality, the Palms Quartzite unconformably overlies the Archean Ramsay Formation and is overlain conformably by the Ironwood Iron-Formation (which underlies the low area north of hill). To the east, the Palms unconformably overlies the Bad River Dolomite, with a thin phosphatic conglomerate at the base. The quartzite dips steeply northward, in accord with the regional dip of Proterozoic rocks in the Gogebic range. This regional dip resulted mainly from northward tilting during Keweenawan time, toward the axis of the (Keweenawan) Lake Superior syncline. The lower Proterozoic rocks were not appreciably deformed or metamorphosed during the tectonic event (Penokean orogeny) that closed lower Proterozoic deposition, but a few folds plunging to the east-northeast at 20-25° have been recognized.

Exposures of the Palms Quartzite at this locality are more or less representative of the formation as a whole which extends for 80 km to the west-southwest. Representative rock types well exposed at the top of the hill include the upper part of the so-called "lower argillaceous member" and the transition to the more massive quartzite of the so-called "upper quartzite member."

The argillaceous member is thin bedded, with beds generally 2-10 cm thick. In general, beds of buff to pink siltstone and white sandstone alternate with buff, red or green beds of more argillaceous material; coarse-grained, dark-red, hematitic sandstone beds are also present. Most beds are quite continuous across the outcrop but "pinch and swell" irregularities impart a waviness to the generally horizontal bedding. Lenticular beds of sandstone, commonly cross-bedded, are common. Flaser bedding is present locally where the mud supply was subordinate to the sand supply. Minor cut-and-fill and soft-sediment deformation structures also are present. Symmetrical but irregular ripple marks, although not visible at this locality, are abundant on the next hill to the east.

Measurement of 42 cross-beds on this hill shows a strong paleocurrent trend to the west, with a weaker trend to the east. More than 100 measurements in the formation as a whole accentuate this bimodality. Correction for plunge, if indeed the entire formation has a plunge as well as a tilt, would rotate the major and minor modes clockwise, thus relocating the modes to the west-northwest and east-southeast, respectively.

General characteristics of the formation, and especially the bimodal cross-bedding pattern and the bedding styles, are highly suggestive of deposition in a tidal environment. The dominant west-northwest cross-bedding mode would thus be the result of ebb tides moving basinward.

Thin sections from this locality show that the sandstone beds are feldspathic quartzite. Well-rounded unit quartz grains and feldspar (mostly fresh K-feldspar) grains are the dominant framework constituents, with chert grains a poor third. Silica cement is abundant and illitic clay is present in many samples as minor to abundant matrix. Illite is also the major consituent of the argillaceous beds with chlorite locally prominent. The coarser grained, hematitic sandstone beds are really thin beds of iron-formation, consisting of granules of hematite, chert and iron silicates in addition to the common quartz grains.

Deformation of the Palms Quartzite has not been well studied. Basically, it is part of a large monocline in which folding is rarely seen except at this locality. On the west flank of the hill, several open, round-crested folds exhibit a cleavage that is flatter than the bedding. The extent, origin, and age of these folds and their associated cleavage are not known, but the folds probably formed when the beds were approximately flat-lying, presumably during the Penokean orogeny.

Return over same route to U.S. Highway 2. Turn right (west) and continue through Wakefield toward Bessemer.

9.75 [167.75] Junction; turn left (south) on road to the Gogebic Country Club.

1.0 [168.75] Railroad cut to the left (east) of the road in trees across a small field just before the road makes a sharp bend to the left (east).

STOP 7.4

ARCHEAN-PROTEROZOIC UNCONFORMITY, OLD NEWPORT MINE. The Marquette Range Supergroup in the Gogebic range was deposited unconformably on a moderately flat erosion surface developed on Archean granite and greenstone. The granite, as exposed at this locality, is named the Puritan Quartz Monzonite (Schmidt, 1976). The greenstone has been named by Schmidt the Ramsay Formation. The contact is a marked angular unconformity.

At this locality, the unconformable contact between the Palms Quartzite and Archean granite is exposed in the cut along the abandoned railway track. The contact dips steeply north, and basal beds of the Palms are subparallel to it. Note that there is no appreciable evidence of weathering of the granite beneath the Palms.

The unconformable surface on which the Palms was deposited apparently was relatively flat over a large area for it is exposed at approximately the same altitude at places between Ironwood and Wakefield, a distance of about 15 km. Small depressions in the surface, as can be seen here, contain laminated cherty material, some of which is granular and somewhat resembles iron-formation. The granules are 0.5 to 1.0 mm in diameter and consist of mixtures of chert, chlorite, and calcite.

As discussed under Stop 7.3, the tilting of the unconformity at the base of the Marquette Range Supergroup is interpreted as having occurred in late Proterozoic (Keweenawan) time, during a late stage of rift-related faulting accompanying development of the Lake Superior syncline. The major evidence for Keweenawan tilting, first documented by Schmidt and Hubbard (1972), is the observation that the Keweenawan volcanic-sedimentary rocks dip as steeply or more steeply than the virtually conformably underlying rocks of the Marquette Range Supergroup. The tilting involved the Archean rocks as well as the Proterozoic strata, and probably resulted from block faulting.

Return over same route to U.S. Highway 2; turn left (west) and continue through Bessemer and Ironwood toward the Michigan-Wisconsin border.

3.75 [172.5] Michigan-Wisconsin border at bridge over U.S. Highway 51. Note roadcuts on right (north) side of the Highway.

STOP 7.5.

TYLER FORMATION OF MARQUETTE RANGE SUPERGROUP. This locality exposes part of the upper succession of the Tyler Formation, which is about 2,000 m thick in this area. The formation thickens westward and thins eastward to an area near Wakefield where it was entirely removed by erosion before the beginning of Keweenawan deposition. At this locality, the Tyler is overlain by the lower Keweenawan Bessemer Quartzite, a thin quartzose unit beneath an extensive thickness of Keweenawan volcanic rocks. The volcanic rocks are exposed on the hill to the north of the highway, and small outcrops of the Bessemer Quartzite are present nearby.

The Tyler Formation conformably (?) overlies the Ironwood Iron-Formation and is correlated with the Michigamme Formation to the east and with the Thomson, Rabbit Lake, Virginia, and Rove Formations to the west and north in Minnesota and Ontario. All of these units were probably deposited in the same basin.

Approximately 200 meters of the upper part of the Tyler Formation are exposed at this roadcut and the one on the roadway to the overpass. As elsewhere on the Gogebic range, the beds here strike east-northeast, dip northwest at 65-70°, and top to the northwest. There is equivocal evidence elsewhere (small folds) that the formation may plunge 10-20° to the west, but in general, the formation has been tilted, perhaps as a single block, into a large northward-facing monocline. The Tyler was only slightly metamorphosed to the subgreenschist facies during the Penokean orogeny; consequently primary sedimentary textures and structures are well preserved.

The Tyler Formation consists dominantly of intercalated argillite and slate with lesser amounts of metasiltstone, and metagraywacke. Graded metagraywacke beds containing Bouma sequences indicative of deposition by turbidity currents are common, but structureless beds are even more abundant and a grain-flow mechanism may have also been operative. Sole marks and small-scale cross-bedding indicate a paleocurrent trend from the east-southeast to the west-northwest (Alwin, 1976).

The "average" Tyler graywacke (Alwin, 1976) consists of 28 percent micaceous matrix and 72 percent framework grains. Of the framework grains, 73 percent are mono- and polycrystalline quartz and chert, 10 percent are feldspar (mostly altered plagioclase), and 17 per cent are rock fragments, mainly of granitic to quartz dioritic and volcanic origin, but some grains of sedimentary and metamorphic origin also are present. Thus, the "average" Tyler graywacke is a compositionally submature quartzose lithic graywacke that is texturally immature as defined by angular framework grains and poor sorting.

End of Day 7

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DAY 8 -- IRONWOOD, MICHIGAN TO EVELETH, MINNESOTA

G.B. Morey

No road log has been prepared for the travel route from Ironwood Michigan to the Minnesota-Wisconsin border. This road log of the Minnesota portion of the travel route starts at the Blatnick Bridge on the Wisconsin-Minnesota border and terminates at the Holiday Inn in Eveleth, Minnesota. Although some aspects of the geology along the route are described, no stops are planned.

Mileage	
0.0	Blatnick Bridge; enter Minnesota and proceed north on U.S. Interstate Highway 535 and U.S. Highway 53.
0.5 [0.5]	Junction with U.S. Highway 53; continue north on U.S. Highway 535.
1.1 [1.6]	Junction with U.S. Interstate Highway 35 and U.S. Highway 61; follow U.S. Highway 35 to the right (east) toward downtown Duluth. Move to the left lane and prepare to exit.
1.0 [2.6]	Left-lane exit onto Mesaba Ave; continue north. Anorthositic gabbro of the Duluth Complex (Keweenawan) crops out on the left.
1.2 [3.8]	Stop-and-go lights; turn left (northwest) and follow Minnesota Highway 194 north. Bedrock is Keweenawan basaltic lava that crops out just downhill to the right.
0.5 [4.3]	Basalt flows on left; the upper contact of the anorthositic gabbro is nearby.
0.7 [5.0]	Outcrops of anorthositic gabbro on hill to right.
1.1 [6.1]	Junction with U.S. Highway 53; continue north on Highways 194 and 53.
0.5 [6.6]	Junction with Maple Grove Road; continue north on Highways 194 and 53.
1.5 [8.1]	Junction with Arrowhead Road; continue north on Highways 194 and 53.
0.6 [8.7]	Stop-and-go lights; continue north on Highways 194 and 53. Duluth International Airport on right.
3.3 [12.0]	Junction with Minnesota Highway 194; continue straight ahead on U.S. Highway 53.

1.2 [13.2]	Stop-and-go lights; continue north on U.S. Highway 53.
5.5 [18.7]	Railroad crossing; caution.
1.5 [20.2]	Village of Twig.
3.0 [23.2]	Crossroad. Northwest front of the Highland Moraine. The topography changes abruptly from knobby morainic forms to smooth, oval, southwest-trending hills of the Toimi drumlin field.
3.2 [26.4]	Junction with Minnesota Highway 33; continue straight ahead on on U.S. Highway 53.
0.2 [26.6]	Cloquet River.
0.1 [26.7]	Village of Independence (on west side of highway).
5.6 [32.3]	Village of Canyon. From here northward for about 15 miles, the road crosses a vast swampland with a few areas of higher ground. The low areas represent the bed of Glacial Lake St. Louis which was damned on the south by moraines or by ice.
8.8 [41.1]	Village of Cotton.
0.8 [41.9]	Bridge over Whiteface River.
7.9 [49.8]	Railroad crossing. From here to Eveleth, many deposits of sand and gravel rise above the swamp. Some are capped with till, whereas other deposits of sand and gravel rest on till. The latter were presumably formed as outwash fans and deltas that were graded into Glacial Lake St. Louis from ice retreating to the north.
0.4 [50.2]	Village of Central Lakes Community Hall on right.
5.4 [55.6]	Bridge over St. Louis River.
2.1 [57.7]	Junction with Minnesota Highway 37. Continue north on U.S. Highway 53 and Minnesota Highway 37.
3.1 [60.8]	Railroad overpass.

1.3 [62.1]	Junction with Minnesota Highway 37 to Gilbert; continue north on U.S. Highway 53 to Eveleth. We are in that part of the Mesabi range commonly called the "Horn" in reference to the Z-curve in the range that reflects two major structural features named the Eveleth anticline and the Virginia syncline. The Eveleth anticline is cored with Archean rocks. Outcrops on left and right hand sides of the highway are of the Biwabik Iron-Formation -- the middle lithostratigraphic unit in the well-known Animikie Group of middle Proterozoic age.
0.4 [62.5]	Village of Eveleth on left. Roadcut on right is in Pokegama Quartzite, the basal lithostratigraphic unit of the Animikie Group. Outcrops in field on right side of road are of Archean chloritic graywacke locally capped by a thin veneer of Pokegama Quartzite.
0.1 [62.6]	Left-lane exit to "Hockey Hall of Fame"; turn right (north) and follow frontage road.
0.3 [62.9]	Turn left (west) at entrance to Holiday Inn.

End of Day 8

DAY 9 -- VERMILION DISTRICT

Leaders: G.B. Morey, D.L. Southwick, R.W. Ojakangas and P.K. Sims

This road log starts and ends at the Holiday Inn in Eveleth, Minnesota. The 12 stops on this segment of the field trip provide an opportunity to examine rock types and structural attributes associated with the western part of the Vermilion greenstone belt, an Archean terrane that comprises the southern part of the exposed Superior province of the Canadian Shield.

Mileage	
0.0 [0.0]	Intersection of Holiday Inn driveway and frontage road; turn right onto frontage road and proceed south.
0.3 [0.3]	Stop sign; turn left (east) and right (south) onto U.S. Highway 53.
0.1 [0.4]	Follow right lane exit to Minnesota Highway 37 to Eveleth and Gilbert.
0.4 [0.8]	Stop sign; turn left (east) and follow Highway 37 to Gilbert.
1.9 [2.7]	Junction with St. Louis County Highway 97 to Sparta; continue east on Highway 37.
0.6 [3.3]	Gilbert city limits; 30-mile zone; continue east on Highway 37.
1.2 [4.5]	Junction with Minnesota Highway 135 and Highway 37; continue east on Highway 135 to Biwabik.
0.1 [4.6]	End 30-mile zone.
2.7 [7.3]	Junction with St. Louis County Highway 20 to McKinley; continue east on Highway 135.
4.1 [11.4]	Biwabik city limits; start 30-mile zone; continue east on Highway 135.
0.2 [11.6]	Stop-and-go lights; continue east on Highway 135.
0.3 [11.9]	Stop-and-go lights; continue east on Highway 135.
0.1 [12.0]	End 30-mile zone; continue east on Highway 135.

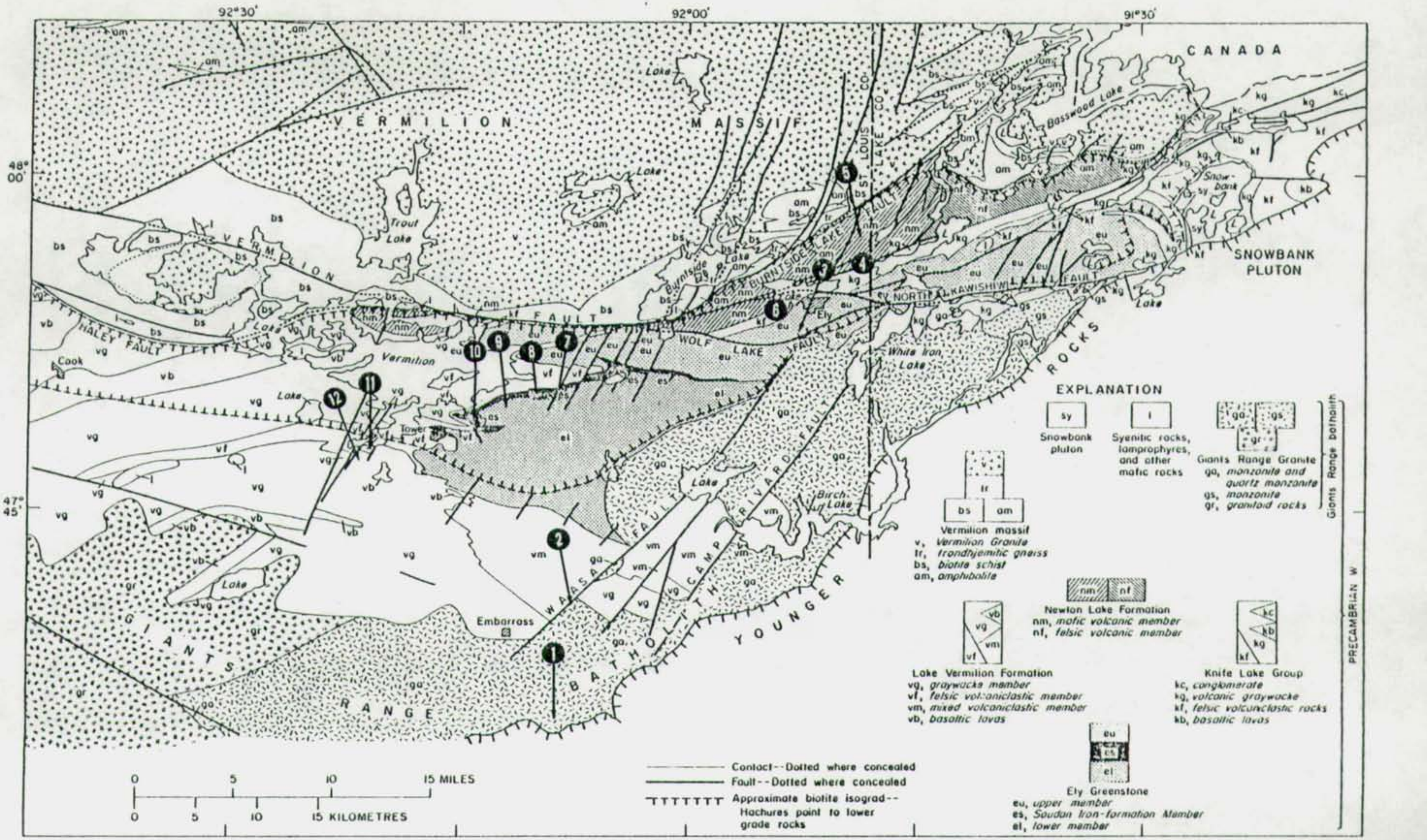

Figure 1. Geologic map of the western part of Vermilion district, northeastern Minnesota showing locations of stops for Day 9.

3.6 Aurora city limits; start 40-mile zone.
[15.6]
0.1 Junction; turn left (north) and follow Highway 135 to Tower.
[15.7]

5.2 Outcrop on left (north) side on Highway 135.
[20.9]

STOP 9.1

GIANTS RANGE BATHOLITH. The Giants Range batholith in this area consists dominantly of coarse-grained, hornblende- or biotite-bearing granodiorite characterized by pink or red, oblong, euhedral grains of microcline and elongate prisms of hornblende. Regional geologic relationships suggest that this phase of the batholith is post-tectonic in age and that it truncates the regional structure in adjacent metasedimentary and metavolcanic rocks. The rocks at this locality exhibit a steep primary foliation that is discordant to the regional structure, but concordant with the structure in adjacent wall rocks that crop out nearby. The Archean rocks are overlain immediately to the south by strata of the Animikie Group of Proterozoic age.

Continue east on Highway 135.

3.1 Embarrass River.
[24.0]

2.5 Junction with St. Louis County Highway 21; turn left (east)
[26.5] and follow Highway 21 to Babbitt.

2.4 Embarrass city limits; start 30-mile zone; continue on Highway
[28.9] 21.

1.2 End 30-mile zone.
[30.1]

3.9 STOP 9.2
[34.0]

COARSE-GRAINED, AMPHIBOLITIC AND BIOTITIC GNEISSES intruded and locally migmatitized by medium-grained orthogneiss of leucotrondhjemitic composition. The amphibolitic and biotitic gneisses are foliated parallel to lithologic layering and are characterized by extensive boudinage and local small-scale folds; long directions of the boudins and the axial traces of the small-scale folds parallel the dominant foliation. The leucotrondhjemite commonly occurs as tabular bodies several centimeters to several meters thick that cut the layering at an oblique angle. If followed far enough, the sill-like bodies branch and swell into pod-like masses.

The leucotrondhjemite lacks relict igneous textures and is foliated parallel to layering in the paleosome, but regional relationships indicate a magmatic origin. Many of the sill-like bodies are folded, a fact implying that the leucotrondhjemite was intruded early in the tectonic history of the greenstone belt and prior to emplacement of the granodioritic rocks seen at Stop 9.1.

Continue east on Highway 21.

6.1 [40.1]	Junction with St. Louis County Highway 698; continue east on Highway 21.
2.6 [42.7]	Junction with St. Louis County Highway 70 to Babbitt (straight ahead); turn left (north) and follow Highway 21 toward Ely.
13.2 [55.9]	Junction; turn left (west) into Harry Homer Lumber Company driveway. Obtain permission at office before examining outcrop.

STOP 9.3

Pillowed metabasalt of the LOWER MEMBER OF THE ELY GREENSTONE is beautifully displayed in a glacially polished outcrop in the lumberyard. The pillows have been flattened tectonically but are exceptionally well preserved.

Return to Highway 21 and continue north to Ely.

1.3 [57.2]	Ely city limits; 30-mile zone; continue north on Highway 21 (Central Ave).
0.9 [58.1]	Junction with Minnesota Highways 169 and 1 (Sheridan Street); turn right (east) and follow Highways 169 and 1 through Ely.
1.1 [59.2]	Junction with Minnesota Highway 1 to Isabella and Illgen City; continue east on Highway 169 to Winton.
0.6 [59.8]	Voyageur Vistor Center on right; continue east on Highway 169.
0.3 [60.1]	Junction with St. Louis County Highway 88; continue east on Highway 169.
0.8 [60.9]	Junction with Section 30 Road; continue east on Highway 169.
0.85 [61.75]	Shagawa River.
.05 [61.8]	Village of Winton; junction with St. Louis County Highway 177.
0.3 [62.1]	Water tower on left. Proceed past water tower, turn left on next street, go 1 block to end of street, turn left; go past

water tower to fork in road near tower; follow right fork and park; walk to outcrops near base of tower.

STOP 9.4

KNIFE LAKE GROUP. This is one of the readily accessible, large exposures of strata assigned to the Knife Lake Group. The exposure consists of phyllitic metasedimentary rocks that are representative of one rock type within a highly variable unit. It can be seen here that shearing is pervasive, bedding is indistinct, and late-stage kink banding is common. Foliation trends to the northeast.

Return to fork, turn left, and follow gravel road to the southwest.

0.4 Railroad tracks; turn right before crossing tracks.
[62.5]

2.8 Intersection with private road on right.
[65.3]

STOP 9.5

MAFIC MEMBER OF THE NEWTON LAKE FORMATION. These low-lying exposures of serpentinized peridotite within the mafic member of the Newton Lake Formation are part of a northeast-trending, 330-meter-thick and several-kilometer-long differentiated sill that is dominantly composed of diabasic gabbro. Where they may be observed in their entirety, the sills of this type typically grade upward from serpentinized peridotite to pyroxenite to coarse-grained hypersthene gabbro to diabasic gabbro to quartz gabbro.

At this locality serpentinized peridotite is exposed within 60 meters of the intersection on the northwest side of the main gravel road, whereas the first outcrops on the private road are hypersthene gabbro. Succeeding outcrops along the private road are diabasic gabbro and quartz-bearing diabasic gabbro. Pillowed lavas also assigned to the mafic member of the Newton Lake Formation are exposed about 280 meters down the private road on both sides of a sharp bend on the crest of a small hill.

Return over same route.

2.8 Intersection at railroad tracks; turn right (southwest) and
[68.1] follow gravel road.

1.0 Junction with St. Louis County Highway 88. Turn left (south).
[69.1]

1.2 Junction with Minnesota Highways 169 and 1; turn right (west)
[70.3] and return to Ely.

2.0 Junction with St. Louis County Highway 21; continue straight
[72.3] ahead.

0.4 Ely city limits; end 30-mile zone.
[72.7]

0.2 STOP 9.6
[72.9]

ELY GREENSTONE. Pillowed metabasalt that is typical of the lower member of the Ely Greenstone is exposed in the roadcut on the north side of the highway. The pillows have smoothly rounded tops, nearly flat bases, and are somewhat drawn out in vertical dimension. The chilled rinds are as much as several centimeters thick. The pillow structures strike approximately north-northeast, dip steeply south, and face southeast; the long dimension of the pillows is subparallel to the intersection of cleavage and bedding and plunges steeply to the northeast.

On the south side of the highway, fine- to medium-grained metadiabase is exposed in the roadcut and on the hill to the south. The metadiabase intrudes and crosscuts the pillowed metabasalt. A contact can be seen in the southern part of the crest of the hill.

Continue west on Highways 169 and 1.

11.2 Junction with St. Louis County Highway 408 (Mud Creek Road);
[84.1] continue west on Highways 169 and 1.

3.3 Turn right (north) onto abandoned road and park.
[87.4]

STOP 9.7

THE SOUDAN IRON-FORMATION MEMBER OF THE ELY GREENSTONE and a crosscutting dike of dacite porphyry are exposed at this locality. The iron-formation consists of thin to thick beds of black, red, and white chert, intercalated with black argillaceous beds having abundant pyrite-rich stringers and pods. Hence, both the oxide and sulfide facies of the iron-formation are represented here. Mafic volcanic rocks associated with the iron-formation are exposed in roadcuts to the east, and both they and the iron-formation are cut by a dacite porphyry dike. There are numerous such dikes and sills in this area; they apparently were feeders for the felsic pyroclastic rocks and flows of the Lake Vermilion Formation, which overlies the Ely Greenstone.

Continue west along abandoned road.

0.6 Narrow driveway to the right (north).
[88.0]

STOP 9.8

SOUDAN IRON-FORMATION MEMBER. Cherty, oxide-facies iron-formation, felsic tuff, felsite porphyry, felsic tuff breccia, pillowed greenstone, and mixed mafic and felsic breccia all are exposed on a hill located approximately 300 feet north of the intersection of the abandoned road and driveway. The beds strike east-west, dip vertically, and become younger to the north. The 15-meter-thick layer of felsic rock at the top of the hill is chiefly intrusive porphyry. North of it is a 20-meter-thick layer of iron-formation that is overlain by pillowed greenstone. Tuffaceous rocks crop out down the steep slope to the north. Complex stratigraphy involving both felsic and mafic volcanic rocks together with ferruginous chert is typical of the Soudan Iron-formation Member in this area.

Continue west along abandoned road.

1.1 [89.1]	Turn left (east) onto dirt track into woods.
0.1 [89.2]	Large open area.

STOP 9.9

ELY GREENSTONE. Although the greater part of the Ely Greenstone in the Tower-Soudan area is massive amygdaloidal basalt, important quantities of tuff, volcanogenic breccia, and cherty iron-formation occur locally. The outcrops in this clearing illustrate some of these lithologies. Massive, medium- to coarse-grained metadiabase crops out at the utility pole and along the low ridge to the east. It is probably a sill. The outcrop in the northwest corner of the clearing is well-cleaved mafic tuff and tuff breccia. The same rock is in contact with a thin unit of cherty iron-formation in exposures behind the old foundations at the east edge of the clearing. Massive amygdaloidal basalt crops out just south of the tuff and iron-formation, and is exposed in the highway cuts. South of the highway there are scattered outcrops of massive metabasalt, pillowed metabasalt, and pillow breccia.

Follow dirt road straight ahead (south).

0.2 [89.4]	Junction with Highways 169 and 1; turn right (west) and follow Highways 169 and 1 to Soudan.
2.2 [91.6]	Soudan city limits; 30-mile zone.
0.1 [91.7]	Turn right (northwest) into Soudan.
0.5 [92.2]	Street ends; turn right (north) and go up the hill toward the headframe at Tower-Soudan State Park.
0.2 [92.4]	Junction; Tower Soudan State Park headframe and other facilities straight ahead; turn right (north) and follow gravel road toward Stuntz Bay on Lake Vermilion.

0.05 Crest of Soudan Hill.
[92.45]

STOP 9.10

SOUDAN IRON-FORMATION MEMBER. Soudan Iron-formation of the type locality is exposed on right (east) side of road. (No hammering, please!) This classical exposure of iron-formation is characterized by numerous folds of at least two generations. Most of the more obvious folds are a result of regional deformation. They plunge east at steep angles. An earlier set of folds, which can be seen in places, may be the result of an earlier period of regional deformation, but may be the result of soft-sediment deformation. Joints and faults related to a third deformation cross the folds.

The nearby Soudan Mine was opened in 1884 and operated continuously until 1962, when it was deeded to the state by the U.S. Steel Corp. for the development of the Tower-Soudan State Park.

The Soudan was the first iron mine in Minnesota and shipped 16 million tons of high-grade ore containing 63-66 percent iron. Initial operations were open-pit. The mine was not closed because of exhaustion of the ore; known reserves total 2.25 million tons. The high cost of mining and the preference of blast furnace operators for taconite pellets rather than for high-grade lump ore caused it to close.

Return over same route.

0.4 Street ends; turn right (west).
[92.85]

0.4 Junction; turn left (south).
[93.25]

0.3 Junction with Minnesota Highways 169 and 1; turn right (west)
[93.55] toward Tower.

1.0 Tower city limits; 30-mile zone.
[94.55]

0.7 Junction with Minnesota Highway 135 to Aurora; continue west
[95.25] on Highways 169 and 1 toward Virginia and Cook.

0.1 End 30-mile zone; continue west on Highways 169 and 1.
[95.35]

1.7 STOP 9.11
[97.05]

LAKE VERMILION FORMATION. This large roadcut of very light gray, medium-grained volcanic sandstone was originally mapped as the feldspathic quartzite member of the Lake Vermilion Formation. The field term, "feldspathic quartzite," was unfortunate, for subsequent studies have shown that this rock type is a slightly reworked dacitic tuff, and have mapped it as volcanic sandstone and breccia. Note the quartz "eyes" that are smaller than those in the dacite tuff and dacite porphyry seen at Stops 9.7 and 9.8. Although the rock is generally structureless, faint bedding and lamination are visible on the outcrop, and some sericitic phyllite (originally fine-grained tuff?) beds are present. At the east end of the south cut, felsic volcanic rock fragments as much as a few centimeters in diameter are present.

The 6-meter-thick dike of diabasic gabbro at the west end of the south cut has a minimum age of 1,570 m.y., and similar dikes a few kilometers away have apparent ages of 1,520 m.y. and 1,685 m.y. The dike has narrow chilled borders and contains some inclusions of volcanic sandstone.

Continue west on Highways 169 and 1.

0.6 STOP 9.12
[97.65]

METAGRAYWACKE-SLATE MEMBER OF THE LAKE VERMILION FORMATION. Highly folded biotite-bearing metagraywacke and slate of the metagraywacke-slate member of the Lake Vermilion Formation. (No hammering, please!) Note the excellent graded bedding. Some geologists have speculated that much of the folding resulted from penecontemporaneous soft-sediment deformation as indicated by small clastic dikes cutting the beds. However, the major deformation can be interpreted as tectonic, for the following reasons:

(A) These structures in graywacke-slates are unique to this small area.

(B) Well-preserved sedimentary structures nearby are not chaotic.

(C) This exposure is located near a major fold axis.

(D) Folding is similar in trend and style to that observed in the Soudan Iron-formation Member at Stop 9.10, which also is on a major fold axis.

(E) Trends of the numerous fold axes fit the regional structural pattern. A third deformation is marked by faults, joints, and kink bands that cut transversely across the folds.

Continue west on Highways 169 and 1.

1.8 [99.45]	Junction with St. Louis County Highway 77; continue straight ahead on Highways 169 and 1.
0.1 [99.55]	Junction with Highway 1 to Cook; follow Highway 169 toward Virginia.

11.2 [110.75]	Junction with St. Louis County Highway 21 to Aurora and Babbitt; continue straight ahead on Highway 169.
6.0 [116.75]	Stop sign; junction with U.S. Highway 53; turn left (south) and follow Highways 53 and 169 south toward Virginia.
0.8 [117.55]	Laurentian Divide. Continue south on Highways 53 and 169 south.
1.5 [119.05]	Junction with U.S. 53 alternate route through City of Virginia business district (left lane); continue south on Highways 53 and 169 south.
1.8 [120.85]	Stop sign; junction with Minnesota Highway 135; continue south on Highways 53 and 169.
0.7 [121.55]	Junction with Minnesota Highway 169 to Hibbing; continue south (left lane) on U.S. 53 to Eveleth.
0.6 [122.15]	Stop-and-go lights; continue south on U.S. 53.
0.4 [122.55]	Stop-and-go lights; continue south on U.S. 53.
1.5 [124.05]	Junction (left lane) with Minnesota Highway 135 north to Gilbert; continue south on U.S. 53 (right lane).
1.7 [125.75]	Right lane exit to Eveleth; continue south on U.S. 53.
0.8 [126.55]	Right lane exit to "Hockey Hall of Fame"; turn right (west), right (north) and follow frontage road.
0.3 [126.85]	Turn left (west) at entrance to Holiday Inn.

End of Day 9.

MESABI RANGE

Ralph W. Marsden
Department of Geology
University of Minnesota, Duluth

GEOLOGY

The Thunderbird Mines near Eveleth, Minnesota are mining magnetite taconite ore from the Biwabik Iron-Formation which is conformably underlain by the graywacke and quartzite of the Pokegama Formation and overlain by argillite of the Virginia Formation. These rocks comprise the Middle Precambrian rocks of the Mesabi range. They rest with a marked structural and metamorphic unconformity on Early Precambrian granites, greenstones and metasedimentary rocks.

Virginia Formation

The Virginia Formation is dominantly composed of fine-grained clastic sedimentary rocks that include argillite, argillaceous siltstone, and sandstone with some graywacke, carbonaceous argillite and a few carbonate beds. In the western Mesabi range area, the lower part of the Virginia Formation contains units of a slaty, carbonate-chert iron-formation. The Virginia Formation is largely known from drill core as it is exposed only in a few mines on the Mesabi Range. The basal part of the Virginia will be observed in drill core at Minntac, Stop 2.

Biwabik Iron-Formation

The Biwabik Iron-Formation is divided into four members: The Upper Slaty, Upper Cherty, Lower Slaty and Lower Cherty. These members are subdivided into a number of stratigraphic units by the several mining companies to suit their particular local needs. The terms "slaty" and "cherty" are in common use by Mesabi range geologists and refer generally to the bedding characteristics of the Biwabik Iron-Formation with the term "taconite" used as a substitute term for iron-formation. Slaty taconite refers to even, straight-bedded, commonly laminated and slabby iron-formation that may contain from 1 to 6 percent alumina. Cherty taconite refers to iron-formation that contains a dominant amount of chert-rich layers that commonly have a granular texture with wavy bedding layers. Commercial magnetite taconite is largely restricted to cherty taconite. The generalized chemical composition of the Biwabik Iron-Formation is shown by Table 1.

The Biwabik Iron-Formation in the Thunderbird Mine area averages about 745 feet in thickness. There are recognizable differences in the lithology of the iron-formation units in the mine area and in the stratigraphic thickness of the units. These variations suggest a local influence of the broad anticlinal structure present in this area, during deposition of the iron-formation. The following description of the Biwabik is by members and subunits recognized by the mine geologists. The thickness are averages for the Thunderbird North and South Mines.

Table 1. Analyses of the Biwabik Iron-Formation.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	CO_2	C Organic	Total Fe
73' Upper Slaty (1)	44.10- 51.66	.29- 3.14	18.52- 21.23	17.90- 22.70	2.88- 5.40	1.18- 4.36	0.0- .18	.05- 1.05	26.86- 33.27
190' Upper Cherty (1)	37.88- 54.68	.09- .90	15.80- 34.93	16.60- 26.70	1.90- 4.48	.44- 6.80	0.0- .54	.06- .19	27.48- 41.45
80' Lower Slaty (1)	41.40- 50.28	1.30- 6.19	3.53- 11.93	22.20- 33.10	2.09- 4.77	.52- 5.20	0.0- 1.60	.19- 3.20	21.51- 30.94
20' Intermediate Slate (1)	41.40- 49.04	4.51- 6.19	3.53- 6.03	24.50- 33.10	4.21- 4.77	.62- 2.08	.48- .53	2.62- 3.20	21.51- 29.94
20' Intermediate Slate (2)	39.70- 59.24-	2.04- 2.87	8.54- 18.72	9.56- 23.25	2.27- 5.14	.20- .84	3.92- 14.56	.14- .22	20.52- 24.02
35' Lower Cherty (1)	38.28- 43.18	.07- .17	21.49- 32.32	18.49- 19.50	.02	5.14- 11.58	1.60- 3.92	.07- .13	29.40- 37.13
215' Lower Cherty (2)	43.68- 53.22	.03- 1.22	6.79- 27.15	11.53- 22.36	1.79- 3.88	.42- 5.68	2.20- 12.48	0.0- .40	22.13- 31.47

(1) Modified from Gruner (1946 page 61) - Drill core from a drill hole 5 miles E of DM&IR tracks, Tower Line.
(2) Modified from Gruner (1946 page 59) - Drill core from a drill hole near Hibbing, Minnesota.

Upper Slaty Member - Average 70'

The Upper Slaty is an even-bedded, laminated, dark-green, iron-slicate and carbonate slaty taconite with a few layers of argillite and layers of jasper. Magnetite is usually a minor constituent which is somewhat more common in the lower part of the member. The contact with the overlying Virginia Formation is gradational.

Upper Cherty member - Average 290'

The Upper Cherty is a wavy-bedded, granular cherty taconite with varying amounts of interbedded fine-grained laminated layers. This member is subdivided into seven subunits and includes an algal horizon which is about 560 feet above the base of the Biwabik. The subunits are listed from the top to the bottom as U.C. 7 through U.C. 1.

U.C.7 - Average 20' - thick- and wavy-bedded, jaspery, granular cherty and silicate taconite. The magnetite content is variable and commonly small with some associated minor hematite. There are a few layers of jasper pebble conglomerate.

U.C. 6 - Average 50' - a cherty, magnetite-silicate taconite with pink carbonate mottles and layers of fragmental chert and jasper.

U.C. 5 - Average 45' - generally massive and reddish or pinkish in color with common conglomerate taconite layers that contain jasper and chert fragments. Algal structures are commonly associated with the conglomeratic zones. The lower portion of the unit contains red and green laminated silicate taconite with jasper lenses.

U.C. 4 - Average 50' - thin-bedded, dark gray-green, silicate taconite in the upper part, a central zone that is thick-bedded cherty taconite with disseminated magnetite and a lower part that contains some carbonate and graphite.

U.C. 3 - Average 50' - a mottled, wavy-bedded, cherty taconite with common massive thick granular cherty beds that contains disseminated magnetite and carbonate lenses and mottles.

U.C. 2 - Average 25' - thick- and thin-bedded, laminated, magnetite-silicate taconite. Magnetite is disseminated and in layers with some hematite. Silicate layers are common in the lower portion of the unit.

U.C. 1 - Average 40' - mainly thin-bedded, laminated, fine- to medium-grained cherty taconite with distinct layers and wavy concentrations of magnetite. Lenses and nodules of silicate chert are common.

Lower Slaty Member - Average 85'

The Lower Slaty Member is divided into three subunits. This member is largely composed of slaty taconite with a central zone of cherty taconite. The lower part of the member is argillaceous and is termed the "Intermediate Slate."

L. S. 3 - Average 30' - a greenish-gray laminated magnetite-silicate taconite with layers of cherty taconite. The magnetite content is variable but generally low.

L. S. 2 - Average 30' - greenish-gray, cherty and slaty, silicate-carbonate taconite that is essentially free of magnetite.

L. S. 1 - Average 25' - The "Intermediate Slate" unit is a marker horizon the entire length of the Mesabi range. It is a black to greenish, laminated, locally fissile, silicate-carbonate, slaty taconite with common cherty layers and nodules.

Lower Cherty Member - Average 300'

In the Thunderbird Mine area the Lower Cherty Member is divided into six subunits, with L.C. 6 at the top. As a generalization, cherty taconite is characteristic of the member.

L.C. 6 - Average 25' - thick-bedded, cherty silicate taconite with a few slaty interbeds in the upper part. The material is commonly massive and contains little magnetite.

L.C. 5 - Average 65' - wavy, massive bedded, mottled silicate-magnetite taconite with common, rather coarse chert fragments and granules in some layers. Magnetite occurs in mottles, thin stringers and as disseminated grains.

L.C. 4 - Average 60' - wavy, thick-bedded, granular cherty taconite with magnetite-rich seams, mottles or layers.

L.C. 3 - Average 55' - largely chert-magnetite taconite with regular seams, layers and disseminations of magnetite with some interbedded layers of laminated silicate taconite.

L.C. 2 - Average 50' - mainly a laminated hematite-magnetite-silicate-carbonate taconite with cherty and jaspery beds. Some clastic quartz grains occur near the base of the unit.

L.C. 1 - Average 45' - a sandy, conglomeratic zone with algal chert and jasper layers and lenses and layers of laminated slaty taconite. A massive graywacke with a green chloritic matrix occurs in the middle part of the unit and is underlain by jasper, algal and conglomeratic beds.

The L.C. 1 unit commonly is underlain by medium-grained quartzite that occurs at the top of the Pokegama Formation. the contact with the Pokegama Formation appears to be comformable.

Pokegama Formation

The Pokegama Formation in the Eveleth-Virginia area commonly has a thin conglomerate zone at the base, a central micaceous quartzite, quartz-mica argillite and graywacke unit, and an upper rather massive quartzite horizon. The basal conglomerate contains fragments of the underlying Early

Precambrian rocks. The graywacke-argillite unit is commonly composed of quartz, feldspar, chlorite and muscovite with a silica, silt and clay matrix and cement. The Pokegama Formation is about 170 feet thick near Eveleth. Along the Mesabi range it varies from absent to 170 feet thick but appears to thicken markedly to the west and south of the Mesabi Range.

DAY 10 -- MESABI RANGE AND EVELETH TO DULUTH, MINNESOTA

Leaders: Ralph W. Marsden, Robert Werner and Wayne L. Plummer

STOP 10.1

THE NORTH AND SOUTH THUNDERBIRD MINE, Eveleth Taconite Company, Oglebay-Norton Company, operators. This stop will allow observation of the Biwabik Iron-Formation and an operating taconite mine. The points visited in the mine will depend on the accessibility of mine faces.

The Thunderbird Mines are located to the northwest and southwest of Eveleth, Minnesota, with the Fairlane concentrating and pelletizing plant approximately 10 miles south on the St. Louis River near Forbes, Minnesota. The crude taconite ore from the Thunderbird North and the Thunderbird South Mines is transported to the Fairlane plant on the Duluth, Missabe and Iron Range Railroad. The pellets are shipped on this railroad to Duluth about 60 miles to the south.

The Thunderbird North is owned by the Eveleth Taconite Company which is owned by Ford Motor Company and Oglebay-Norton Company. The Thunderbird South Mine is owned by the Eveleth Expansion Company which is owned by Armco Steel company, Dominion Foundries and Steel Company, the Steel Company of Canada and Oglebay-Norton company. Both mines are operated by the Oglebay-Norton Company. Production started at the Thunderbird North Mine in 1965 and at the Thunderbird South Mine in 1977. The investment in the mines and plant totals about $320,000,000. The mines and plant employ about 1200 people. About 18,000,000 tons of magnetite taconite crude ore is mined annually to yield about 6,000,000 tons of iron ore pellets.

The mine operation includes the stripping of glacial overburden and rock to expose the taconite ore, then mining the ore. Drilling for ore production is done by jet piercer and rotary drills with drill holes located on a carefully engineered pattern. The holes are about 35 feet apart, 9, 12-1/4 or 15 inches in diameter, and 50 feet deep. Because of the proximity of the mines to inhabited areas, special blasting procedures were developed to minimize vibrations, airblast and flyrock. The seismic vibrations are controlled by the use of millisecond delays and by other factors such as the energy content and detonation velocity of the explosive, depth below the surface of the explosive column and the nature of the rock to be broken. A suitable technique was developed to handle airblast. A pilot shot consisting of two pounds of explosive is detonated just prior to the planned production blast and the airblast effect measured at several points. If the determined airblast effects are in the safe range, the blast is detonated, if not, the blast is altered. This procedure is patented by Oglebay-Norton Company and was developed at this mine. The flyrock problem is controlled for each blast hole by the planned amount of stemming and the amount of explosive used. Flyrock is held to carefully determined distances that do not present a hazard to the mine equipment or the community. The average blast breaks about 600,000 tons of rock. area and its inhabitants. A careful stewardship of water resources is maintained. Water is obtained from the St. Louis River for the Fairlane plant

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Table 2. A typical Minntac taconite stratigraphy.

Depth		Thick- ness	Geol. Layer	Rock Description
From	To			
0	121	121	Surf.	Glacial debris.
121	201	80	Vasl.	Virginia argillite - laminated black and gray.
201	218	17	US	Rich carbonate, thin bedded - minor chert.
218	236	18	US	Massive granular cherty - minor argillite.
236	263	27	UC	Massive granular jasper cherty and laminated argillite.
263	272	9	UC	Wavy laminated argillite and massive jasper granular cherty.
272	293	21	UC	Massive granular jasper cherty and irregular bedded argillite.
293	300	7	UC	Fragmental jasper granular cherty and minor argillite.
300	309	9	UC	Fragmental conglomerate.
309	331	22	UC	Fine jasper granular cherty and sandy argillite.
331	337	6	UC	Conglomerate and massive granular jasper cherty.
337	357	20	UC	Massive granular jasper cherty and sandy argillite.
357	389	32	UC	As 337-357 with minor fragmental.
389	398	9	UC	Algal debris conglomerate.
398	425	27	UC	Fragmental granular jasper cherty conglomerate and irregular bedded argillite.
425	435	10	UC	Laminated argillite and massive granular jasper cherty.
435	443	8	UC	Laminated gray argillite.
443	455	12	UC	Granular cherty conglomerate and sandy argillite.
455	465	10	LS	Laminated argillite and granular cherty conglomerate.
465	472	7	LS	Laminated argillite.
472	489	17	LS	Massive granular cherty and minor argillite.
489	546	57	LS	Massive granular cherty.
546	579	33	LS	Nodular argillite.
579	619	40	LS	Nodular argillite and laminated argillite.
619	649	30	LC5B	Transitional granular cherty and argillite.
649	679	30	LC5A	Fragmental silicate rich granular cherty.
679	756	77	LC4	Wavy thin bedded silicate matrix granular cherty.
756	794	38	LC3	Wispy bedded chert matrix granular cherty.
794	828	34	LC2	Primary hematite pink granular cherty.
828	863	35	LC1	Primary hematite granular chert and argillite.
863	872	9	Basal	Sandstone.
872	878	6	Basal	Argillite and granular cherty.
878	879	1	Basal	Fragmental jasper conglomerate.
879	881	2	Basal	Argillite.
881	882	1	Basal	Algal chert.
882	883	1	Basal	Argillite.
883	894	11	Pok.	Pokegama vitreous quartzite.
894	962	68	Pok.	Pokegama thin bedded quartzite 10-12 dip.
962	968	6	Pok.	Pokegama conglomerate.
968	1043	75	K.L.	Knife Lake quartzose hornfels 70-90 dip.
				Bottom
0	121	121	Surf.	Glacial debris.
121	201	80	Vasl.	Virginia Formation.
201	236	35	US	Biwabik Iron Formation - upper slate.
236	455	219	UC	Biwabik Iron Formation - upper chert
455	619	164	LS	Biwabik Iron Formation - lower slate.
619	863	244	LC	Biwabik Iron Formation - lower chert.
863	883	20	Basal	Biwabik Iron Formation - basal.
883	968	85	Pok.	Pokegama Formation.

which is operated with a closed water circuit. About 97 percent of the process water is contantly being recirculated with about 3 percent lost through evaporation and seepage. Tests show no noticeable effects on water quality resulting from the taconite operations. Dust is controlled as are problems related to the sloping, stabilizing and vegetation of waste, rock, dumps, lean ore dumps and overburden piles.

STOP 10.2

THE MINNTAC MINE CORE-HANDLING FACILITY, north of Mountain Iron, Minnesota.

Wayne L. Plummer, Senior Geologist for the Minntac Mine, will have drill core available that shows the lower part of the Virginia Formation, the Biwabik Iron-Formation, Pokegama Formation and about 75 feet of the underlying Early Precambrian rocks. A generalized description of the various rocks represented by the drill core is given in Table 2. The group will have an opportunity to study the core, but sampling of the core will not be permitted.

TRAVEL ROUTE FROM EVELETH, MINNESOTA TO DULUTH, MINNESOTA.

Leader: G.B. Morey

This abbreviated road log starts at the Holiday Inn in Eveleth, Minnesota and ends at Spirit Mountain in Duluth, Minnesota. Note that mileages are approximate.

Mileage	
0.0	Intersection of Holiday Inn driveway and frontage road; turn right onto frontage road and proceed south.
0.3 [0.3]	Stop sign; turn left (east) and right (south) onto U.S. Highway 53.
0.1 [0.4]	Junction with Minnesota Highway 37 (east) to Gilbert; continue south on U.S. Highway 53.
4.3 [4.7]	Junction with Minnesota Highway 37 (west) to Hibbing; continue south on U.S. Highway 53.
31.3 [36.0]	Junction with Minnesota Highway 33; follow Highway 33 to the right (south) to Cloquet.
8.0 [44.0]	Stop sign; junction with U.S. Highway 2; continue south on Highway 33.

9.0 [53.0]	City of Cloquet.
2.0 [55.0]	Junction; continue straight ahead (south) on U.S. Interstate Highway 35.
1.0 [56.0]	Junction; follow right-lane exit to Minnesota Highway 210.
0.1 [56.1]	Stop sign; Junction with Highway 210; turn left (east) toward Carlton.
1.9 [58.0]	Carlton city limits; 30 mile zone; continue straight ahead on Highway 210.
0.5 [58.5]	Stop sign; junction with Minnesota Highway 45; continue straight ahead on Highway 210.
0.9 [59.4]	Turn right into parking lot at bridge over the St. Louis River.

STOP 10.3

THOMSON FORMATION. This is the type locality of the Thomson Formation of Middle Precambrian age. Approximately 760 meters of Thomson Formation are exposed in the Thomson-Carlton area. Data from two measured sections, one between the dam and the railroad bridge and the other south of the railroad bridge, indicate that the exposed section consists of 34 percent graywacke, 35-43 percent siltstone, and 23-31 percent slate. X-ray and thin-section stud-ies reveal that the graywacke consists of 4-35 percent quartz, 2-28 percent feldspar, 1-10 percent rock fragments, 15-85 percent matrix material consisting of muscovite, chlorite and quartz, and 1-17 percent calcite. Mineralogically, the siltstone and shale units are the fine-grained and very fine-grained equivalents of the graywacke.

Most beds, regardless of grain size, are less than 30 centimeters thick and apparently have consistent thicknesses over the lengths of the longest exposures--a distance of approximately 30 to 50 meters--and give the impression of having a wide lateral extent. The graywacke and siltstone units are commonly graded and contain other well-defined internal structures and sole marks common to turbidite sequences. Therefore the graywacke and siltstone beds are interpreted as individual sedimentation units deposited by turbidity currents that flowed from the north.

The Thomson Formation is intensively folded at this locality. Wave lengths of observed folds range from a meter or so to 180 meters, and amplitudes from about 45 meters to 50 meters. The folds vary from broad, open, symmetrical folds in graywacke to tight, asymmetric, overturned folds in the less competent slate units. All folds have a near-vertical axial plane cleavage and plunge gently both to the east and to the west. Both normal and reverse faults are present, but they appear to have displacements of only 10 meters or less. The normal faults strike N. 30° E., are nearly vertical and have a dominantly dip-slip component. The reverse faults strike approximately east and dip southwest at angles of 20°-40°. Joint sets are well developed. They dip steeply and strike about N. 10° W. and N. 30° E. These sets define a conjugate joint system that probably formed in response to a north-south compressional stress at the time of folding.

Small to large quartz veins with minor amounts of pyrite and chalcopyrite occupy extension fractures near the crests of anticlines, and medium- to fine-grained ophitic microgabbro dikes occupy the northeast-trending joint sets. The age of the quartz veins is unknown, but the dikes are inferred to be of Keweenawan age.

Return to Highway 210 and continue straight ahead (east) toward the village of Thomson.

0.3 [59.7]	Turn left (east).
3.3 [63.0]	Junction; turn right (east) and follow U.S. Interstate Highway 35 toward Duluth.
7.3 [70.3]	Junction; follow right-hand exit toward Proctor.
0.1 [70.4]	Stop sign; junction with frontage road; turn right (south) and follow signs to Spirit Mountain resort area.
0.25 [70.65]	Turn left (southeast) onto Skyline Drive and follow signs to Spirit Mountain resort area.
0.2 [70.85]	Turn right (south) into Spirit Mountain resort area; proceed to parking area.

End of Day 10.

HALF-DAY TRIP -- SPIRIT MOUNTAIN TO FOND DU LAC AND RETURN

Leaders: G.B. Morey and R.W. Ojakangas

The purpose of this half-day excursion is to examine middle Precambrian (Proterozoic X) - upper Precambrian (Proterozoic Y) relationships in a small area west of Duluth.

0.0	Spirit Mountain resort area; turn left (north) and proceed toward Skyline Parkway.
0.2 [0.2]	Junction with Skyline Parkway; turn left (west) and follow Skyline Parkway toward U.S. Highway 35.
0.2 [0.40]	Junction with frontage road; turn right and follow the frontage road to the northeast toward U.S. Highway 35.
0.3 [0.70]	Junction with U.S. Highway 35, turn left (north) and proceed over Highway 35.
0.1 [0.80]	Junction; turn sharply to the left (west) and follow the entrance ramp. Continue on U.S. Highway 35 toward Esko and Carlton.
4.3 [5.1]	Junction; follow right-hand exit to the Midway Road.
0.1 [5.2]	Stop sign; turn right and follow the Midway Road (St. Louis County Highway 13) to the north.
0.8 [6.0]	Narrow gravel road on the right (east) side of the Midway Road. Park and walk east approximately 0.35 mile to base of west-facing slope of steep hill. Note small outcrops of Thomson Formation (middle Precambrian) that occur along the road. Walk to the left (north) along the slope face for approximately 500 feet.

STOP 1

Approximately 7.5 meters of quartzite and quartz-pebble conglomerate assigned to the so-called Nopeming Sandstone (upper Precambrian; lowest Keweenawan) are exposed at this locality. These sedimentary rocks dip gently eastward and appear to unconformably overlie near-vertical beds of the middle Precambrian Thomson Formation, although the basal contact is not exposed anywhere.

Two and one-half meters of conglomerate is interbedded with quartzite near the bottom of the exposed sedimentary rocks. The conglomerate is composed of 10 percent pebbles and 90 percent quartzite matrix. The pebbles are well rounded and rarely exceed 4 centimeters in diameter. The majority of them are composed of white quartz, but a small number of quartzite pebbles also are present. The overlying quartzite beds may be divided into two lithotopes; the upper lithotope is a fine-grained, laminated to thin-bedded metasiltstone, whereas the lower lithotope consists of cross-bedded, medium- to coarse-grained quartzite.

The sedimentary rocks are overlain conformably by flows of gray, fine-grained, augite basalt porphyry and augite porphyritic basalt assigned to the Ely's Peak basalts (lower Keweenawan) of the North Shore Volcanic Group. Small-scale load structures in the upper 15 centimeters of the quartite and pillow structures in the overlying basal lava flows suggest that flows were extruded into the same body of water in which the sediments were deposited.

Return after same route to the Midway Road, and to U.S. Highway 35.

0.8 [6.8]	Junction with U.S. Highway 35; continue straight ahead on Midway Road.
1.7 [8.5]	Junction, turn left (southeast) and follow St. Louis County Highway 3 toward Gary-New Duluth.
1.1 [9.6]	Railroad crossing; continue straight ahead. The large quarry on the left (east) side of the highway is developed in gray, fine- to medium-grained, subophitic and poikilitic basalt of the Ely's Peak basalts of the North Shore Volcanic Group of lower Keweenawan age.
2.3 [11.9]	Suburb of Gary and junction with Minnesota Highway 23; turn right (south) and follow Highway 23 toward New Duluth.
0.9 [12.8]	Suburb of New Duluth and junction with Minnesota Highway 39 to Oliver, Wisconsin; follow Highway 23 toward Fond du Lac.
2.6 [15.4]	Suburb of Fond du Lac; turn right (north) into Fond du Lac.
3.5 [15.75]	Park gate; continue straight ahead.
0.45 [16.3]	STOP 2

Exposures at this locality are typical of the Fond du Lac Formation (upper Precambrian; upper Keweenawan) throughout much of east-central Minnesota. The formation consists predominantly of red sandstone, siltstone and interbedded shale or mudstone, but conglomerate beds containing clasts of vein quartz, basalt, felsite, chert and quartzite are common locally. Sandstone beds are generally lenticular in shape and arkosic or subarkosic in composition. They consist of 36-68 percent quartz, 5-29 percent feldspar (microcline and albite-oligoclase), 1-10 percent rock fragments, 1-15 percent matrix material composed of quartz, illite and rare kaolinite, and 1-20 percent cement of hematite, calcite, quartz and dolomite. The siltstone units also occur as lenticular beds and, although finer grained, are mineralogically equivalent to the sandstone units. Shale units occur both as thin lenses and as thick beds of fairly uniform thickness; they consist predominantly of illite with minor amounts of kaolinite, montmorillonite-illite, quartz and feldspar.

The formation was deposited by fluvial-deltaic processes, as indicated by the presence of filled stream channels, intraformational fragments, mud cracks, ripple marks, rain imprints and extensive large- and small-scale cross-bedding.

Return over same route.

0.8 [17.0] Junction; turn right (west) and follow Minnesota Highway 23.

0.2 [17.2] Junction; turn right (northwest) and follow Minnesota Highway 210 toward Jay Cooke State Park.

1.9 [19.1] Sharp bend in road; St. Louis River straight ahead.

0.4 [19.5] Mouth of Little River with a small pond on right (north) side of road; park nearby and follow the river to the north. Stop 3 can be reached only by walking about 0.4 mile along the creek bed. Stop 4 is midway between the road and Stop 3.

STOP 3

Basal quartz-pebble conglomerate of the Fond du Lac Formation. The quartz-pebble conglomerate exposed at this locality unconformably overlies folded and metamorphosed rocks of the Thomson Formation (middle Precambrian) throughout much of Jay Cooke State Park. Although the contact cannot be seen at this locality, exposures of Thomson Formation are present about 0.1 mile to the north and the unconformable contact itself can be seen several miles to the northwest in the valley of the St. Louis River below Oldenburg Point.

The conglomerate is at least 18 meters thick and consists dominantly of pebbles and cobbles as much as 15 centimeters in diameter. Clasts of vein quartz predominate, but there are minor amounts of chert, quartzite, graywacke and slate. The matrix is mostly a coarse grit of angular quartz and feldspar, with some clay-sized matrix material and dolomite cement. Pyrite and marcasite are common and occur as concretions or individual grains in the matrix; locally the sulfides have been altered to limonite.

The conglomerate grades upward through a stratigraphic interval of approximately 1 meter into arkosic sandstone like that seen at Stop 1. There is no distinct break between the conglomerate and the sandstone--the conglomeratic clasts become progressively smaller and less abundant as the amount of sand-size material increases.

Return toward the highway.

STOP 4

Extraformational basalt-pebble conglomerate in the Fond du Lac Formation. This exposure, consisting of fine-grained reddish-brown sandstone that contains rounded pebbles of highly altered basalt and basalt porphyry, is representative of extraformational conglomeratic units in the Fond du lac Formation, although it is thicker than most and contains more clasts.

Continue south along Little River to the highway.

Minnesota Highway 210; continue west toward Thompson and Carlton.

2.5 Junction; turn right (northwest) and follow unnumbered Silverbrook
[22.0] Township road.

1.4 Junction; turn left (west) and follow Carlton County Highway .
[23.4]

0.95 Junction; turn right (northeast) and follow Carlton County Highway
[24.35] 1 toward Esko.

1.4 Junction; turn right (east) and follow U.S. Interstate Highway 35
[25.75] toward Duluth.

7.4 Junction; follow right-hand exit to Proctor.
[33.14]

0.1 Stop sign; turn right and follow frontage road to Skyline Parkway.
[33.24]

0.4 Junction; turn left (southeast) and follow Skyline Parkway toward
[33.65] Spirit Mountain Resort area.

0.2 Junction; turn left (south) into Spirit Mountain Resort area.
[33.85]

End of field trip