GEOLOGICAL SURVEY OF CANADA

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Geology and ore deposits of the Sudbury Structure, Ontario (Field Trip 7)

edited by

W.V. Peredery

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GEOLOGY AND ORE DEPOSITS OF THE SUDBURY STRUCTURE, ONTARIO

[FIELD TRIP 7]

BY

W.V. PEREDERY[1]

8TH IAGOD SYMPOSIUM

FIELD TRIP GUIDEBOOK

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8th IAGOD SYMPOSIUM

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GEOLOGY OF THE SUDBURY MINING AREA, ONTARIO

INTRODUCTION

The Sudbury Structure consists of three main components and is located in a complex part of the Canadian shield where three Structural Provinces are in close proximity to each other. The Sudbury Structure comprises:

1) **Sudbury Breccia** commonly found in the Archean basement and Proterozoic cover peripheral to the Sudbury Basin,

2) **Sudbury Basin** containing the Whitewater Group which includes the Onaping, Onwatin, and Chelmsford Formations,

3) **Sudbury Igneous Complex,** (SIC) a noritic and granophyric, basin-shaped body emplaced approximately coincident with the base of the Sudbury Basin. The Ni-Cu-PGE sulphide ore deposits are spatially closely associated with this Complex, and more specifically with a distinctive phase of it, known as the Sublayer. The Sublayer occurs at the base of the norite sheet and also includes the offset dykes of quartz diorite which extend away from the norite deep into the footwall rocks.

The size of the Sudbury Structure (Fig. 1) as defined by the outer limit of the Sudbury Breccia is an oval-shaped area measuring about 190 km in diameter (Peredery and Morrison, 1984). The size of the Sudbury Basin is approximated by the shape of the SIC. Its shape now has an elliptical outline, elongate in a northeasterly direction, and is to some extent a product of prolonged Penokean-Hudsonian tectonism (1900-1600 Ma), collapse phenomena related to magmatism, and late tectonism related to the Grenville Front. There is considerable debate whether the original shape of the Sudbury Basin was circular, or polygonal, or non-circular (see OGS Special Volume 1).

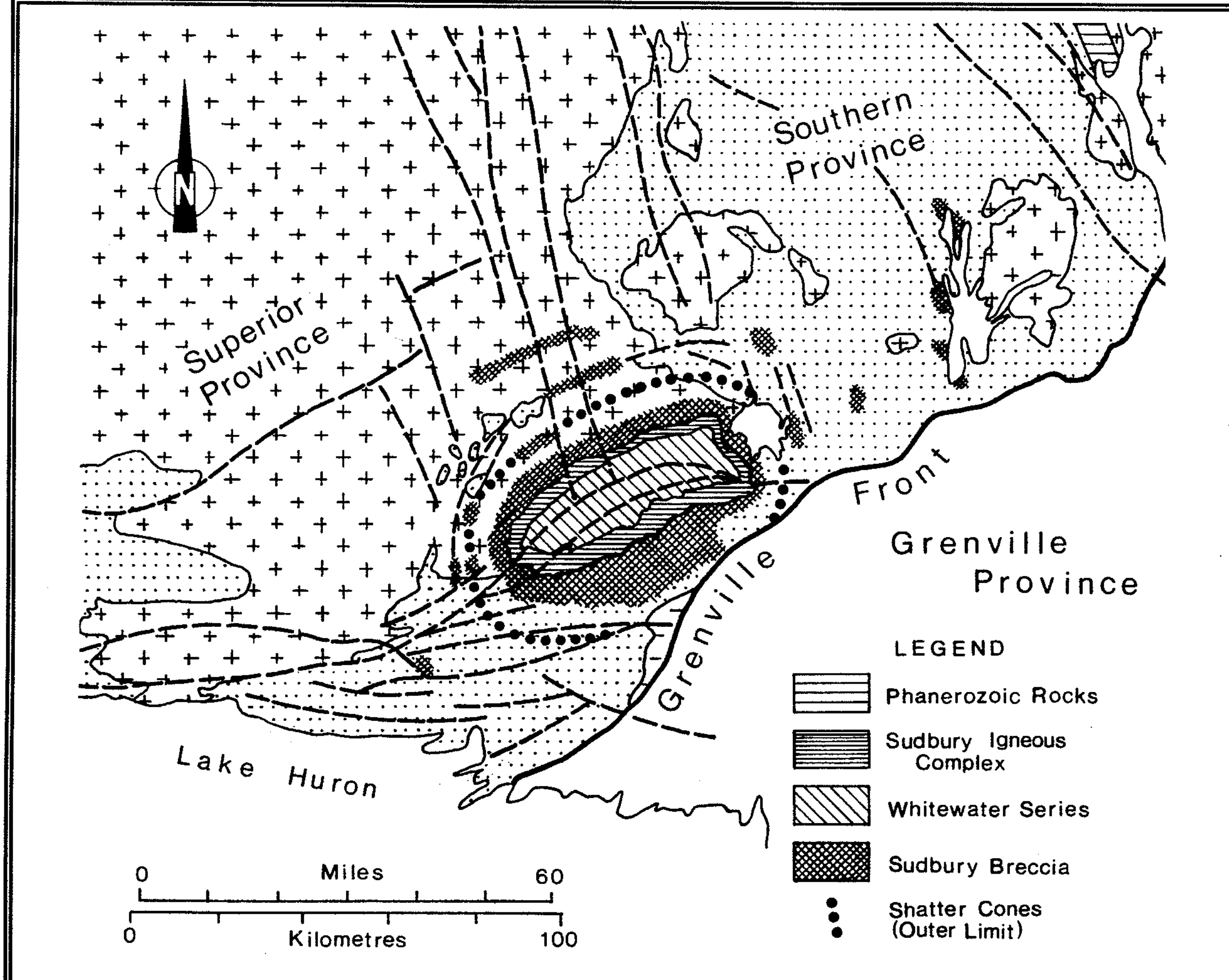


Figure 1. Distribution of the Sudbury Breccia and shatter cones in the Sudbury area. Note the concentric faults on the East and North Ranges of the Sudbury Structure.

On the northern and eastern sides the SIC is in contact with migmatized high grade gneisses (2711 ± 13 Ma, Krogh et al., 1984), and quartz monzonite plutons (2500 Ma) of the Superior Province which contains remnant greenstone belts (2700 Ma) and outliers of Proterozoic rocks (Fig. 2). On the southern side the SIC is in contact with the Proterozoic metavolcanic and metasedimentary rocks of the Huronian Supergroup (2550-2110 Ma) which is part of the Southern Province. Felsic intrusive rocks of the Creighton (2333 Ma, Frarey et al., 1982) and Murray plutons (2388 Ma, Krogh et al., 1984) intrude the Huronian sequence south of the SIC. Nipissing basic magmatism (2160-2110 Ma) is widespread in the area. Nipissing rocks occur as dykes in the Archean, and as sills in the Huronian Supergroup. Intrusion of these rocks coincided with a pre-Penokean folding event (2150 Ma, Van Schmus, 1965).

The age of the Sudbury Structure is approximated by the time of emplacement of the Sudbury Igneous Complex (1849 Ma, Krogh et al., 1984) which is considered to have been intruded shortly after the Sudbury Structure was produced.

The Sudbury Structure was produced by a Sudbury Event. It is recognized and accepted now by all investigators of the Sudbury Structure that the shock metamorphic features present in the Archean basement, Huronian cover, and in the Onaping Formation are related to this Event. It either originated from within the Earth, as is argued by some investigators, or was a giant meteoritic impact as maintained by others.

Post-SIC mafic dykes, generally known as "traps" or quartz diabases, occur commonly in the Sudbury area. Northwest trending olivine diabase dykes (1200-1500 Ma) indicate the last major magmatic activity in the area.

The high grade metamorphic gneisses of the Grenville Province occur southeast of the Sudbury Structure. The contact between the Southern Province and the Grenville Province is marked by a tectonic zone known as the Grenville Front. The last major metamorphic event in the Grenville Province peaked in the interval 1000-1200 Ma.

In Table 1, major geological subdivisions of the Sudbury area are summarized.

In discussing various parts of the Sudbury Structure the terms North Range, East Range, and South Range are used to denote geographic sectors of the Structure.

ARCHEAN BASEMENT

Archean basement rocks surround the SIC on its western, northern and eastern sides. They are commonly felsic banded gneisses of granodiorite, tonalitic to quartz dioritic compositions, but locally gabbroic, anorthositic andultrabasic rocks are also present. Associated with these rocks are pockets of metasedimentary-metavolcanic assemblages. All of these rocks show various stages of migmatization, implying complex high grade metamorphic and tectonic histories, and many are intruded by granitic rocks which are mineralogically similar to the pluton-size bodies found further to the north.

The gneisses are most common on the North Range where they have been grouped into the "Levack gneisses complex" (Langford, 1960). Originally they were probably part of a large differentiated pluton. In some places, such as in southern Levack Township, the gneisses including the migmatitic material exhibit granulite facies mineral assemblages (two pyroxenes ± garnet). In other places, such as in northern Levack Township, amphibolite facies mineral assemblages are predominant. Locally, some metasedimentary relics are metamorphosed to sillimanite-cordierite-orthopyroxeneassemblages. The orthopyroxene is unusual in that it contains up to 2 wt.% scandium.

Archean metavolcanic rocks and associated metasedimentary rocks, typical greenstone assemblages, occur on the northern side of the SIC. Northwest of the SIC, the Benny Belt

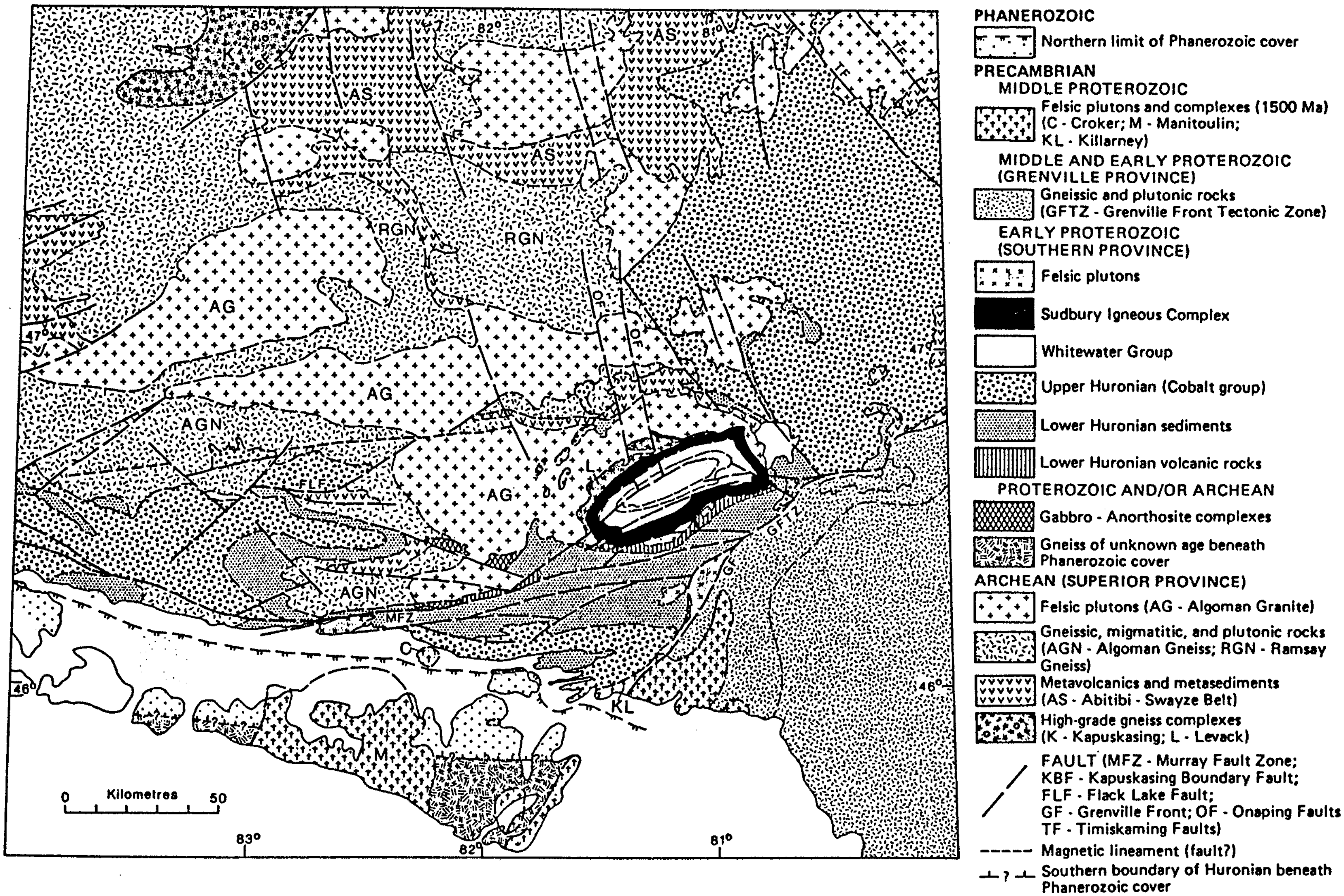


Figure 2. Regional geologic setting of the Sudbury Structure (after Card et al., 1984).

TABLE 1. PRECAMBRIAN LITHOSTRATIGRAPHY, SUDBURY AREA *

	GRENVILLE PROVINCE	SOUTHERN PROVINCE	SUPERIOR PROVINCE
MIDDLE PROTEROZOIC	Mafic to Ultramafic Stocks		
	Late Pegmatite (900-1100 Ma) High rank regional metamorphism		
	Late Mafic Intrusive Rocks		
	Anorthosite Suite Intrusive Rocks (1200-1500 Ma)	Olivine Diabase (1200-1500 Ma)	Olivine Diabase (1200-1500 Ma)
EARLY PROTEROZOIC	Early Pegmatite (1600-1700 Ma)		
	Granitic Intrusive Rocks (1590-1700 Ma)	SUDBURY STRUCTURE: Trap Dykes Intrusive Contact Sudbury Igneous Complex (1849 Ma) Norite (1849 Ma) Gabbro Granophyre (1849 Ma) Sublayer Footwall Breccia Whitewater Group Chelmsford Formation Onwatin Formation Onaping Formation Sudbury Breccia Shock Metamorphism Sudbury Event (1849 Ma)	
	Early Mafic Intrusive Rocks (some younger than Granitic Intrusive Rocks) Intrusive and Metamorphic Contact	Nipissing Intrusive Rocks (2160-2110 Ma) Intrusive Contact	
		Creighton and Murray Plutons (2333 Ma) Intrusive Contact	
	Metasedimentary Rocks	Huronian Supergroup (2550-2110 Ma) Unconformity	
ARCHEAN		Archean Superior Province basement (2550-2711 Ma)	Diabase Intrusive Contact
			Mafic Plutonic Rocks and Anorthosite
			Intrusive Contact
			Migmatite and Felsic Plutonic Rocks (2500-2600 Ma) Intrusive and Metamorphic Contact
			Metavolcanic and Metasedimentary Rocks (2700 Ma)
			Granodioritic-Quartzdioritic Gneisses and Associated Mafic Rocks (2711 Ma)

*** Modified after Dressler (1984).**

has been described by Card and Innes (1981), and in Hutton and Parkin Townships, northeast of the Complex, a metavolcanic-metasedimentary sequence has been described by Meyn (1970).

Intrusive into the gneisses and the greenstone assemblages are massive felsic plutons which underlie much of the terrane extending from Agnew Lake, southwest of the SIC, around the North Range of the Complex to about the position of Bowlands Bay in Wanapitei Lake which lies to the east of the SIC. These rocks are medium to coarse grained, pink or grey, and range in modal composition from granite to granodiorite, and less commonly tonalite.

Gabbroic and anorthositic bodies having lens-like and plug-like intrusive shapes occur in several places close to the SIC. The anorthositic bodies are found at the base of the Huronian Supergroup and range in width from 30 to 900 m in Drury and Hyman Townships, southwest of the Complex Card et al., 1977), and from 750 to 2,000 m in Falconbridge Township, southeast of the Complex.

Metamorphosed diabase dykes of pre-Sudbury Event age intrude the Archean felsic plutonic and the older gneissic rocks, and also the gabbroic-anorthositic rocks in Drury, Hyman and Falconbridge Townships, but apparently not the sedimentary and volcanic rocks of the Huronian Supergroup. These dyke rocks are apparently Late Archean or Early Proterozoic in age.

PROTEROZOIC HURONIAN SUPERGROUP

Early Proterozoic rocks of the Huronian Supergroup and Nipissing intrusive rocks occur south, east, and northeast of the SIC but, small outliers are also found northwest of the SIC associated with the Benny greenstone belt.

The Huronian Supergroup (Table 2) is part of the Penokean Fold Belt of the Southern Province. It comprises a thick sequence (up to 12 km) of terrigenous clastic sedimentary rocks with minor volcanics and chemical sediments. The succession generally thickens from north to south. Accumulation took place in a fault-initiated, intracratonic basin superimposed on down-dropped Archean basement rocks. Much of the sequence is characterized by cyclical units of conglomerate, mudstone, wacke, and arenites. Based on this cyclicity, the Huronian Supergroup is subdivided into four groups - the Elliot Lake, Hough Lake, Quirke Lake and Cobalt Groups. The Huronian lithostratigraphy is presented in Table 2 together with various paleoenvironmental interpretations.

Many workers believe the cyclicity is due to widespread glaciation, followed by deposition of fluviatile cross-bedded sandstones. Others feel that the whole pile can be interpreted in terms of regressive marine cycles which only periodically became emergent surfaces.

In the Sudbury area the Lower Huronian Elliot Lake Group consists of a thick sequence of tholeiitic metabasalts and greywackes (Elsie Mountain and Stobie Formations), felsic metavolcanics (Copper Cliff Formation) and turbidites (McKim Formation). This is a local development and elsewhere in the Southern Province the dominant strata are an interfingered sequence of feldspathic sandstone and various conglomerates including uranium-bearing quartz-pebble conglomerate (Matinenda Formation), siltstones and greywacke (McKim Formation) and local volcanic accumulations.

The two succeeding groups - the Hough Lake and Quirke Lake Groups - constitute two major sedimentary cycles each consisting of a lower conglomerate unit, a middle shale unit, and an upper sandstone unit. The conglomerate units (Ramsay Lake and Bruce Formations) have been interpreted as grounded ice shelf deposits (Young, 1970), while Card (1978) prefers a marine debris flow model. The muddy shale units include the carbonate-rich Espanola Formation, unique in the Huronian sequence, probably representing shallow marine deposits in a migrating shoreline environment. The

TABLE 2. GENERALIZED STRATIGRAPHY AND SEDIMENTOLOGY OF THE HURONIAN SUPERGROUP IN THE SUDBURY AREA

SOUTH AND SOUTHWEST OF SUDBURY IGNEOUS COMPLEX (CARD et al., 1977)

GROUP	ESTIMATED THICKNESS	STRATIGRAPHY	PRIMARY STRUCTURES	PALEOENVIRONMENTS
Cobalt	1500-2400 m	**Lorrain Formation** arkose, feldspathic protoquartzite, wacke, quartz arenite, conglomerate	Festoon crossbedding, graded crossbedding, ripples, ripple-drift cross-lamination	Rapid deposition in a high energy environment; deltaic, beach and marine deposits (Casshyap, 1971); near shore-coastal (Card, 1976)
	180-1200 m	**Gowganda Formation** polymictic paraconglomerate, orthoconglomerate, laminated	Planar crossbedding, festoon crossbedding, parallel lamination,	Marine-glacial (Coleman, 1905a, b; Casshyap, 1969; Young, 1970; Lindsey, 1971)
Quirke Lake	180-1500 m	**Serpent Formation** protoquartzite, feldspathic quartzite, arkose, minor siltstone, conglomerate, limestone	Festoon crossbedding, parallel lamination	Fluvial (Long, 1970); fluvial-deltaic (Frarey and Roscoe, 1970)
	150- 550 m	**Espanola Formation** limestone, dolostone, wacke, protoquartzite	Ball and pillow structures, clastic dykes, slump folds, planar lamination, ripple-drift cross-lamination, desiccation cracks	Shallow marine
	60- 460 m	**Bruce Formation** pebbly wacke, conglomerate	Dropstones	(See under Gowganda Formation)
Hough Lake	760-3000 m	**Mississagi Formation** orthoquartzite, arkose, wacke, conglomerate	Festoon crossbedding, planar crossbedding, ripple-drift cross-lamination	Rapid deposition in a high energy environment; fluvial (McDowell, 1957); fluvial-deltaic or fluvial (Frarey, 1970); fluvial-deltaic (Casshyap, 1971); tidal flat, marine shelf (Palonen, 1971, 1973)
	60- 600 m	**Pecors Formation** wacke, quartz feldspar arenite	Bouma layering, ball and pillow structures, clastic dykes	Deposition of wackes and mudstones below wave base
	60- 180 m	**Ramsey Lake Formation** polymictic paraconglomerate, pebbly sandstone	Dropstones	(See under Gowganda Formation)
Elliot Lake	1500-1800 m	**McKim Formation** laminated wacke and mudstone protoquartzite	Bouma layering, clastic dykes, ball and pillow structures, parallel lamination	Deposition of wackes and mudstone below wave base
	180- 300 m	**Matinenda Formation** feldspathic protoquartzite, laminated wacke, oligomictic quartz-pebble conglomerate, polymictic conglomerate	Planar crossbedding	Deposition in a high energy environment
	up to 730 m	**Copper Cliff Formation** felsic flows, felsic pyroclastic rocks	Amygdules, flows	
	up to 1500 m	**Stobie Formation** mafic flows, pyroclastic rocks, minor wacke	Flow, pillowed flow, amygdules, breccia	
	up to 1000 m	**Elsie Mountain Formation** mafic flows, minor pelitic metasediments, and mafic tuffaceous rocks	Flows, pillowed flows, amygdules, pillow breccia	

argillites indicate turbidity current activity during transgressive stages (McLennan et al ., 1978).

The upper sandstone units (the Mississagi and Serpent Formations) are crossbedded, immature to submature arenites and have been variously interpreted as regressive marine (Palonen, 1971) and prograding deltaic deposits (Card, 1978). Alternative models include a fluviatile, braided stream environment (Long, 1970), or a fluvial-deltaic origin (Casshyap, 1971).

The upper half of the Huronian, the Cobalt Group, consists of a heterogeneous assemblage of conglomerates, siltstones, sandstones and greywackes. The controversy concerning a glacial-fluvial versus marine interpretation of these formations continues. The pelitic units are seen as turbidites by Card (1978), and as glacial lake deposits by Lindsay (1969) and others. Card (1976) interprets the sandstones of the Lorrain and Bar River Formations as near-shore coastal shelf deposits laid down during repeated marine transgressions and regressions. Hadley (1968) views them as deltaic fringe and beach deposits. Many other workers prefer a fluvio-deltaic origin. In the Cobalt area the lower half of the Huronian is missing and the Gowganda Formation rests directly on the Archean basement with profound angular unconformity.

Within the Huronian Supergroup, paleocurrent data indicate that sediments were deposited by two major current flow directions southeast and southwest, which coalesced in the southern Huronian area and thence flowed south. There is evidence that tectonic movements continued throughout the deposition of the Huronian Supergroup, as contacts between groups are disconformable and locally unconformable. Rapid facies variations occur around the main centre of volcanic activity at Sudbury. There is abrupt thickening across the Murray Fault System, indicating active fault-control of depositional patterns. Thickening of the McKim and Mississagi Formations, and thinning of the Espanola Formation towards the Grenville Front indicate that the Murray Fault System was an important paleogeographic boundary in the developing Middle Precambrian basin.

PROTEROZOIC TECTONISM AND IGNEOUS INTRUSIVE ACTIVITY

At about 2200 Ma major compressional tectonism began with folding of the Huronian strata. Deformation and metamorphism of the Penokean Orogeny culminated at around 1900 Ma. Metamorphic grade ranges from subgreenschist facies in the northwest and northeast to amphibolite facies in the south. Here, the higher grade metamorphic zones display a nodal pattern similar to that of Penokean metamorphism in Michigan. Coincident with the deformation there was felsic and mafic magmatic activity, giving rise to pluton-size intrusions and extensive silling (Fig. 2). Examples of the felsic magmatism include Creighton and Murray granitic plutons which occur along the South Range of the SIC. The Murray Pluton may represent a higher level intrusion than the Creighton Pluton because it is commonly finer grained than the latter. The Creighton Pluton has been dated at 2333 Ma (U-Pb zircon; Frarey et al., 1982) and the Murray Pluton at 2388 Ma (Krogh et al ., 1984).

The mafic magmatism was of tholeiitic character and extensively distributed. Mafic sill-like bodies intrude Huronian and older rocks throughout the Southern Province in an area extending from Sault Ste. Marie to Cobalt, Ontario. These rocks are collectively known as Nipissing Diabase or, in the Sudbury area, as Sudbury gabbro. Their Rb/Sr whole rock radiometric ages have been determined at 2150 $\pm$ 50 Ma in the Blind River area (Van Schmus, 1965) and at 2160 $\pm$ 60 Ma in the Gowganda area (Fairbairn et al., 1969). Mineralogically they can be described as quartz- and granophyre-bearing gabbroic and noritic rocks with diabasic textures. Minor sulphides and sulphide deposits are commonly found in the Nipissing diabase intrusions, but no economic deposits are known to be associated with these rocks in the Sudbury area. Elsewhere, as in the Cobalt area, silver orebodies occur in the Nipissing diabases.

After the Nipissing magmatism there were several other phases of igneous activity (the Sudbury Igneous Complex, 1849 Ma; the Cutler Granite, 1750 Ma; and the Grenville Front plutons, 1730 and 1600 Ma) accompanied by low grade deformation and metamorphism possibly correlative with the Hudsonian orogeny. Swarms of northwest-trending dykes were emplaced between 1200 and 1500 Ma, and the high grade Grenville metamorphic event culminated at about 1000 Ma.

The deformational events in the Southern Province produced moderate to tight folding and extensive faulting. Major folds are open to near isoclinal, flattened, concentric buckles with upright to slightly overturned (northward), commonly curved axial surfaces. Near Sudbury, where secondary 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.

The major east-west faults of the Murray System and the northwest Onaping System were probably initiated prior to the Huronian sedimentation and underwent subsequent periodic reactivation. Foliations of several ages are associated with these tectonic features.

THE SUDBURY EVENT

There is compelling evidence for a single major explosive event centred on the Sudbury Structure. The nature of the event, whether endogenic or exogenic, is still open to active debate.

The Sudbury Structure is an oblong east-northeast trending feature about 190 km long and 100 km wide. It includes the Sudbury Breccia, the Sudbury Igneous Complex, the Whitewater Group infilling the Sudbury Basin, the Ni-Cu-PGE ore-bearing units, and the various shock-induced phenomena in the country rocks. The sequence of events is thought to be as follows:

a) A major explosive event at about 1850 Ma resulted in intensive and extensive brecciation (Sudbury Breccia), the formation of a large crater-like depression (Sudbury Basin), and extensive development of shock-induced features in the country rocks, Sudbury Breccia, and Onaping Formation. Coincident with the shock metamorphism, shatter cones developed in the country rocks peripheral to the Sudbury Basin and in country rock fragments in the Onaping Formation. At this time the Onaping Formation breccias infilled the Basin, either as fallback debris resulting from the meteorite impact or as some internally derived brecciation product as yet unexplained.

b) The remainder of the Whitewater Group, which includes the Onwatin Formation (pyritic shales) and the Chelmsford Formation (greywackes), continued to accumulate by normal sedimentation. The Whitewater Group has been preserved only inside the Basin.

c) The deep fracturing and shock of the initial event triggered the intrusion of the Sudbury Igneous Complex. It was emplaced along the interface between the Onaping Formation and the extensively brecciated country rocks. Genetically related to the main igneous body is the igneous textured ore-bearing Sublayer, although the exact timing of its emplacement relative to the main body is not certain.

Different interpretations of various aspects of the Sudbury Event may be found in Williams, 1957; Stevenson, 1961, 1972; Dietz, 1962, 1964, 1972; French, 1970, 1972; Peredery, 1972; Guy-Bray, 1972; Muir, 1984; and Peredery and Morrison, 1984.

The principal evidence in favour of a meteorite impact origin includes:

1) Shock-induced features in the Footwall, the Sudbury Breccia, and

the Onaping Formation; these include a variety of microscopic features (French, 1970), chemical features (Peredery, 1972a), and shatter cones (Dietz, 1964) - a peculiar fracturing in rocks;

2) the nature of the Onaping breccia which is considered to be similar to the suevite breccias of accredited impact sites (French, 1972; Peredery, 1972);

3) the ring-like shape of the structure (it may originaly have been circular, but there is some evidence that its present form is due to subsequent known crustal shortening and faulting) (Morrison, 1984);

4) the character and areal distribution of Sudbury Breccia (Peredery and Morrison, 1984).

Arguments advanced in favour of a volcanic origin include the relationship of the Sudbury Structure to major tectonic elements such as the junction of structural provinces and the faults of the Murray and Onaping systems, the pronounced magnetic and gravity anomalies indicating large scale crustal peculiarities in the area of the Sudbury Structure, the abrupt facies variations in adjacent Huronian rocks, and the presence of Pb-Zn-Cu-Ag sulphide deposits within the Onwatin Formation (Card and Hutchinson, 1972). Workers supporting the volcanic caldera-collapse theory consider the Sudbury Structure to be an integral part of its regional setting in time and space (Card et al., 1984; Muir, 1984). It is argued by some that the chances of a meteorite impacting into such an environment are unlikely, but others do not see this as a problem.

Sudbury Breccia

A pseudotachylitic breccia, generally known as Sudbury Breccia, is ubiquitous in the Archean basement and the Proterozoic cover rocks in the Sudbury area (Dressler, 1984). It occurs in a zone up to 50 km wide peripheral to the SIC, and in places up to 80 km distant from the Complex. It forms veins, lenses, irregular patches and anastomosing networks in the rocks, and is commonly found developed along joints and natural weaknesses in rocks such as foliation along bedding, on contacts of dykes, and other lithological boundaries. No Sudbury Breccia has been found cutting the SIC or the rocks in the Sudbury Basin. Three main types of Sudbury Breccia are recognized:

1) massive breccia
2) fluidal breccia
3) igneous textured breccia

The massive and fluidal types are the most common, and the igneous textured variety is the least common. The latter variety is found associated with the massive type and occurs up to 2 km away from the contact with the SIC.

The Sudbury Breccia matrix is generally very fine grained, dark in colour, and is commonly similar in composition to the rock fragments it encloses, or the country rocks in the area. The rock fragments range in size from millimetres to tens of metres. These fragments are commonly rounded to subrounded, and display some evidence of shock metamorphism in a zone up to several km wide peripheral to the SIC. Some fragments appear to be transported from elsewhere as they do not occur in the immediate vicinity.

On the South Range, the Sudbury Breccia has been affected by regional metamorphism related to the Penokean-Hudsonian orogeny. As a result, the matrix of the Breccia is recrystallized and coarser grained than on the North Range, and the shock metamorphic features are extensively obliterated.

Contact metamorphism of the Sudbury Breccia by the SIC is generally evident within the adjacent zone about 100 m wide with pyroxene hornfels development (Dressler, 1984). Where the hornfels has the most intense development the Breccia is highly recrystallized and resembles or approaches in texture and mineralogy the matrix of the Footwall Breccia, a variety of mineralized breccia closely associated with the Sublayer.

Whitewater Group

The Whitewater Group occurs only within the Sudbury Basin. The Group comprises three formations. In stratigraphic succession from bottom to top they are the Onaping, Onwatin, and Chelmsford Formations. The Onaping Formation is older than the SIC and is intruded by it. The Group is cut by gabbroic dykes trending approximately east-west, but their absolute age is not known. Some of these dykes are ultramafic in character and are generally altered to amphibole, chlorite and carbonate.

Onaping Formation

The Onaping Formation consists of three members which in stratigraphic order from bottom to top are: Basal Member, Gray Member, and Black Member (Fig. 3). In addition, Melt Bodies occur as discontinuous masses in Gray and Black Members. The sequence is some 1,800 m thick and is generally crudely stratified. All members have been interpreted either as products of volcanic activities (i.e. Williams, 1957; Stevenson, 1972; Muir, 1984), or as products of impact of a meteorite (Dietz, 1964; French, 1972; Peredery, 1972a; Peredery and Morrison, 1984). The Formation has been described in detail by Muir and Peredery (1984) who reached two opposing conclusions about its origin.

The Basal Member is the lowermost unit of the Onaping Formation. It ranges in thickness from a few metres to over 100 m and appears to be absent at several places, probably because of the intrusion of the SIC. Previously it has been described by Stevenson (1961) as "Quartzite Breccia" and by Coleman (1905a, b) as "Trout Lake Conglomerate". Its upper contact with the Grey Member or Melt rocks is generally sharply defined. On its lower side it is intruded by the SIC.

The Basal Member consists of subangular to subrounded rock fragments of probable Archean and Proterozoic age that vary in abundance from approximately 20 to 50 percent and in places to 90 percent of the total rock. They vary from millimetre sized particles to fragments several tens of metres in diameter; less commonly, blocks over 100 m in diameter have been observed. The fragments are metasedimentary, granitic and gneissic on the North and East Ranges, and mainly metasedimentary on the South Range. Mafic rock fragments are relatively scarce. The matrix of the Basal Breccia is medium-grained, metamorphic to igneous-looking in texture and composed mainly of albitic plagioclase and quartz, and also contains some potassic feldspar, chlorite and amphibole. Shock metamorphic features such as planar features in quartz and feldspar are commonly present in inclusions.

The Onaping Melt rocks commonly occur on top of the Basal Member but are also observed within the Gray and Black Members and rarely as inclusions in the uppermost granophyre of SIC. Melt rocks form irregularly shaped masses and, much less commonly, dykes. Archean and Early Proterozoic country rock fragments are common to abundant within the Melt rock, make up as much as 70 percent (Peredery, 1972b) of the rock, and commonly contain shock metamorphic features. The "Melt" itself is aphanitic, fluidal or fine to medium grained and igneous textured. It commonly has some amygdules which are filled by quartz-chlorite±carbonate±sulphides. The sulphides include pyrite, pyrrhotite and chalcopyrite.

In the past these melt rocks have been interpreted as the andesitic lavas and feeder dykes (Williams, 1957; Thomson, 1957) that erupted violently to produce the "glowing avalanche" deposits of the Gray and Black Members. Later Stevenson (1963) interpreted the Melt rocks as a chilled phase of granophyre (micropegmatite). Peredery (1972a) reinterpreted these rocks as impact melts related to the meteorite impact.

The Gray Member of the Onaping Formation overlies the Basal Member and in turn is overlain by the Black Member. The rocks that make up the two Members have been described as

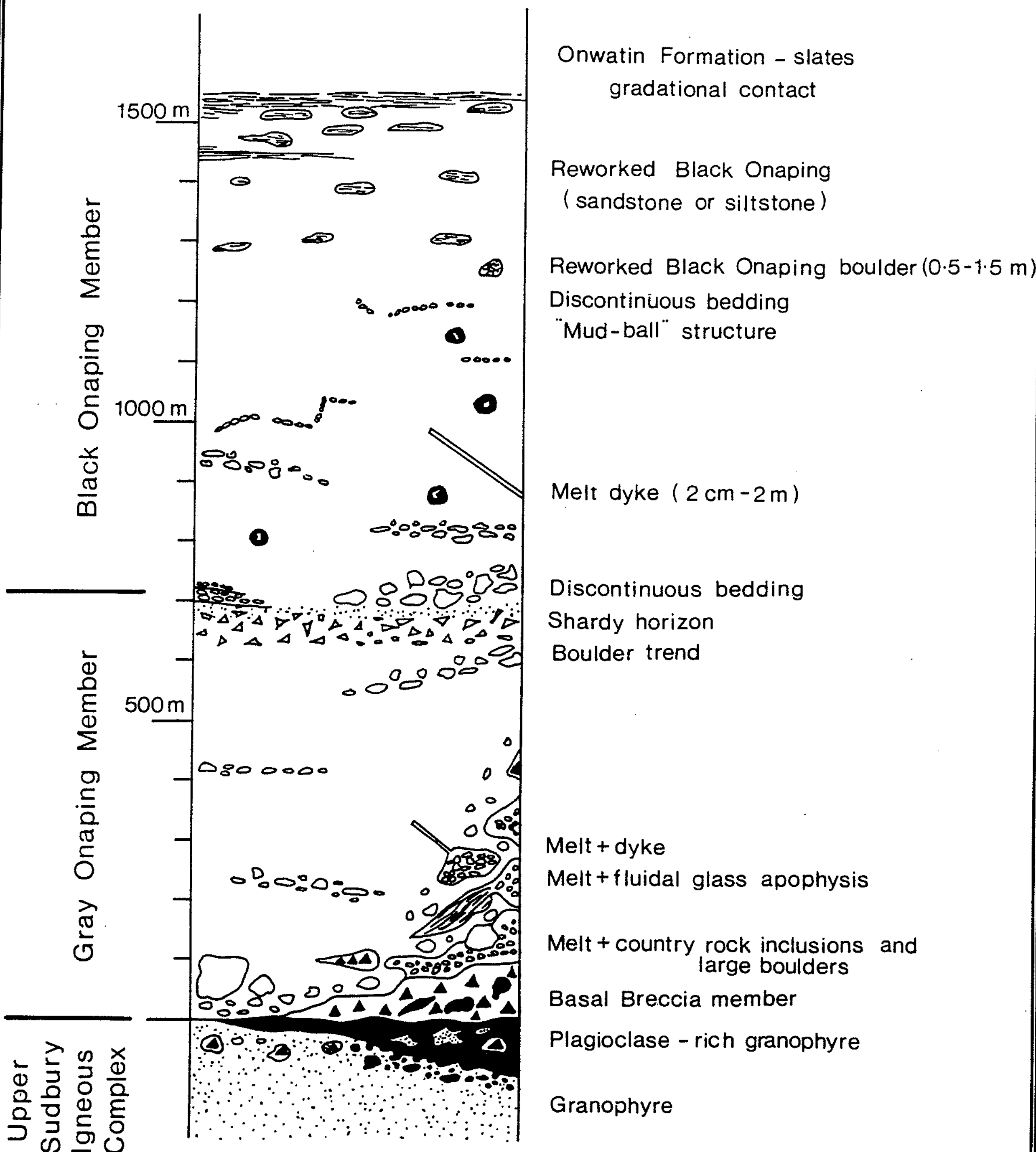


Figure 3. Generalized composite section through the Onaping Formation. Sketch shows a variety of relationships within and among member, Melt Bodies, and granophyres of the Sudbury Igneous Complex (modified after Muir and Peredery, 1984)

volcanic tuffs (Burrows and Rickaby, 1930), as a glowing avalanche deposit (Williams, 1957; Thomson, 1957), and as an ash flow tuff sheet (Stevenson, 1972). French (1967, 1972) and Peredery (1972a, b) interpreted the Gray Member as a fallback breccia formed in one continuous process and originally ejected from a crater produced by the impact of a meteorite. The Black Member is furthermore interpreted by Peredery (1972a) as a "wash-in" representing the fallback from outside of the crater that had been transported by a tsunami-like wave back into the crater.

Both the Gray and Black Members are heterolithic, little sorted breccias consisting probably of Archean and Early Proterozoic igneous, metamorphic and sedimentary rock fragments, and of recrystallized or devitrified glass fragments. The rock fragments range in size from submicroscopic to over 100 m in diameter. Peredery (1972a, b) described recrystallized, slab-like glass bodies up to 30 m in length. No distinct bedding has been recognized in the main mass of the Gray Member, but it is generally stratified as a unit with distinct fining of the fragments towards its upper part where discontinuous bedding has been observed locally (Muir and Peredery, 1984). The matrix of the Gray Member is greenish-grey to greyish-green; that of the Black Member is dark grey to black. In both Members the matrix consists of rock flour, fragments of rocks and minerals and glass. The dark colour of the Black Member is attributed to carbonaceous material. Discontinuous bedding and evidence of reworking by water are present in the Black Member and are well developed in the upper levels. The upper contact is gradational to the Onwatin mudstones. Shock metamorphic mineral deformation is common in many rock and mineral fragments. The devitrified complex glass fragments are possibly diaplectic in origin and related to the maskelynite stage of shock metamorphism.

Sulphides, such as pyrrhotite, pyrite, marcasite and chalcopyrite, are commonly observed in the country rocks and glass fragments, and display replacement textures. They have been interpreted to be hydrothermal in origin (French, 1972; Peredery, 1972a,b). However, it has been suggested that perhaps some of the sulphides could represent original fragments (Rousell, 1984).

Onwatin Formation

The Onwatin Formation (Rousell, 1984) is up to 600 m thick and consists of laminated mudstone or slate with minor intercalated fine grained wacke. It is generally carbonaceous, locally pyritic, and characterized by a well developed slaty cleavage. The carbon content of the slate ranges from 6.8 to 10 percent (Coleman, 1905b). In places the slates are fractured and filled with anthraxolite (a variety of coal).

The contact of the Onwatin Formation with the underlying Onaping Formation is conformable and gradational. The lower part of the Formation is characterized by a zone of siliceous carbonate-rich rocks, the "Vermilion Member", which contains appreciable amounts of lead, zinc and copper mineralization formerly mined at the Errington and Vermilion Mines near Vermilion Lake (Rousell, 1984). Minor silver and gold were produced as by-products. The contact between the Onwatin Formation and the overlying Chelmsford Formation is conformable and gradational.

Chelmsford Formation

The Chelmsford Formation (Rousell, 1984) is the uppermost formation of the Whitewater Group and has a preserved thickness of about 850 m. It comprises a sequence of graded and massive wackes, with minor intercalated slaty mudstones. The Formation has been described by Coleman (1905b), Burrows and Rickaby (1929), Thomson (1957), Cantin and Walker (1972) and Rousell (1972). Fairbairn et al. (1968) reported a Rb/Sr isochron age of 1720 ± 30 m.y. that represents a minimum, metamorphic age of the Formation.

The Chelmsford Formation is characterized by turbiditic Bouma sequences, and has well preserved sedimentary structures such as convolute laminations, load structures, current marks, U-shaped channels and carbonate concretions, and possible biogenic structures. Rousell (1972) described these sedimentological features in detail and concluded that much of the Formation was deposited by turbidity currents. Paleocurrent data (Rousell, 1972; Cantin and Walker, 1972) suggest that the Chelmsford Formation rocks were deposited by west-southwesterly flowing currents approximately parallel to the present long axis of the Sudbury Basin. This implies that at the time of the deposition of these sediments the Sudbury Basin may have been already deformed.

Sudbury Igneous Complex (SIC)

The Sudbury Igneous Complex (also known as the Nickel Irruptive or Sudbury Irruptive) is an elliptical-shaped body intruded into Archean rocks of the Superior Province to the north and east, and Huronian rocks of the Southern Province to the south of the Sudbury Structure. The intrusion lacks layering in general but on a gross scale it has been subdivided into four main members:

1) an upper, granophyric member,
2) a middle, quartz gabbro member,
3) a lower, noritic member, and
4) a discontinuous, basal member, generally known as the ore-bearing Sublayer. It occurs below the noritic member and is in contact with it, or extends as a series of ore-bearing "offset dykes" which penetrate deep into the adjacent wallrocks.

Naldrett et al. (1970) described the textural and mineralogic variations in several traverses across the SIC and discussed the principal differences between the North and South Ranges. These are summarized in figure 4. Such detailed studies have documented a cryptic layering, consisting of a gradual and systematic enrichment in iron in the pyroxenes, and sodium enrichment in plagioclases towards higher levels in the noritic member and the quartz gabbro member above it. These changes are accompanied by an increase in the potassic feldspar and quartz content of the rock. In the quartz gabbro noticeable increases in the oxide and apatite contents occur. The oxide consists of an intergrowth of magnetite and ilmenite. Naldrett et al. (1970) concluded that gravitational settling played an important role in the crystallization and differentiation of SIC magma.

The contact between the quartz gabbro and the overlying granophyric rocks has been generally described as gradational or transitional in character. However it has been noted that in this transitional zone there are locally abundant inclusions of country rocks and inclusions of granophyric and gabbroic rocks, zones of strongly chloritized rocks, and variations in grain size, texture and mineralogic composition. Above this zone the granophyric rocks carry relatively few inclusions and are generally fairly homogeneous. In the uppermost several hundred metres the granophyric rocks become inhomogeneous texturally, inhomogeneous in terms of the modal mineralogy, and either gradually merge into a finer grained plagioclase-rich variety of granophyre or are in sharp contact with it. The plagioclase-rich granophyric rocks are similar to the quartz gabbro in modal mineralogy, and whole-rock and mineral composition, and have been interpreted as having been separated from the quartz gabbro by a later granophyric intrusion (Peredery and Naldrett, 1975). This suggestion offered a possible explanation for the present large volume of granophyre relative to the mafic rocks below it.

Naldrett and Hewins (1984) interpreted the main mass of the SIC to be a body of fractionated and contaminated magma with a complex path of intrusion. Faggart and Basu (1985) have further indicated that on the basis of the samarium-neodymium isotopic data the SIC could be largely molten crustal rocks. On isotopic grounds Naldrett and Evenson (1987) have estimated that the South Range Sublayer and the main mass of

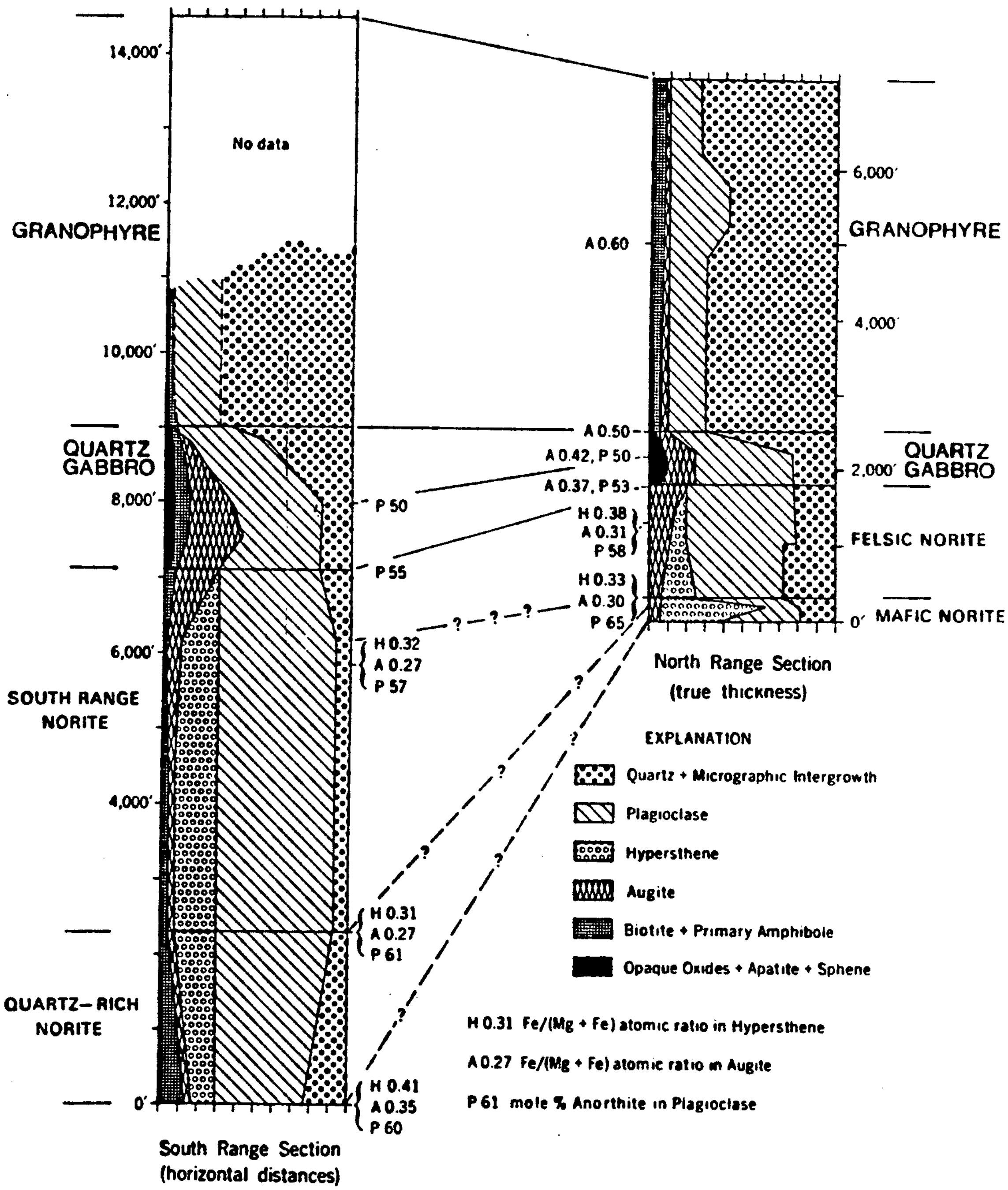


Figure 4. Partially idealized diagram illustrating mineralogical variations on sections through the North and South Ranges (after Naldrett et al., 1970)

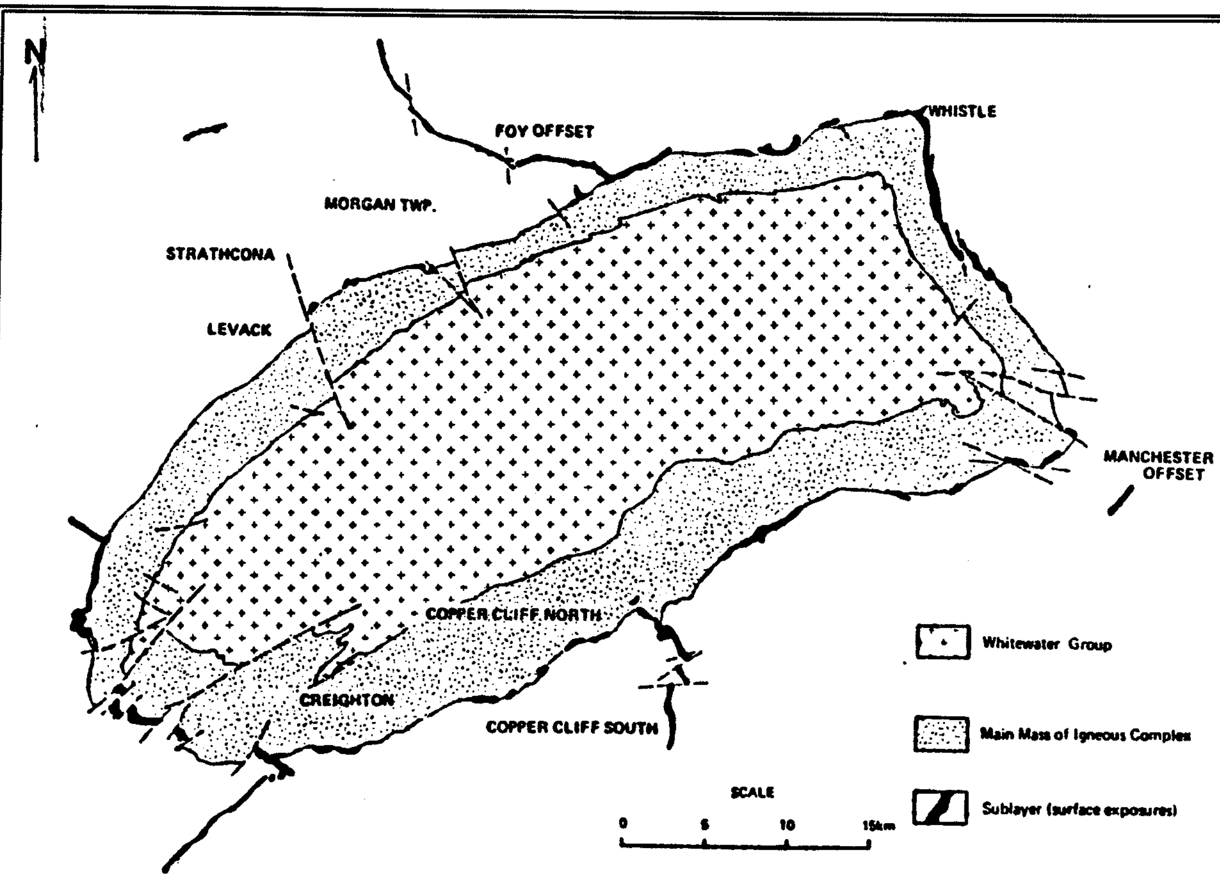


Figure 5. Map of the Sudbury Igneous complex showing the distribution of the Contact Sublayer and Offset dykes (modified after Souch, Podolsky et al., 1969)

the norite in the SIC consist of about 70% upper crustal material.

Paleomagnetic studies (Morris, 1980, 1981) of the SIC rocks suggest a number of intrusive events: one for norite, one for quartz gabbro, possibly three in the granophyre, and indications of possibly two events related to sulphide deposition. However, field relationships and mineralogical studies do not support the proposition of a separate intrusion for the quartz gabbro. It is suggested here that the crystallization of the quartz gabbro may have been affected by the instability of the Sudbury Structure and collapse of the magma chamber, as the paleomagnetic work indicates the original attitude of the noritic member was originally dipping at much smaller angles than they are at present. Similarly, the two episodes suggested for the sulphides may be related to later deformational events. The three possible episodes suggested for the granophyre are more or less in agreement with the observed relationships in the field.

The Sublayer and Mineralized Footwall Breccia

The Sublayer, a distinctive, inclusion-bearing noritic facies related to the SIC, carries the Ni-Cu ore deposits in the Sudbury area (Souch and Podolsky et al., 1969) (Fig. 5). It occurs as discontinuous lenses and sheets along the lower contact of the SIC with the underlying country rocks commonly known as the Footwall (Fig. 6). The

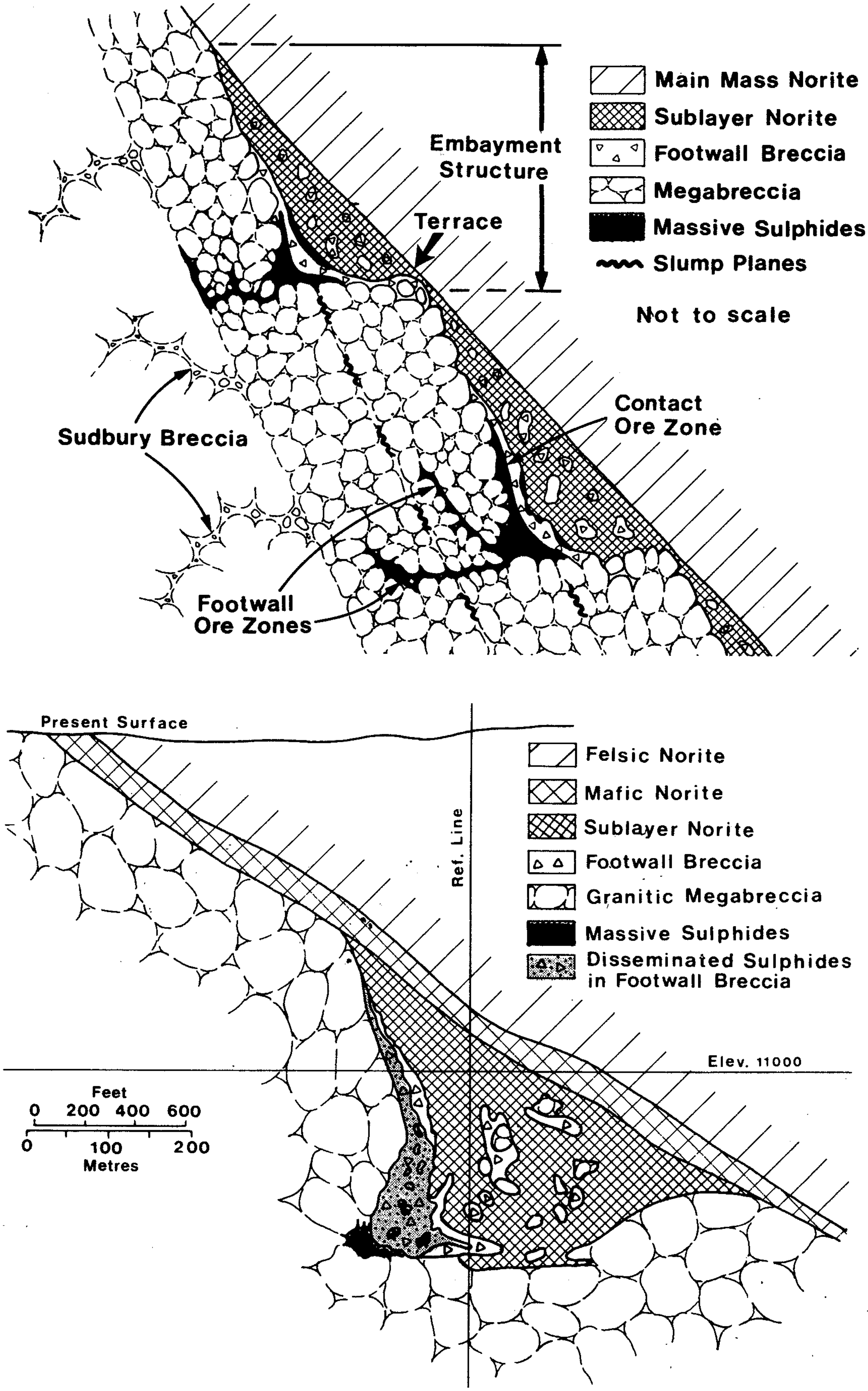


Figure 6. TOP - an idealized representation of the embayment structures and their relationship to slump terraces of the Sudbury Structure.
Bottom - section through the Levack No. 4 orebody (after Morrison, 1984)

Sublayer is found generally in embayments or depressions in the Footwall, and also forms "offset dykes" of quartz diorite intruding the country rocks (Fig. 5 and 7). Sulphide veins, stringers, and massive sulphides occur also in the country rocks, in the Sudbury Breccia, and in the Footwall Breccia generally found in "embayment" structures closely associated with the Sublayer. In places, minor disseminated sulphides occur also in the noritic rocks overlying the Sublayer, but elsewhere the noritic rocks do not carry any significant quantities of sulphides (Duke and Naldrett, 1976).

The relationships between the Sublayer and the main mass norite have led investigators to suggest both a pre-norite (Pattison, 1979) and a post-norite (Naldrett and Kullerud, 1967) age for the Sublayer. The arguments presented for both sides are summarized by Naldrett et al. (1984). These authors have presented an outline of a number of sublayer phases, both sulphide- and non-sulphide-bearing, pre- and post-norite, but in this Field Guide descriptions will be restricted to the mineralized Sublayer as defined earlier by Souch and Podolsky et al., (1969). Detailed descriptions of the mineralogy and other features of the sublayer are given in Naldrett et al. (1984). Naldrett (1984b) also presented a scheme of genetic relationships between the Sublayer and the SIC.

The Sublayer consists, in general, of a noritic rock which hosts disseminated or massive sulphides, and contains a variety of inclusions - some exotic in character, others locally derived. Where there is a high concentration of sulphides, the sulphides commonly form the matrix to various inclusions in the Sublayer, or penetrate into the adjacent footwall rocks and Sudbury Breccia as veins, stringers, networks, and as massive sulphide bodies. The sulphides also occur in the Footwall Breccia, a distinctive breccia commonly found below the Sublayer, in depressions or embayments in the footwall. The sulphides occur as disseminations of irregularly shaped blebs and larger patches that have the appearance of fragments (Pattison, 1979), some of them angular in shape, and as massive sulphides. Exotic inclusions and locally derived country rock fragments are also present in the Footwall Breccia. Field relationships indicate the Footwall Breccia could be later than the Sublayer as Footwall Breccia appears to be locally intruded into the Sublayer. However, inclusions of Footwall Breccia occur also in the Sublayer (Fig. 6).

The matrix of the Footwall Breccia is felsic, fine grained, and is characterized by optically large patches of quartz and variably recrystallized, very fine to fine grained plagioclase. The textures appear to be metamorphic in character, and the denucleation textures in plagioclases support this, but where the plagioclases are highly recrystallized their shapes tend to be lathy and the rock assumes an igneous-looking texture (Pattison, 1979). Dressler (1984) is inclined to think that the Footwall Breccia formed by recrystallization of Sudbury Breccia (or some allochthonous breccia) because of contact metamorphism related to the SIC. However, inclusions of distinctly outlined Sudbury Breccia found in the Footwall Breccia is not consistent with this explanation.

The exotic inclusions in the Sublayer have been studied by a number of investigators (Rae, 1975; Scribbins et al., 1984). The exotic inclusions can be subdivided into two main groups: 1) primary textured and 2) metamorphic textured rocks. In both groups a variety of rock types are recognized, ranging in composition from gabbroic to peridotitic rocks. The gabbroic rock types are the most abundant and are commonly olivine-bearing; some are quartz and granophyre-bearing and are texturally and mineralogically similar to the noritic rocks of the Sudbury Igneous Complex. Some inclusions have disseminated interstitial sulphides similar to those in the enclosing Sublayer. Mineralogical studies suggest the exotic inclusions with primary

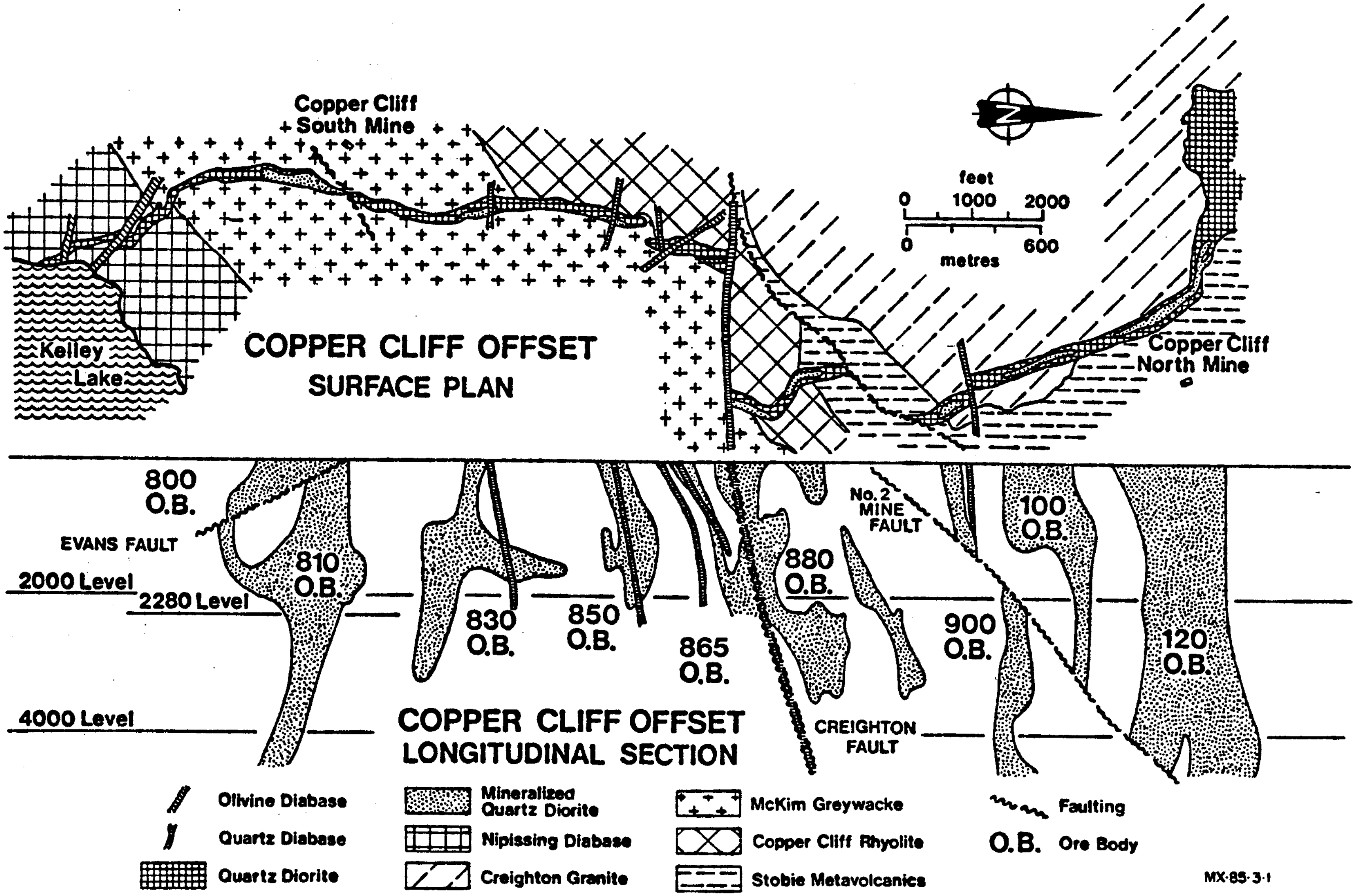


Figure 7. Geological map of Copper Cliff Offset and a longitudinal section showing various deposits.

textures could be part of a continuum with the noritic rocks of the Sudbury Igneous Complex and could be derived from a layered mafic-ultramafic sequence at depth.

The exotic inclusions with metamorphic textures have been less studied. Perhaps some of them could be correlated with some of the rocks found in the footwall environment. One notable feature of many of these inclusions is that their plagioclase minerals have undergone very fine recrystallization, producing a variety of textures, such as fine grained polygonal, mosaic, and fan-like or spherulitic patterns. These latter patterns are especially similar to those developed in highly shocked rocks in the Sudbury area. In spite of the recrystallization the original lathy shapes of plagioclases are still commonly evident. The olivine and pyroxenes have either been recrystallized or appear to have primary shapes.

The country rock inclusions in the Sublayer can be correlated with the rocks in the footwall. They show all the features found in the footwall rocks described earlier. Their abundance in the Sublayer ranges from high concentrations in some ore types to very low concentrations in others.

In the offset dyke environment (Fig. 7) the orebodies occur as steeply plunging, sheet-like and pipe-like bodies parallel or sub-parallel to the strike of the offset. The ore zones generally comprise an inner core of inclusion- and sulphide-rich quartz diorite grading outwards into barren or weakly mineralized inclusion-free quartz diorite. The most common ore type consists of disseminated blebs of sulphide in quartz diorite but inclusion-bearing massive sulphides are also found.

Detailed descriptions of the offset dykes are given by Grant and Bite (1984), and the associated ores have been described by Souch and Podolsky et al. (1969) and Cochrane (1984).

The Sulphide Ores

General descriptions of the ore types and sulphide mineralogy have been given by Souch and Podolsky et al. (1969) and Hawley (1962). The mineralogy and chemistry of the sulphide ores at Sudbury have been studied by Hawley (1965), Naldrett et al. (1979), Naldrett et al. (1982) and Naldrett (1984). Studies of the sulphide ores with particular reference to the PGE include those of Cabri and Laflamme (1976), Chyi and Crocket (1976), Hoffman et al. (1979), Keays and Crockett (1970), and Naldrett et al. (1979).

The sulphide minerals pyrrhotite, chalcopyrite and pentlandite account for the bulk of the Sudbury sulphide orebodies. Locally pyrite, cubanite, bornite and millerite are important ore minerals. In the South Range ores, arsenides and sulfarsenides are generally present in very minor to trace quantities, but in places higher concentrations are found. They usually correspond to enrichment in the platinum group elements (PGE). In the North Range ores the arsenides and sulfarsenides are less abundant. In addition to arsenides and sulfarsenides, the Sudbury ores carry minor to trace quantities of platinum and palladium group minerals, generally present as tellurides, bismuthinides, stannides, and native silver, bismuth and gold. Naldrett (1984) summarized the mineralogy of the Sudbury ores (Table 3). The precious metal content of the Sudbury ores accounts for up to ten percent of the total value of the ore.

Copper, Nickel and PGE Distribution

The Sudbury orebodies in general show a progressive change across them and from the upper to the lower levels in terms of Cu and Ni metals. The Ni and Cu are progressively enriched from the hangingwall to the footwall side, and there is commonly an enrichment in Cu with respect to Ni towards the lower levels of the orebodies. Enrichment in Cu is generally accompanied by enrichment in Pt, Pd and Au. The Cu-rich stringers and veins occur up to several hundred metres away from

TABLE 3. MINERALS OF THE SUDBURY ORES (after Naldrett, 1984).

METALLIC MINERALS NAME	FORMULA	NOTES	REFERENCES
	MAJOR		
Pyrrhotite			
Hexagonal	$Fe_{1-x}S$	Distribution of hexagonal and monoclinic studied intensively at Strathcona Mine	Cowan (1968)
Monoclinic	$Fe_{1-x}S$		Corlett (1972)
Pentlandite	$(Fe,Ni)_9S_8$	Ni content 33 to 35 wt. % Co content 1 wt. %	Hawley and Stanton (1962)
Chalcopyrite	$(CuFe)S_2$		Hawley and Stanton (1962)
Magnetite	Fe_3O_4	Magnetite in the ores is low in TiO_2	Hawley and Stanton (1962) Naldrett and Kullerud (1967)
Pyrite	FeS_2	4 types 1. Pink Nickelean 2. Early Resorbed 3. Exsolved 4. Hypogene Replacement	
	MINOR		
Cubanite	$CuFe_2S_3$	Found particularly in the Frood-Stobie deposit and in Cu-zone at Strathcona.	Hawley and Stanton (1962) Abel *et al.* (1979)
Galena	Pbs	Found as small veins in fractures and as small flecks in pyrite.	
Sphalerite	ZnS	Present with chalcopyrite as late veins and fault filling.	Hawley and Stanton (1962)
Millerite	ZnS	Originally regarded as secondary. Hypogene mineral found in Footwall at Strathcona Mine.	
Niccoline	NiAs	Found at Worthington, Frood, and Garson in association with other arsenides	Hawley and Stanton (1962)
Gersdorffite	NiAsS	Occurs with chalcopyrite and as late stage veins	Hawley and Stanton (1962) Cabri and Laflamme (1976)
Cobaltite	CoAsS		
	RARE		
Gold	Au	Found in siliceous mineral zone at Frood Mine	Hawley and Stanton (1962) Michener (1940)
Silver	Ag	Found near base of Frood Mine	Hawley and Stanton (1962)
Bismuth	Bi	Found associated with galena or with parkerite and bornite at Frood	Hawley and Stanton (1962)
Tetradymite	Bi_2Te_2S	Commonly associated with veins of galena	Hawley and Stanton (1962)
Hessite	Ag_2Te	Found at Frood Mine	Hawley and Stanton (1962)
Maucherite	$Ni_{11}As_8$	Commonly occurs with niccolite and gersdorffite	Hawley and Stanton (1962)
Bornite	Cu_5FeS_4	Only observed in Cu-rich zones at Frood deposit	Hawley and Stanton (1962)
Parkerite	Ni_3Bi_2S		Michener (1940)
Schapbachite	$AgBiS_2$	Frood Mine–1 grain observed	Hawley and Stanton (1962)
Altaite	PbTe	Found at Coleman, Frood, and Crean Hill Mines, often associated with PGM	Cabri and Laflamme (1974 and 1976)
Argentiferous Pentlandite	$(FeNi)_8AgS_8$	Light pink, probably confused with bornite	Karpeakov *et al.* (1973)† Cabri and Laflamme (1976)
Breithauptite Hauchecornite Mackinawite	$Ni_9(Bi,Sb,Te)_2S_8$		
Wehrlite	(BiPb)(1.05-1.28) (TeSb)(0.95-0.72)	Associated with chalcopyrite-cubanite	Cabri and Laflamme (1976)
PGM (in relative order of abundance)			
Michenerite	PdBiTe	Principal Pd mineral at Sudbury and occurs in most deposits	Cabri and Laflamme (1976) Hawley and Berry (1958)
Moncheite	$PtTe_2$	Observed at Creighton and Levack West	Cabri and Laflamme (1976)
Sperrylite	$PtAs_2$	Most common Pt mineral of South Range	Hawley and Stanton (1967) Cabri and Laflamme (1976)
Insizwaite	$PtBi_2$	Found at Coleman Mine	
Sudburite	PdSb	Found at Copper Cliff South and Frood	Cabri and Laflamme (1976)
Froodite	$PdBi_2$	Found at Frood, Vermilion, Creighton, Levack West, and Coleman	Hawley and Berry (1958) Cabri and Laflamme (1976)
Kotulskite	PdTe	Found at Levack West and Creighton	Cabri and Laflamme (1976)
Niggliite	PtSn	Found at Coleman Mine	Cabri and Harris (1972)
Merenskeyite	$PdTe_2$	Found at Creighton, Crean Hill, and Levack West	Cabri and Laflamme (1976)
Mertieite II	$Pd_8(SbAs)_3$	Found at Creighton Mine	Cabri and Laflamme (1976)
Unnamed	Ps(Bi,Sb,Te)	Found at Vermilion Mine	Cabri (1973) Cabri and Laflamme (1976)
Unnamed	$Ag_4Pd_3Te_4$	Found at Levack Mine West	Cabri and Laflamme (1976)
Palladian melonite	$(Ni,Pd)(Te,Bi)_2$	Found at Falconbridge, Strathcona, Crean Hill, and Creighton	Cabri and Laflamme (1976)
	SECONDARY		
Violarite	$FeNi_2S_4$	Found in many ores subject to weathering	Hawley and Stanton (1962)
Marcasite	FeS_2	Found as a replacement in cross-cutting seams and fractures	Hawley and Stanton (1962)
Valleriite	$(Fe,Cu)S_2$ $(Mg,Al)(OH)_2$	Found in chalcopyrite-rich samples	Hawley and Stanton (1962)

the Sublayer occur deep in the footwall rocks as at Strathcona Mine, and appear to be tenuously connected to the main orebody (Abel et al., 1979). Naldrett (1984b) attributed this distribution pattern to fractionation in the original monosulphide solid solution (MSS) invoking liquidus and solidus temperatures of the order of 1120° and 1040° C, respectively. During this process the fractionated liquid would tend to be enriched in Ni, Cu, Pt, Pd and Au, and the remaining solid would tend to be enriched in Fe, Co, Rh, Ru, Ir and Os. This distribution of metals reflects the elemental content of different ore types; the Cu-rich ores are generally enriched in Pt, Pd and Au, and the pyrrhotite-rich ores are enriched in Co, Rh, Ru, Ir and Os. The pyrrhotite-rich ores, however, contain appreciable quantities of Ni so that it appears that this metal was not highly affected by such fractionation process.

The relative proportions of PGE mined in Sudbury (Inco mines) recalculated to 100% are given in Table 4, (together with the corresponding gold content). The platinum and palladium metals are present in approximately equal proportions and the ratio of (Pt+Pd)/(Rh+Ru+Ir+Os) is about 9.

The presence of bornite and millerite in some of the Cu-enriched sulphide ore types further suggests that during the fractionation there may have been losses of sulphur from the system resulting in the more sulphur-deficient mineralogy. The lost sulphur was probably contributed to the secondary pyrite that is commonly present in the footwall rocks in the vicinity of the orebodies. The Cu-rich stringers in the footwall rocks locally have very high concentrations of PGE, silver and gold. In such cases native gold appears as a common phase as at the Vermilion deposit on the South Range. Some of the Cu-rich stringers and veins at this deposit are rich in gold or silver but very poor in Pt or Pd, while others are practically barren of Pt, Pd, gold and silver. Such barren Cu veins occur at other ore deposits and represent either extreme cases of fractionation of MSS, or remobilized emanations from the ore deposits at different times in the history of deposition of these veins.

The compositional variation between deposits is marked by significant differences in Ni, Cu and PGE contents. Naldrett (1984) suggested that these differences could best be explained as a result of segregation of varying amounts of

TABLE 4. RELATIVE PGE AND GOLD CONTENTS IN THE MINED ORES (INCO) AT SUDBURY

Pt	38.	44.	Pt/Pd ~1
Pd	40.	46.2	
Rh	3.3	3.8	
Ru	2.8	3.2	
Ir	1.2	1.4	(Pt+Pd)/(Rh+Ru+Ir+Os) ~10
Os	1.2	1.4	
Au	13.5	------	
	100.0%	100.0%	

sulphide from a given batch of magma. Sulphide liquids would tend to be rich in Cu, Ni and PGE which formed at an early, less evolved stage of segregation from a given magma, or be poor in Cu, Ni and PGE if they formed at late, more progressed stage of segregation. It could be added here that the fractionation in the MSS, as it is inferred for different orebodies, could account to some degree for the variation present among various orebodies.

Table 5 gives data on metal content of a number of Sudbury orebodies recalculated to 100% sulphide. The averages in this Table give an approximation to the original composition of sulphide liquids from which the orebodies are derived.

TABLE 5. METAL CONTENT OF SUDBURY ORES RECALCULATED TO 100% SULPHIDE (after Maldrett, 1984).

	Wt.%			ppb							ppm[1]						
	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Au	Zn	Pb	As	S/Se	$\delta^{34}S$	Cu/(Cu + Ni)	(Pt + Pd)/(Ru + Ir + Os)
LEVACK WEST																	
Footwall Breccia Ore	5.6	3.3	0.17	1098	1223	228	73	62	26	166	153	28	—	4900	2.6	0.37	14.4
Footwall Ore	5.8	5.3	0.11	1334	1350	53	22	17	10	97	529	39	—	4050	2.9	0.48	54.8
Cu-rich Stringers	2.6	27.8	0.027	3370	5948	10	<3	0.3	<2	167	3716	258	—	1860	3.13	0.91	1760
Average[2]	5.7	3.7	—	1150	1250	186	60	47	22	150	227	31	<3.5	4550	2.71	0.39	18.6
STRATHCONA																	
Hanging Wall Ore	3.1	0.37	0.21	114	105	60	52	29	20	19	122	9	—	—	—	0.11	2.2
Footwall Breccia Ore	3.4	1.2	0.14	413	380	20	12	7	4	78	160	21	—	—	—	0.26	34.5
Footwall Ore	4.0	2.3	0.13	750	701	16	4	4	3	112	227	26	—	—	—	0.37	132
Cu Zone	0.51	32.3	0.087	137	40	4	3	0.2	2	13	2750	—	—	—	—	0.98	34
Average (i)[3]	3.63	1.23	0.15	420	372	30	21	12	8	54	233	26	—	—	—	0.25	19.3
Average (ii)	3.63	2.8	0.14	590	511	19	9	8	5	79	—	—	—	—	—	0.44	50
LITTLE STOBIE NUMBER 1																	
Average	3.8	4.4	0.19	1930	2120	119	123	62	29	862	100	15	160	3800	1.08	0.54	18.9
LITTLE STOBIE NUMBER 2																	
Average	4.0	3.6	0.17	2130	3170	303	247	113	46	868	96	14	93	3600	0.46	0.47	13
FALCONBRIDGE																	
Average	5.35	1.52	0.22	546	381	287	225	144	40	174	120	14	—	—	—	0.22	2.3

[1] Zn, Pb, and As have not been recalculated to 100% sulphide.
[2] Does not include Cu-rich stringers.
[3] Average (i) is straight average of data, Average (ii) is a weighted average to give the Cu/(Cu + Ni) ratio of the ore reserves.

ROAD LOG AND STOP DESCRIPTIONS

Figure 8 shows the stop locations on a map of the Sudbury Structure. The field trip will start from the Sheraton-Caswell Inn on Regent Street South in Sudbury. Proceeding north, the route follows Regent Street and Elm Street and continues on Highway 144 to the north.

Sheraton-Caswell Inn	**0.00 km** **0.00 miles**
Regent Street N. at Elm Street - proceed north	**4.10 km** **2.55 miles**
Highway 144 N. at Godfrey Drive - stay on highway.	**7.40 km** **4.60 miles**
Highway 144 N. at Regional Road 8 (Levack turn-off) - stay on highway.	**46.80 km** **29.07 miles**

Stop 1 SUDBURY BRECCIA 50.00 km 31.62 miles

The Sudbury Basin is surrounded by a zone of Sudbury Breccia about 50 km wide. The brecciation is limited to rocks outside the Sudbury Igneous Complex. The Sudbury Breccia in these outcrops does not appear to have preferred orientation but ramifies through the host rocks in every direction. Fragments in the breccia generally consist of the same material as the wall rocks. They are usually rounded to varying degrees. The matrix of the breccia consists of finely comminuted wall rock material that has been recrystallized to a coherent mass.

Here on the North Range, the Sudbury Breccia bodies are found in the Archean gneissic and granitic terrain of the Superior Province. The Breccia is typical of the massive type and has evidence of shock metamorphism in the country rock fragments. Some of the country rock fragments are gabbroic and are derived from a local gabbroic dyke in the gneisses which have been dated by zircons at 1711 Ma.

There are several turning places along Hwy. 144 N. within a few kilometres of Stop 1. Mileage will continue from Stop 1.

Stop 2 FOOTWALL BRECCIA 63.80 km 39.63 miles

Strathcona loading tower is on the south side of the road. The hill on the north side is a well exposed outcrop of Footwall Breccia. The inclusions in this outcrop comprise a variety of footwall fragments and igneous- and metamorphic-textured members of uncertain origin. A small body of Sublayer material can be seen within the breccia. Note the minor disseminated sulphides in the gossanous area in the Breccia.

Turn around at the loading tower and proceed southwest back along the road towards the Levack Mine gate.

Stop 3 FOOTWALL BRECCIA ON CONTACT WITH BASAL NORTH RANGE NORITE 64.40 km 40.00 miles

Barren Footwall Breccia occurs as a dyke-like protuberance in sharp contact with weakly mineralized mafic norite. Mafic norite is the basal phase of the Igneous Complex on the North Range. There is an apparent weak alignment of the long dimensions of the inclusions in the Footwall Breccia parallel to the contact.

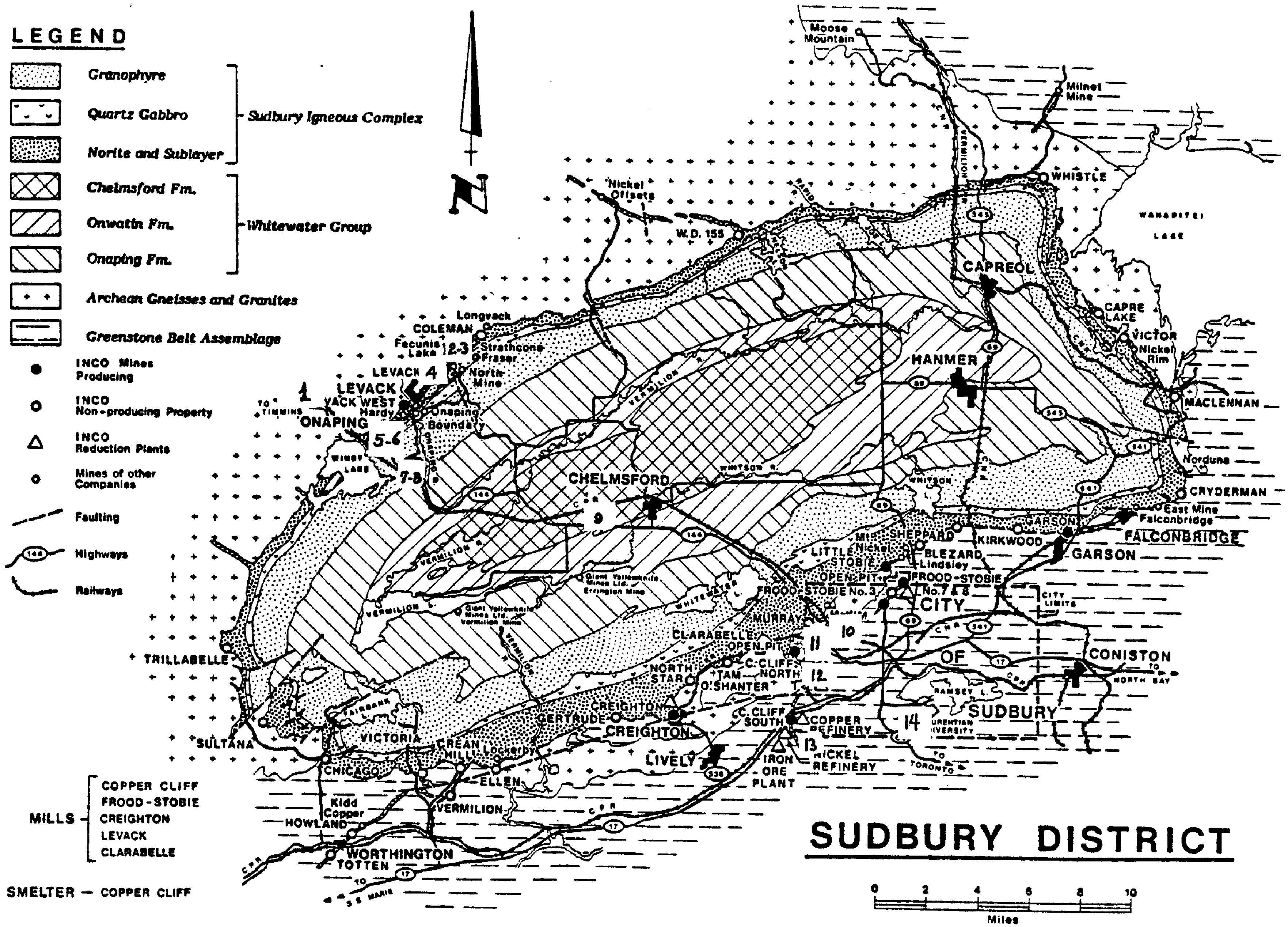


Figure 8. *Geological Map of the Sudbury Structure and Stop Locations.*

Stop 4 SUBLAYER 65.10 km 40.44 miles

Sublayer is well exposed, approximately 150 m northwest of the road on the edge of a gravel pit. Rounded to subrounded fragments, consisting of exotic mafic and ultramafic igneous rocks, are set in a matrix of medium grained hypersthene-bearing gabbroic rock. Patches of sulphide occur in the matrix and in some of the mafic fragments.

Continue southwest back through Levack Mine gate along Regional Road 8 to the junction with Highway 144.

Stop 5 QUARTZ GABBRO AND GRANOPHYRE 72.30 km 44.91 miles

The upper member of the Sudbury Igneous Complex consists of granophyre, formerly called micropegmatite. It is pink in colour and comprises about three parts micrographic intergrowth to one part plagioclase. Quartz, biotite, amphibole, chlorite and opaques are also present.

Below the granophyre, occurs a thin member (225 m) known as the quartz gabbro (or transition zone). It is also called the oxide-rich gabbro due to its content of opaque oxides (up to 8%), largely ulvospinel. Apatite is common and locally pyrite is present. The quartz gabbro is much more mafic than the granophyre and consists principally of plagioclase, clinopyroxene, amphibole and intercumulus micrographic intergrowth and quartz. The plagioclase has a characteristic beige colour in hand specimen due to sericitic alteration.

At Stop 5 the quartz gabbro can be seen in the road cuts to the north and south of the road; the granophyre is further to the southwest, past the south side of the lake.

To reach Stop 6, turn north on Highway 144E to the Elk's Club Road.

Stop 6 FELSIC NORITE 73.70 km 45.78 miles

Felsic norite is the main basic memter of the Sudbury Igneous Complex on the North Range. It is approximately 450 m thick and is a coarse grained hypidiomorphic granular rock consisting of plagioclase, hypersthene and augite (ratio 2:1), biotite, interstitial granophyre, quartz, and minor pyrite, apatite and ilmenite.

No layering is evident but the mineralogy changes gradually producing a "cryptic layering".

Turn around in the Elk's Club parking lot and rejoin Highway 14, turning south at the junction. Mileage is taken from the junction.

Stop 7 ONAPING FORMATION 79.50 km 49.38 miles

Park in a large sandy area east of the highway. From this area, walk 300 metres north to the large hill. See detailed Fig. 9 for location of various members in the Onaping Formation. (a) The Basal Member here is in sharp contact with the granophyre and the plagioclase-rich variety of granophyre. The two varieties of granophyre carry inclusions of Basal Member and have complex contact relationships with each other. The plagioclase-rich granophyre also is intruded in irregular lenses in the Basal Member. The Basal Member is a breccia composed of granitic, gneissic, and metasedimentary and basic rock fragments, commonly shocked, embedded in an originally pulverized and now recrystallized felsic matrix. The rock has been described previously as a "conglomerate" or a "rhyolite breccia"; the matrix has been interpreted as a "phase of micropegmatite" and, more recently, as a "shocked breccia related to the meteorite impact". (b) Basal Members upper contact with the Gray Onaping is sharp and irregular. This contact is defined by a change in the country

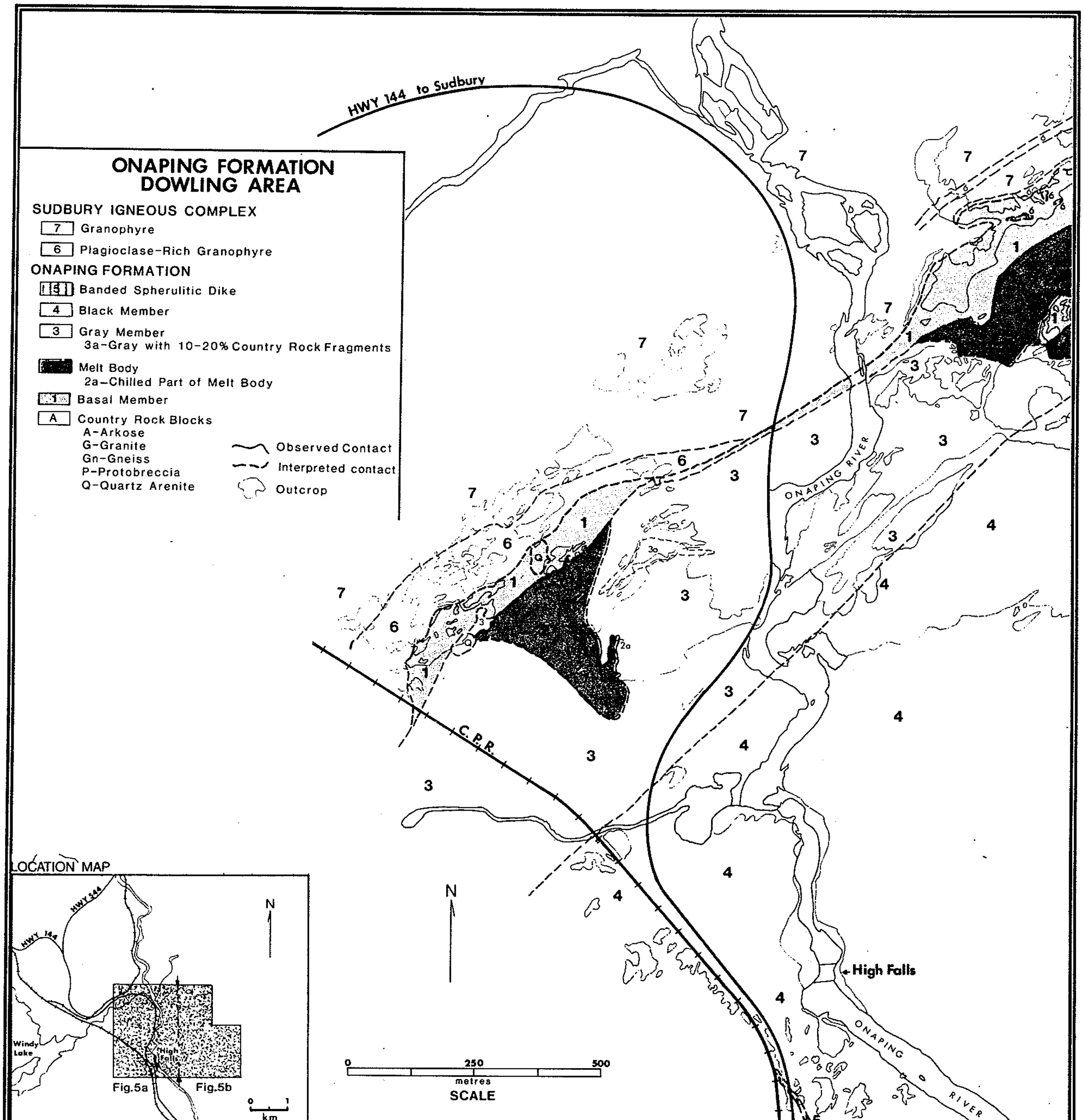


Figure 9. Detailed geology of the Onaping Formation, Dowling Township. (Modified after Peredery, 1972a)

rock fragment population and the appearance of small shard-like fragments in the matrix of the Gray Onaping. (c) The Basal Member is also in contact with the Melt Body, an igneous-textured, chilled rock containing country rock fragments similar to those in the Basal member. The melt rock appears to be in part intrusive and in part extrusive with chilled, chilled-brecciated, and flow-lined melt phases. It commonly has vesicles, usually filled by quartz, chlorite or sulphides. The Melt rocks have been previously interpreted as "feeder structures for the andesitic glowing avalanche deposits of the Onaping Formation", as a chilled phase of micropegmatite", and more recently as "impact melt" related to the meteorite impact. (d) The large roadcut on Hwy. 144 exposes a classic outcrop of Gray Onaping comprising an unsorted chaotic mixture of country rocks similar to those in Basal Member, a variety of glasses, and a very fine matrix of pulverized minerals, rock fragments and glasses. The country rock fragments commonly show some internal brecciation, fluidization or melting, and shock features. Note the fluidal glass bodies with flowage lines which frequently show folding, contortion and truncation of flow lines. The flow lines are usually in tones of green and grey and are compositionally different - the darker bands being more mafic than the lighter. A feature peculiar to both the Gray and Black Onaping is the occurrence of country rock fragments rimmed by fluidal glass showing well developed flow lines. Sulphides (pyrite, pyrrhotite, chalcopyrite, galena and sphalerite) are common in the glassy and country rock fragments. The Gray Onaping has been interpreted as a "glowing avalanche deposit" or a "sheet of tuff", or as "fallback" debris related to meteorite impact.

Stop 8 BLACK ONAPING 80.00 km 50.1 9 miles

The transition between the Gray and Black Onaping occurs over 15 - 60 m and is marked by a rapid increase in the content of carbonaceous material and the appearance of chloritized glass shard fragments. Apart from the black colour and the presence of the shards, the Black Onaping has a similar chaotic assemblage as in the Gray Member, but it also shows a progressive decrease in the size and abundance of fragments. Locally the Black Member has well developed bedding but it has no lateral continuity. Irregular bedding of highly reworked materials occurs on a small scale and becomes more common in stratigraphically higher levels. The uppermost contact of the Black Onaping with the Onwatin slate is gradational.

At this location there are "mudball structures". They consist of country rock or glass fragments surrounded by very fine grained material rich in carbon. Sulphides (mainly pyrite) are also common and occur both in the matrix and within the fragments. Very fine microscopic matrix material makes up about 50% of the rock. The remainder of the fragmental material consists of metasedimentary and igneous or gneissic country rock. The origin of the carbonaceous material is uncertain. The Black Onaping was previously interpreted in the same manner as the Gray Onaping. From the meteorite impact point of view (Fig. 10), it was interpreted as a wash-in of materials from outside of the crater deposited by a highly turbulent tsunami-like wave.

Stop 9 CHELMSFORD FORMATION 93.00 km 77 miles

The outcrop is on the north side of the road. The Chelmsford Formation is the youngest member of the Whitewater Group and occupies the central portion of the Sudbury Basin. The rocks strike northeast, and here dip gently to the northwest.

The Formation consists of proximal turbidites which mark an abrupt change in the pattern of sedimentation within the Basin (the underlying Onwatin Formation is a series of carbonaceous and pyritic siltstones and mudstones).

Paleocurrent and petrographic

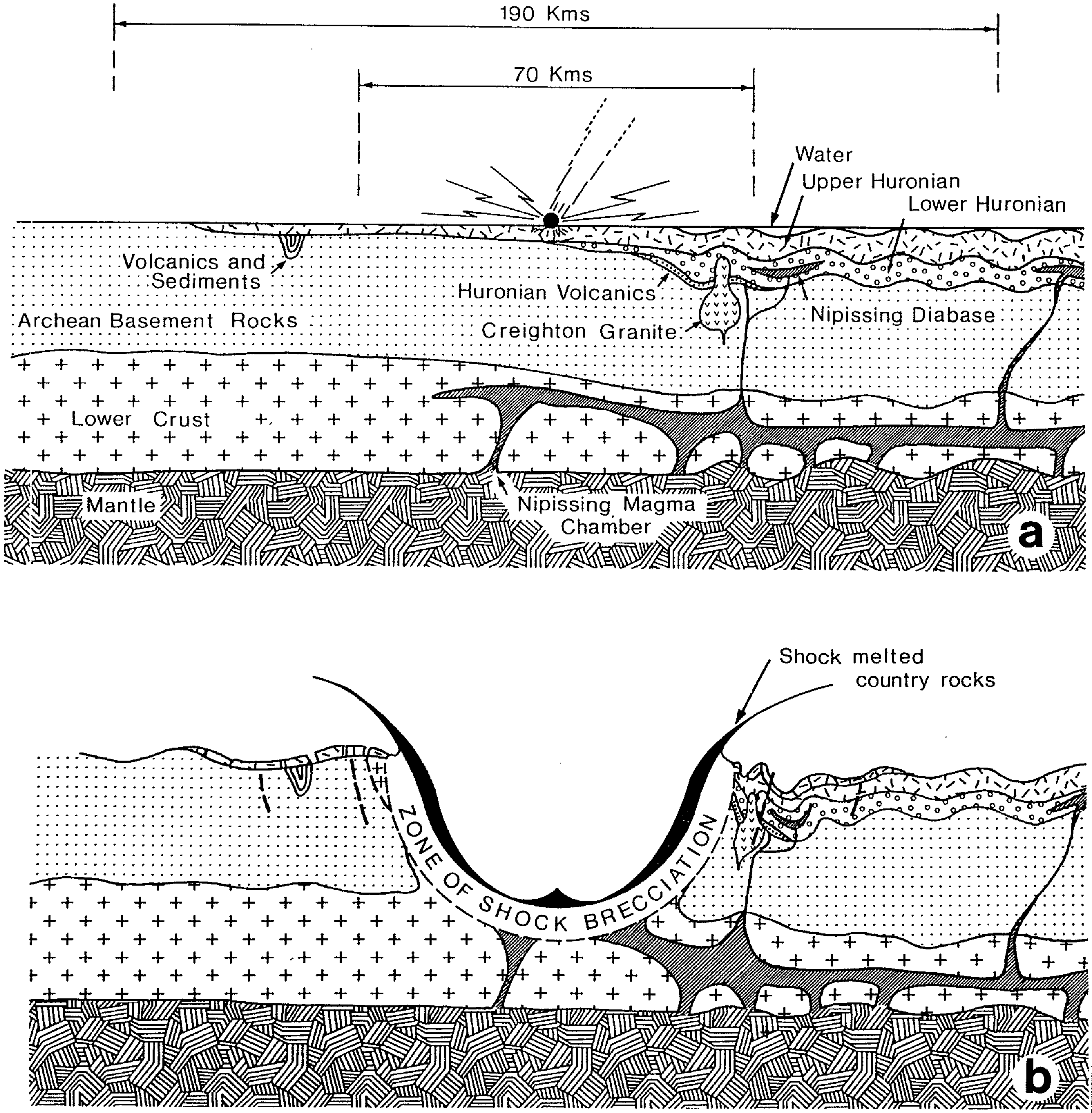
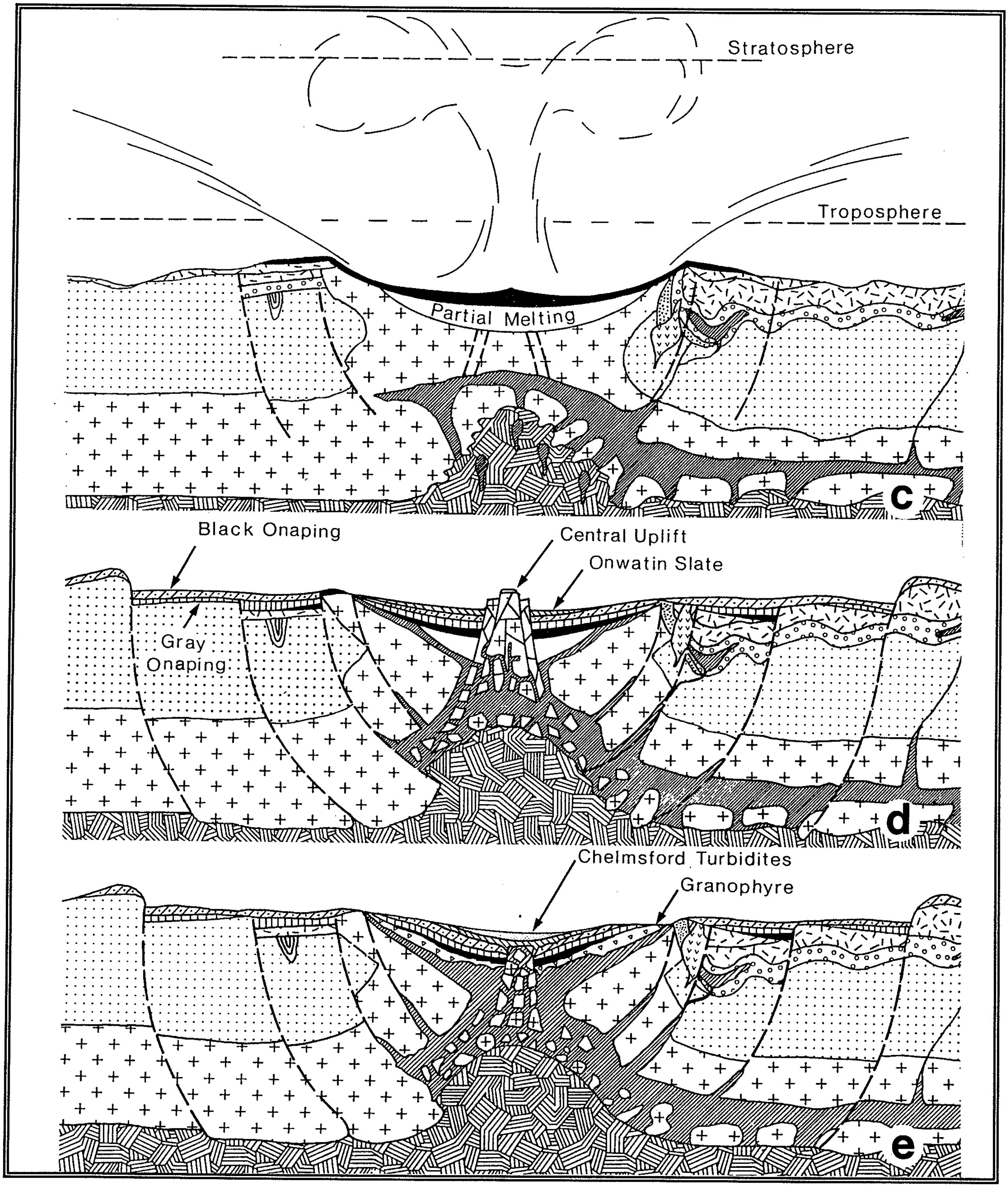


Figure 10. Impact model for the Geological Evolution of Sudbury Complex.


Stratosphere
Troposphere
Partial Melting
c
Black Onaping
Central Uplift
Onwatin Slate
Gray Onaping
d
Chelmsford Turbidites
Granophyre
e

studies indicate that the Chelmsford sediments were derived from a granitic terrain to the north and northeast, and that they were transported by turbidity currents flowing southwest parallel to the major axis of the Sudbury Basin.

Rusty-weathering concretions and lenses are common and represent concentrations of ferruginous carbonate. At this locality a partial Bouma sequence is present and sedimentary flame structures cross-bedding and convoluted bedding can be seen.

Stop 10 DISCOVERY SITE 108.10 km 67.15 miles

Be alert for a small paved area to the east (left) of the highway. Nickel was first reported from the Creighton Mine site in 1856 by A. Murray of the Geological Survey of Canada. However, it was not until 1883, during construction of the Canadian Pacific Railway, that a railway rock-cut near the present site exposed copper-nickel mineralization, which was subsequently developed as the Murray Mine orebody. Within a few years of this discovery, prospectors had found many of the ore deposits of the area, and production commenced in 1889.

The original discovery outcrop was located close to the rim of the present Murray Mine open pit and remained intact until the mid-1970's. At that time the highway and railway were relocated to permit mining of the ore. The Clarabelle No. 2 Open Pit and headframe of the inactive Murray Mine are visible to the southwest.

On the east side of the railway track quartz-rich norite is exposed. This is the basal unit of the Complex on the South Range. A typical modal analysis of the quartz-rich norite gives plagioclase (An60) 51%, orthopyroxene 14%, clinopyroxene 5%, quartz 16%, biotite 6%, primary amphibole 6%, and others 2%. The quartz often displays a distinctive pale blue opalescence.

Weakly mineralized Sublayer is exposed nearby on the west side of the tracks. The Sublayer dips northward at about 60° beneath the norite. The adjacent norite contrasts sharply with the Sublayer, being homogeneous, free of inclusions, and has a very minor sulphide content.

Note: Be careful! This is the transcontinental line of the C.P.R., and train traffic can be heavy.

Continue south along Hwy. 144. 110.00 km (68.33 miles). Turn right on Godfrey Drive. Turn right on Murray Mine Road. 110.40 km (68.58 miles).

Stop 11 ELSIE MOUNTAIN FORMATION 112.60 km 69.95 miles

Park in vicinity of garages, Murray townsite.

Mafic metavolcanics of the Elsie Mountain Formation represent the basal part of the Huronian sequence in the Sudbury area. The Formation is intruded by the Sudbury Igneous Complex and the Creighton and Murray granite plutons. The Elsie Mountain Formation has a maximum preserved thickness of 1,000 m and consists mainly of metabasalt with minor amounts of intercalated pelitic metasediments and mafic tuffaceous rocks. Mafic flows vary in thickness from 25 to 90 m and decrease upward in the sequence. Many flows in the lower part of the Formation are porphyritic, with large phenocrysts (up to 5 cm) of plagioclase. Higher in the sequence pillows and amygdaloidal tops are common. The amygdules are composed of quartz, chlorite and amphiboles and are up to 1 cm in diameter. The pillows, which are often tectonically deformed, are up to one m in longer dimension and some are outlined by thin, dark green, fine grained selvages.

The metabasalts consist mainly of amphibole, plagioclase, quartz and chlorite with minor mica, epidote, garnet and sulphides. The rocks have undergone metamorphic recrystallization under conditions corresponding to the amphibolite and greenschist facies of regional metamorphism.

At the base of the hill some small pits can be seen. These were among the first workings on the Sudbury ore deposits.

Return to Godfrey Drive and continue south.

Stop 12 COPPER CLIFF OFFSET DYKE 117.10 km 72.75 miles

A small fenced pit on the east (left) side of the road marks this stop.

At this location an example of an ore-bearing 'offset dyke' is seen. The quartz diorite dyke is part of the Sublayer. It merges with the Sudbury Igneous Complex in a wide, funnel-like embayment to the north, where the Clarabelle orebody is mined by a number of open pits. The dyke is less than 60 m wide at this stop and remains narrow over the rest of its 5 km length to Kelley Lake. Ore grade mineralization is confined to a zone within the dyke - as here - or at one margin, having great longitudinal and vertical extent.

At this locality the offset is in contact with the Creighton granite. The mineralized zone within the offset is defined by an abundance of sulphide blebs and small, generally amphibolitic inclusions. The Copper Cliff North Mine lies a few hundred metres to the north.

Continue south through the Town of Copper Cliff. Junction of Balsam Street and Hwy. 17 (119.4 km 74.18 miles). Continue east on Hwy. 17 towards Sudbury.

Optional Stop McKIM FORMATION AND SUDBURY BRECCIA

At junction of Balsam Street and Hwy. 17. The outcrop area on the right hand side of Balsam Street just before the junction with Highway 17 is McKim Formation which consists of a thick sequence of wackes and mudstones. At this locality it is a thinly bedded turbidite, with well developed flame structures. Inconspicuous zones of Sudbury Breccia are locally present.

Junction of Hwy. 17 and Kelley Lake Road. 121.10 km (75.24 miles). Turn right on Kelley Lake Road.

Junction of Kelley Lake Road and Southview 122.6 km (76.17 miles). Turn right on Southview.

Stop 13 SUDBURY BRECCIA 123.7 km 76.7 miles

At this locality the road runs between Robinson Lake and Kelley Lake which extends to the southwest along the strike of the Huronian rocks. On the south side of the road polymictic matrix-supported conglomerate of the Ramsey Lake Formation and feldspathic quartzite of the overlying Pecors Formation are exposed. The Pecors contains a well exposed zone of Sudbury Breccia. Here, well rounded fragments of Pecors quartzite are prominent, occurring in a very fine grained, black-weathering matrix. The matrix penetrates the wall rocks of the principal breccia zone in narrow tongues, occasionally separating blocks in what appears to be a stoping process.

Please - no hammering at this location.

Turn around at Stop 13 (from which mileage continues). Follow Southview Drive and Bouchard Street to Regent Street.

Junction of Bouchard Street with Regent Street. Turn left on Regent. 125.90 km (78.10 miles)

Junction of Regent Street with Walford Road. Turn right on Walford. 126.30 km (78.35 miles)

Junction of Walford Road with Paris Street. Turn left on Paris. 127.00 km (78.79 miles)

Junction of Paris Street with Ramsey Lake Road. Turn right on Ramsay Lake Road. 127.60 km (79.16 miles).

Stop 14 SHATTER CONES 129.00 km 80.03 miles

Park in the lookout on the north side of the road. The outcrop is on the south side.

The distinctive fractures termed shatter cones are known to form by passage of shock waves through rocks. The Sudbury Igneous Complex is surrounded by a zone, over 16 km wide, of rocks containing abundant shatter cones. It has been pointed out that if the sedimentary rocks were returned to their original supposedly horizontal orientation during the Sudbury Event, the apices of the shatter cones appear to point inwards towards the Basin (Guy-Bray, 1972).

This outcrop has some of the best formed and most abundant shatter cones found to date in the Sudbury area. The cone surfaces are best seen when obliquely illuminated by the late afternoon sun. The shatter cones appear as conical striated features whose surfaces are often micaceous. They range in length from a few centimetres to a metre or so. Large cones often have numerous small cones developed on their flanks. Cone surfaces are exposed only where they parallel the outcrop surface; on other surfaces the shatter cones are seen as the intersecting crescentic fractures which impart a characteristic shattered appearance to the rock. The host rock here is quartzite of the Mississagi Formation.

Please - no hammering on this outcrop.

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