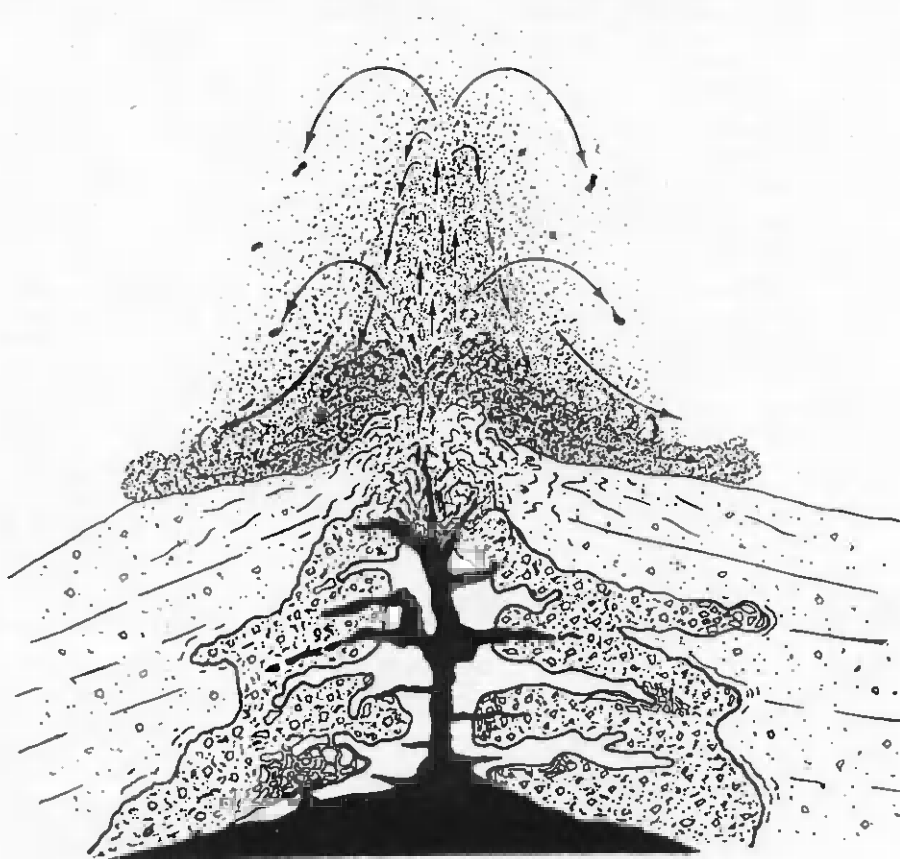


**THE SUDBURY STRUCTURE
WITH EMPHASIS ON THE
WHITEWATER GROUP**

**BY
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with Emphasis on the
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Frontispiece: Schematic diagram illustrating the style of development and emplacement of intrusive hydroclastic breccias and hyaloclastite deposits of the Sandcherry member of the Onaping Formation (modified from Smith and Batiza 1989, Hanson 1991, and Gibson, unpublished)

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INTRODUCTION

The Sudbury Structure is located in south-central Ontario at the present boundary between the Archean Superior Province (gneissic, metavolcanic and metasedimentary rocks, and granitic intrusions) and the Proterozoic Southern Province (metavolcanic and metasedimentary rocks), and lies approximately 10 km north-west of the Grenville Province (high grade gneisses) (Figure 1).

The 1.85 Ga old (Krogh et al. 1984) Sudbury Structure is known world-wide for its Ni-Cu-PGE ore deposits and its debated origin: endogenic volcanic explosion versus meteorite impact. Two carbonate hosted Zn-Cu-Pb-Au-Ag massive sulphide deposits also occur in the interior of the Sudbury Structure, located at the top of the Onaping Formation of the Whitewater Group.

The Sudbury Structure is defined by three components: 1) the Sudbury Igneous Complex (SIC), 2) surrounding brecciated footwall rocks (both Superior and Southern Structural Provinces) that extend some 80 km away from the Complex, and 3) the Sudbury Basin, comprising rocks of the Whitewater Group, found in the interior of the Complex (Figures 1 and 2). The Sudbury Igneous Complex, which has a noritic base and granophyric top, occurs at the base of the Whitewater Group and overlies the surrounding brecciated footwall rocks. The Whitewater Group, found only within the Sudbury Basin, comprises, from base to top, initially glass-rich breccias of the Onaping Formation, carbonates and argillites of the Vermilion and Onwatin Formations, and arkosic sandstones (wackes) of the Chelmsford Formation. The SIC has been dated at 1850 Ma (Krogh et al. 1984) and is interpreted to have been emplaced shortly after or during the deposition of the Onaping Formation (Rousell 1984c). In plan, the SIC is elliptical in shape and approximately 60 km by 27 km in size. In section, seismic reflection shows that the north margin (North Range) of the Sudbury Structure consists of, shallowly dipping strata of sediments, breccias and layered rocks of the SIC and footwall gneisses. In contrast, the south margin (South Range) is dominated by a series of moderately south dipping reflectors interpreted to be thrust faults or shear zones on which considerable north-west-south-east shortening of the Sudbury Structure has occurred (Milkereit et al. 1992). The present shape of the Sudbury Structure, as delineated by the SIC, is due to the combination of structural shortening and subsequent erosion. The Sudbury Structure, in plan, is interpreted to have been originally more circular, with dimensions in the 150 - 200 km range (Grieve et al. 1991).

Shanks and Schwerdtner (1991) attributed the present elliptical shape of the Sudbury Structure to be the result of north-westerly directed thrusting related to the Penokean Orogeny, dated at 1750 Ma (Rousell 1984c). This thrusting event was responsible for several low-angle reverse faults that cut across the SIC and rocks of the Whitewater Group, from the south-west to the south-east. Deformation has also resulted in the formation of isoclinal folds and a slaty cleavage within the Onwatin Formation, open, upright concentric folds in the Chelmsford Formation, and locally overturned rocks in the South Range (Rousell 1984c). The effects of structural deformation are confined primarily to rocks of the South Range and the central part of the Sudbury Basin. Rocks in the North Range are metamorphosed to greenschist facies, those in the South Range are metamorphosed to lower amphibolite facies (Dressler 1984a; Shanks and Schwerdtner 1991).

The origin of the Sudbury Structure has been attributed to volcanism or meteorite impact (see below for authors). Advocates of a meteorite impact origin specify shock features and brecciation associated with the Sudbury Structure, the extreme crustal contamination of the SIC, heterolithic glasses and rapid deposition of the Onaping Formation, and the original circular shape

SUDBURY STRUCTURE

WHITEWATER GROUP

CHELMSFORD Fm

ONWATIN Fm

ONAPING Fm

SUDBURY
IGNEOUS
COMPLEX

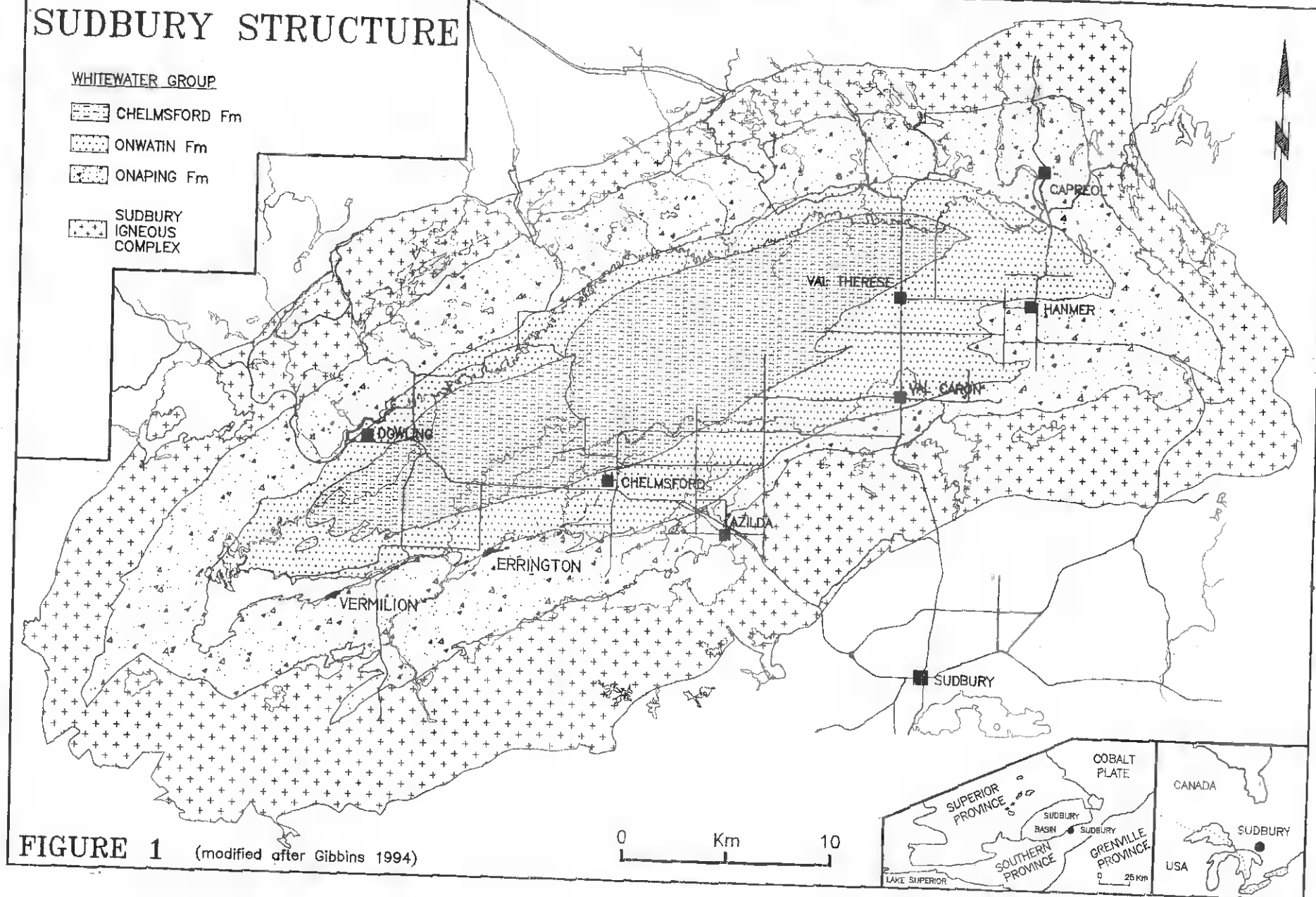


FIGURE 1 (modified after Gibbins 1994)

NOMENCLATURE

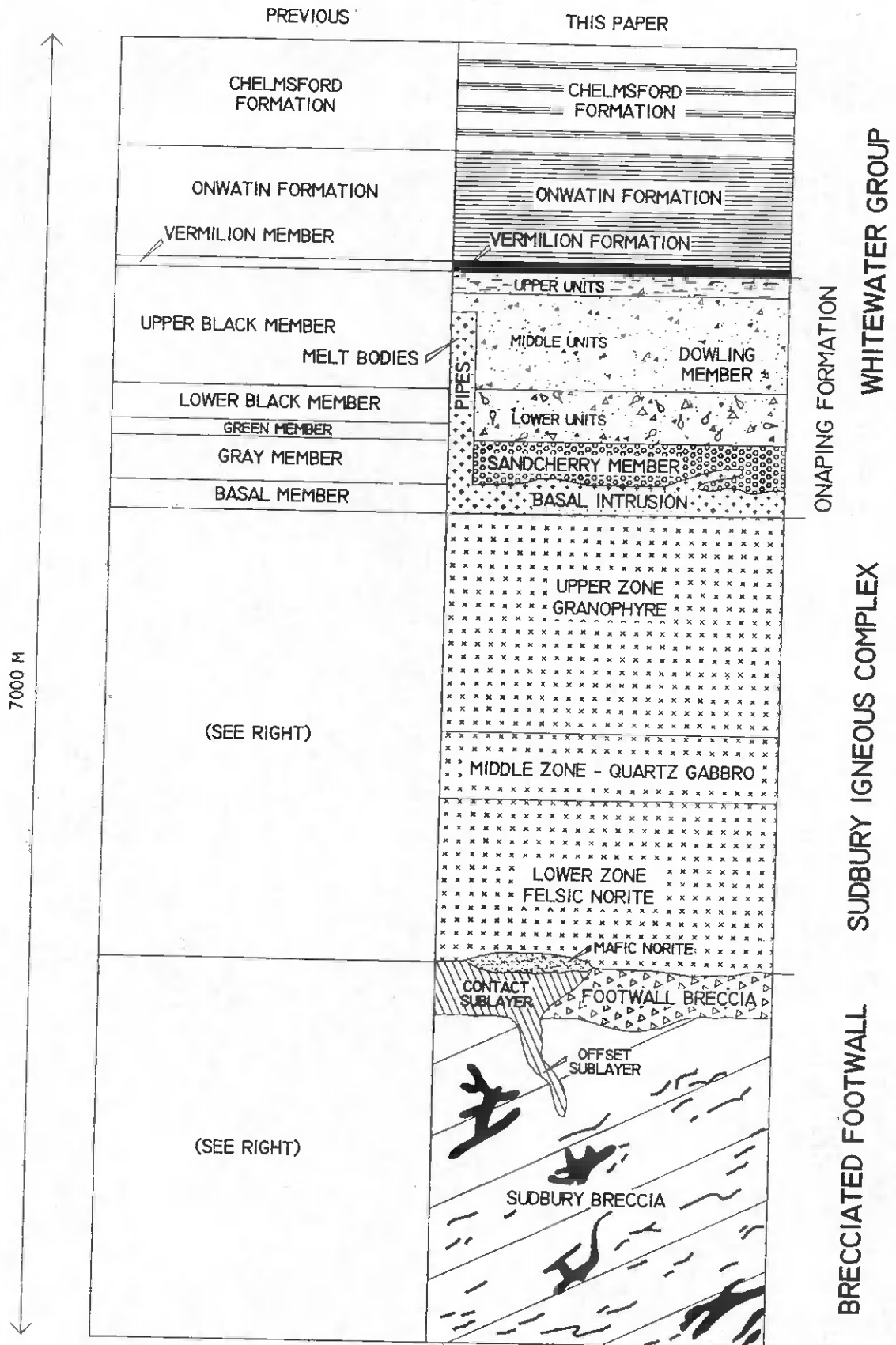


Figure 2: Stratigraphic Section of the Sudbury Structure (modified Grieve et al. 1991)

of the Sudbury Structure as evidence for a meteorite impact. Proponents of a volcanic origin argue that features such as Sudbury Breccia dykes cutting across other Sudbury Breccia dykes, composite fragments ("breccia within breccia") and igneous activity within the Onaping Formation, and various regional endogenic events/structures that predate and post-date the "Sudbury Event" are evidence that the Sudbury Structure is the result of prolonged endogenic processes, unexplainable by a one time event such as a meteorite impact.

An extensive amount of literature exists on the geology and evolution of the Sudbury Structure, with the most recent comprehensive compilation contained within Pye et al. (1984). The Onaping Formation, the footwall rocks to the Errington and Vermilion deposits, has been described and interpreted to be the product of: 1) volcanism (Bell 1893; Coleman 1905; Burrows and Rickaby 1930; Thomson 1957; Williams 1957; Stevenson 1961a, 1961b, 1972, 1990; Muir 1981, 1984, 1986; discussion by Muir in Muir and Peredery 1984); 2) meteorite impact (French 1968; Dence 1972; Peredery 1972a, 1972b; discussion by Peredery in Muir and Peredery 1984; Peredery and Morrison 1984; Dressler et al. 1987; Brockmeyer and Deutsch 1989; Stoffler et al. 1989; Grieve et al. 1991; Avermann 1992; Avermann and Brockmeyer 1992; Krogh et al. 1996, Deutsch et al. 1995); or 3) impact-induced volcanism (Thomson 1969; Muir 1982, 1983; Dietz 1964; Gibbins 1994). Additional research has been directed towards specific features within the Onaping Formation, including intrusive rocks (Peredery 1972a, 1972b; Paakki 1990; McKinley 1992), mineralization (Chubb 1990; Drake 1992), geochemistry (Ding and Schwarcz 1983; Schandl et al. 1986; McKinley 1992), geology, geochemistry, stratigraphy and mechanisms of emplacement (Gibbins 1994) and alteration (Ames et al. 1995 and Ames et al. 1996). A brief summary of the Onaping Formation is presented by Dressler et al. (1991) in an overview of the Sudbury Structure.

Detailed descriptions of the Onwatin and Chelmsford formations are contained within Coleman (1905), Burrows and Rickaby (1930), Martin (1957), Thomson (1957), Williams (1957), Sadler (1958), Cantin (1971), Cantin and Walker (1972), Rousell (1972, 1984a), Beales and Lozej (1975), Arengi (1977), and Vezina (1992). Mineralization in the Whitewater Group has been discussed by Burrows and Rickaby (1930), Martin (1957), Desborough and Larson (1970), Card and Hutchinson (1972), Arengi (1977), Rousell (1983, 1984b), Davies et al. (1990), Whitehead et al. (1990), and Paakki (1992), Gibbins (1994) and Gray (1995). The structural geology of the Whitewater Group has been addressed by Martin (1957), Rousell (1984c), Cowan and Schwerdtner (1990), Shanks and Schwerdtner (1991), and Milkereit et al. (1992).

SUDBURY STRUCTURE

The Sudbury Structure is composed of, in ascending stratigraphic order, brecciated footwall rocks, the Sudbury Igneous Complex, and the Whitewater Group.

Brecciated Footwall Rocks

Breccias in the footwall are divided into two types: Sudbury Breccia and Footwall Breccia. Their origin is a subject of considerable debate (Dressler et al. 1991).

Sudbury Breccia bodies (pseudotachylites) occur within all footwall rocks that predate the Sudbury Structure-forming event, and extend as far as 80 km away from the SIC, but are most abundant in a 10 km wide zone that surrounds the SIC (Dressler 1984a). The breccias form sub-vertical irregular dyke-like bodies ranging in size from a few millimetres to zones 0.5 by 11 km in size (Dressler 1984a). The matrix of Sudbury Breccia is gray or black and consists of microscopic, weakly recrystallized rock (Dressler 1984a). Large fragments, predominantly of the host rock, are rounded, the smaller ones are more angular (Dressler et al. 1991). Igneous textures, amygdules, and flow banding are not uncommon. Contacts with surrounding host rocks are sharp. Sudbury Breccia dykes cutting across other Sudbury Breccia dykes, and fragments of Sudbury Breccia within Sudbury Breccia have been observed (Dressler et al. 1991). The Sudbury Breccia

is interpreted to have formed by sudden, explosive brittle failure leading to a violent milling and crushing process that involved little or no melting (Dressler 1984a).

The Footwall Breccia, also described as "late granite breccia" and "leucocratic breccia" (Langford 1960; Souch et al. 1969; Greenman 1970; Pattison 1979; Muir 1981, 1983; Dressler 1984a; Lakomy 1986, 1989), occurs as sheet-like bodies up to 150 m thick, parallel to the contact with the base of the SIC, and hosts much of the Ni - Cu ore in the North Range (Dressler et al. 1991). Contacts with the overlying SIC are sharp, whereas contacts with the underlying footwall rocks are gradational (Pattison 1979). The matrix of the Footwall Breccia is light coloured with granoblastic and granophyric textures. Fragments of variable size and lithology are derived from the local footwall (Dressler et al. 1991). Dressler et al. (1991) interpreted the Footwall Breccia to be a mass of crushed and shock-metamorphosed rocks, similar to Sudbury Breccia, that formed along the walls of the original endogenic-volcanic or meteorite crater, before the deposition of the lower Onaping Formation and the intrusion of the Sudbury Igneous Complex.

Sudbury Igneous Complex

The Sudbury Igneous Complex (SIC) is subdivided into Sublayer (Contact Sublayer and Offset Sublayer) and the Main Mass (norites, quartz gabbros, and granophyres) (Pye et al. 1984). In plan view, the SIC is elliptical in shape with a long axis of 60 km and a short axis of 27 km. Seismic reflection data (Milkereit et al. 1992), albeit limited to one cross-section, shows the three-dimensional shape of at least the north half of the Sudbury Igneous Complex to be similar to a sheet-like sill, rather than a funnel-shaped intrusion as previously suggested by, amongst others, Wilson (1956); Naldrett and Kullerud (1976).

The Sublayer, a fine- to medium-grained mafic to intermediate rock (quartz diorite - norite) occurring at the base of the Sudbury Igneous Complex (Contact Sublayer) and as dykes in the surrounding country rocks (Offset Sublayer), is host to much of the Ni - Cu sulphide ores of the Sudbury Structure (Dressler et al. 1991). The Contact Sublayer and Offset Sublayer have been described in detail by Naldrett et al. (1984) and by Grant and Bite (1984), respectively. Dressler et al. (1991) provided evidence that at least some of the Sublayer post-dates the Main Mass of the SIC.

The Main Mass of the Sudbury Igneous Complex is subdivided into a Lower, Middle and an Upper zone (Pye et al. 1984; Dressler 1984b). The lower zone consists of mafic and felsic norites, the Middle Zone consists of quartz gabbro, and the Upper Zone of granophyres. The contacts between these major phases are gradational (Dressler et al. 1991). The granophyres of the Upper Zone have been divided by Peredery and Naldrett (1975) into an early plagioclase-rich phase and a contemporaneous to slightly later "normal" phase. The SIC does not exhibit fine-scale layering common to other large, mafic igneous complexes such as the Bushveld Complex. The rocks of the Sudbury Igneous Complex are also unique in being abnormally rich in normative SiO_2 and K_2O . This observation led Irvine (1975) and Naldrett and Macdonald (1980) to suggest that the Sudbury Igneous Complex represented a magma strongly contaminated by silica-rich country rocks.

Naldrett and Hewins (1984) summarized much of the published literature on the Main Mass of the Sudbury Igneous Complex, and stated that three main models have been proposed for the Igneous Complex (Dressler et al. 1987). These are: 1) the Complex is a folded differentiated sill; 2) both the norite and granophyre intruded separately as ring dikes, and 3) the Complex is a funnel shaped intrusion. These three models require an initial cataclastic fracturing of the earth's crust with the formation of a crater into which a basic magma, rising from depth (possibly from a reactivated Nipissing magma chamber), intruded and formed the SIC. The Main Mass of the Sudbury Igneous Complex has also been interpreted to be the clast-free component of a melt sheet, formed *in situ* by meteorite impact (Faggart et al. 1985; Brockmeyer 1990; Grieve et al. 1991).

The upper contact of the SIC with the overlying Onaping Formation has been described as exhibiting both gradational and sharp intrusive contact relationships (Dressler et al. 1991).

Whitewater Group

The Proterozoic Whitewater Group consists of, in ascending stratigraphic order, a conformable sequence of initially glass-rich breccias and melts of the Onaping Formation, carbonates and gray argillites of the Vermilion Formation, carbonaceous argillites and siltstones of the Onwatin Formation, and wackes of the Chelmsford Formation.

Onaping Formation

The Onaping Formation is the lowermost formation of the Proterozoic Whitewater Group. The formation consists of a 1400 m thick succession of initially glass-rich breccias and igneous-textured rocks within the Sudbury Basin (53 by 17 km). Rocks of the Onaping Formation are underlain by intrusive granophyres of the Upper Zone of the Sudbury Igneous Complex and are conformably overlain by carbonates and argillaceous rocks of the Vermilion and Onwatin Formations. The Onaping Formation is the stratigraphic footwall to the carbonate-hosted Vermilion and Errington Zn-Cu-Pb-Au-Ag deposits that are found in the south-west quadrant of the Sudbury Basin (Figure 1). Coeval with the Sudbury Event, the Onaping Formation has been interpreted as a meteor impact fallback breccia or a volcanic deposit.

The Onaping Formation consists of 3 major units that are discontinuous around the Sudbury Basin; from the base upward, they are the Basal Intrusion, the Sandcherry Member and the Dowling member (Gibbins 1994). These are different subdivisions than described by other workers. Figure 2 illustrates correlative nomenclature used in this paper and most recent previous workers. Previous workers, such as Muir and Peredery 1984; Grieve et al. 1991; Avermann 1992; Avermann and Brockmeyer 1992, subdivided fragmental rocks of the Onaping Formation into a lower Gray Member, an upper Black Member, and a middle Green member, distinguished, as their names suggest, by colour. The same authors subdivided the igneous- and fluidal-textured rocks of the Onaping Formation into Basal member and Melt Bodies. Table 1 summarizes the nomenclature and stratigraphic subdivision used by previous workers.

Stratigraphic subdivision of the Onaping Formation breccias by Gibbins (1994) using a systematic, non-genetic, detailed mapping approach based on Fisher's classification of fragmental rocks (Fisher 1966), in conjunction with standard bedrock mapping criteria and detailed morphological examination of 'glass' fragments, showed that carbonaceous material within the matrix of the breccias is not time stratigraphic and is, therefore, not a viable criterion for the stratigraphic subdivision of the Onaping Formation. Gibbins (1994) noted a pronounced stratigraphic difference in the percentage, size and type of fragments (Figure 3), the morphology of glass shards, and in the mechanisms of emplacement for the various depositional units that were delineated. Based on these differences Gibbins (1994) proposed a revised stratigraphic classification scheme for the Onaping Formation that is not based on colour (i.e. carbon content) (Figure 4).

In the Dowling area, the Onaping Formation is a 1400 m thick succession of devitrified glass-rich breccias and hypabyssal intrusions that dips gently at 25° towards the interior of the Sudbury Basin and strikes parallel to the contact with the Sudbury Igneous Complex. According to Gibbins (1994), the succession consists of (1) a coarse, shard-rich, matrix-poor, lower Sandcherry member, that is subdivided into Fluidal Fragment-rich and Shard-rich units, (2) a finer, shard-poor, matrix-rich upper Dowling member, that is subdivided into Lower, Middle and Upper Units, and (3) coeval intrusions, referred to as sheet-like and pipe-like bodies of Basal Intrusion and Aphanitic dykes (Figures 4 and 5). The contact between the Sandcherry and

PRESENT PAPER	PAST STUDIES								
GIBBINS (1997)	AVERMANN & BROCKMEYER (1992)	MUIR & PEREDERY (1984)	MUIR (1983, 1981)	PEREDERY (1972a, 1972b)	STEVENSON (1961, 1972)	THOMSON (1957) WILLIAMS (1957)	BURROW & RICKABY (1930)	COLEMAN (1905)	BELL (1893)
Dowling Member									
Upper and Middle Units	Upper Black Member	Black Member	Black Member	black Onaping	black tuff	andesite tuff, tuff-breccia			
Lower Units	Lower Black Member Green Member						volcanic tuff, flow breccia		siliceous volcanic breccia
Sandcherry Member	Gray Member	Gray Member	Green Member	gray Onaping	grey tuff	lapilli-tuff, glowing avalanche deposits		pyroclastic sediments	
Shard-rich & Fluidal Fragment-rich Units									
Basal Intrusion									
Pipe-like Bodies	Melt Body	Melt Body	Grey Member	melt rock melt body	pepper-and- salt micro- pegmatite (chilled)	andesite with rhyolite fragments	lavas	part of Trout Lake Conglomerate (with igneous- looking matrix)	(unspecified)
Sheet-like Bodies	Basal Member	Basal Member	Basal Member	basal breccia	quartzite breccia (tectonic)	rhyolite, rhyolite breccia	rhyolite, agglomerate	Trout Lake Conglomerate	quartzite conglomerate

Table 1: Nomenclature - Present and Past (after Muir and Peredery 1984)

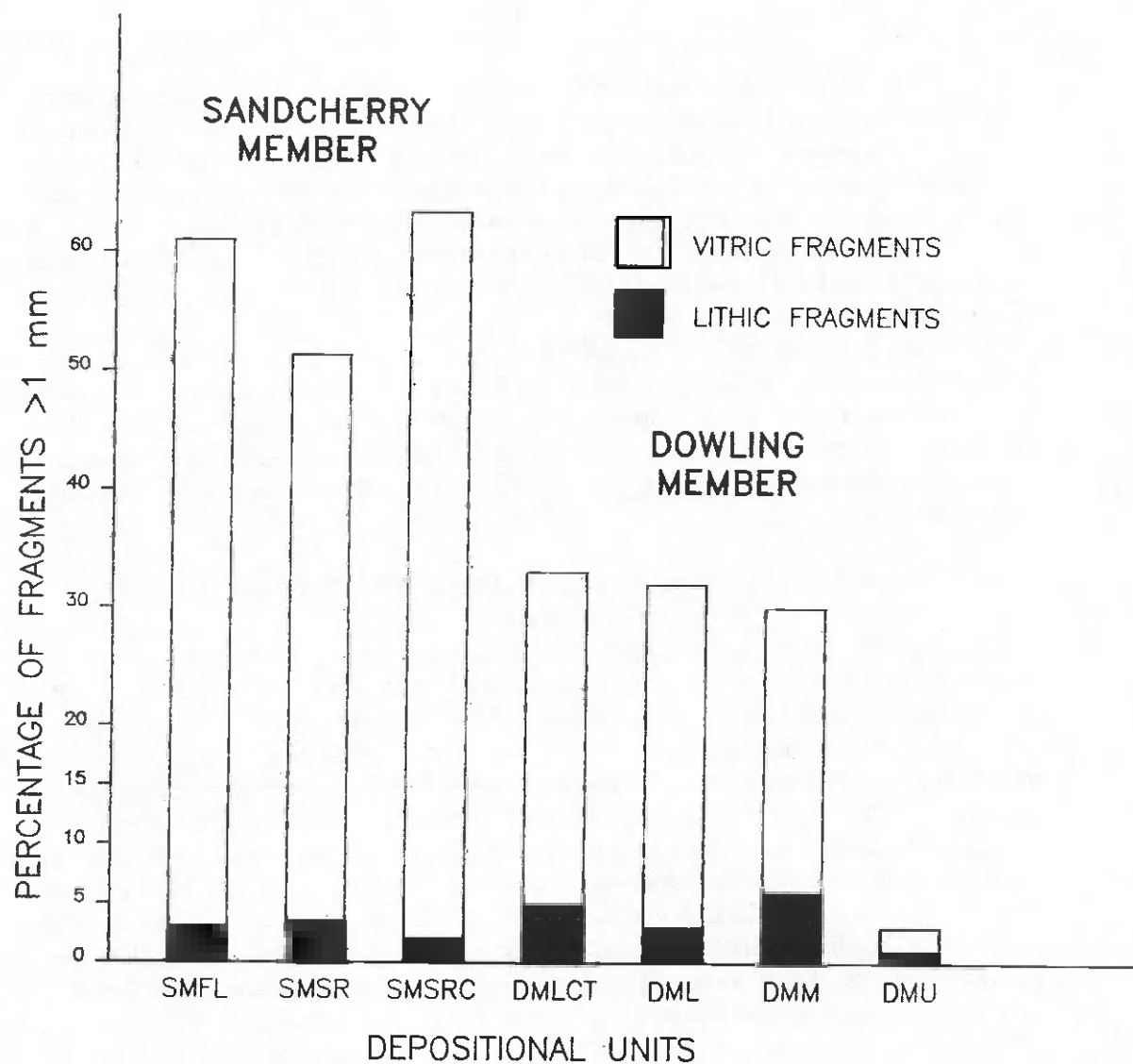


Figure 3:

Average percentage of juvenile and basement lithic fragments greater than 1 mm in size in the fragmental units of the Onaping Formation (SMFL = Fluidal Fragment-rich units of Sandcherry Member, SMSR = Shard-rich units of Sandcherry Member, SMSRC = Conductive Shard-rich units of Sandcherry Member, DMLCT = Lower Contact Unit of Dowling member, DML = Lower units of Dowling Member, DMM = Middle units of Dowling Member, DMU = Upper units of Dowling Member. (after Gibbins 1994)

Dowling members marks a rapid stratigraphic change in the percentage of matrix, morphology and size of shards, percentage of lithic fragments, and depositional character of units.

The following detailed description of the Onaping Formation is based on work presented by Gibbins (1994).

Sandcherry Member

The Sandcherry member (an average of 250 m thick) is distributed along the base of the Onaping Formation and is subdivided into Fluidal Fragment and Shard-rich Units (Figure 5).

Sandcherry member rocks contain at least 60% fragments (>1 mm in size), that are predominantly altered "andesitic" glass shards with approximately 5% lithic, basement fragments (Figure 4). Glass shards within the Sandcherry member are weakly vesiculated (<15% vesicles) and of two predominant types: (1) equant, blocky shards (average <1 x 1 cm in size), characteristic of Shard-rich Units and (2) tabular to ribbon, flow banded (fluidal), lapilli-sized shards, characteristic of Fluidal Fragment Units.

Sandcherry member units, as defined by mapping, are massive, extremely poorly bedded, laterally discontinuous (<3 km), irregular-shaped breccia deposits that range in thickness from 50 to 350 m. Contacts between units are characteristically gradational, may be conformable or discordant, and commonly represent a facies-like change. The Sandcherry member encompasses both carbon-poor and carbon-bearing units. Where carbon-bearing, the matrix of the units is conductive.

Fluidal Fragment Units (SMFLa, SMFLb, SMFLc, SMFLtr) - 2a, 2b, 2c, 3

Fluidal Fragment Units comprise four distinct map units (Figures 6 and 7) based on the percentage and size of fragments that characteristically contain a prevalence (50 - 90%) of tabular to ribbon, flow banded shards, lapilli, blocks and bombs (fluidal fragments) of aphanitic 'andesite', a relatively minor amount of white, equant, blocky shards (0.5 - 1.0 cm in size), and an extremely low percentage of fine ash-sized matrix material. The matrix ground mass consists primarily of increasingly diminutive shards of the same flow banded aphanitic 'andesite'. The units may also contain up to 5% dark green chlorite-actinolite fragments, 2 - 10% lithic fragments and blocks, and 3% composite fragments of other Sandcherry member units. Fluidal Fragment Units are massive, non-bedded, dense, coarse, fluidal fragment-rich breccias. The four units (autobreccia, lapillistone, lapilli-tuff, and transitional) are differentiated based on clast size and percentage and represent a continuous sequence from coarse, semi-massive, flow-banded, 'andesite' autobreccia through to tuff-sized material of similar composition. The transitional unit (SMFLtr) is a hybrid unit containing fluidal fragments as well as equant, blocky shards that are characteristic of the Shard-rich Units, described below. The transitional unit is included within this subgroup due to the abundance of fluidal fragments.

Fluidal Fragment Units are commonly spatially associated with Aphanitic dykes and bodies of Basal Intrusion and when grouped together represent "Fluidal Breccia Complexes". Fluidal Breccia Complexes typically are several hundred metres to kilometres in size, and are found throughout the strata of the Sandcherry member (sometimes "stacked"), but are more common towards the base. Fluidal Fragment Units are conformable with other fragmental units (including carbon-bearing tuffs), but also intrude discordantly through them.

Shard-rich Units (SMSRa, SMSRb, SMSRc, SMSRC) - 4a, 4b, 4c, 5

The Shard-rich Units consist of four mappable units that are distinctive from the Fluidal Fragment Units (Figures 6 and 7). Characteristic of the Shard-rich Units is the prevalence of 40 -

85%, moderately well sorted, white to pinkish-white, equant, blocky shards, (<1 x 1 cm in size) within a fine ash-sized microcrystalline light green matrix. Where carbonaceous material occurs within the matrix of the Shard-rich Units, the matrix is dark gray to black and conductive. The Shard-rich units also contain up to 15% cored bombs, <10% fluidal fragments, 1-5% accretionary lapilli, <5% lithic fragments, and up to 5% composite fragments of other Sandcherry member units. The Shard-rich Units are distinguishable from the Fluidal Fragment Units by the occurrence of moderately well sorted blocky white shards within a fine matrix.

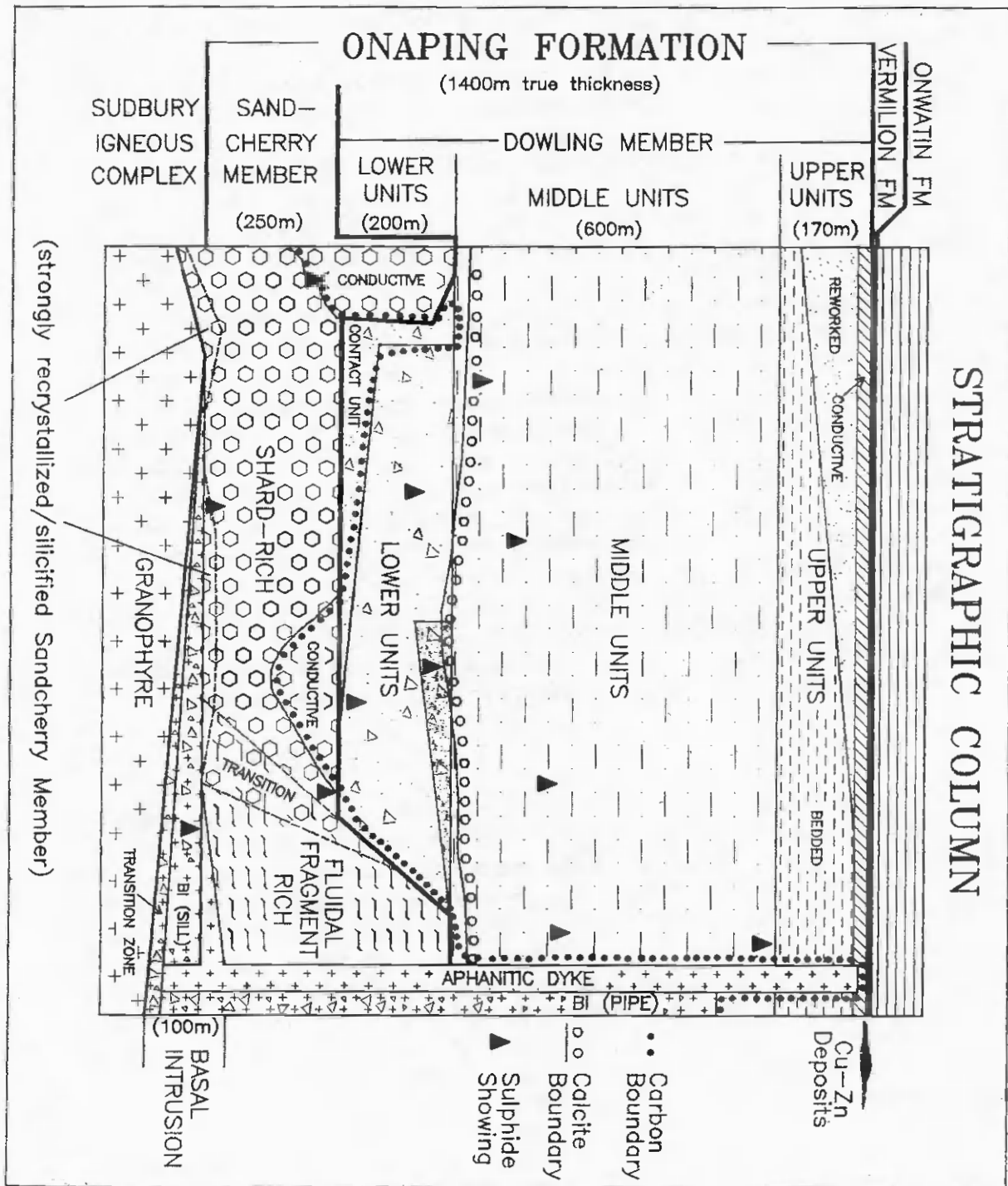
Non-carbonaceous Shard-rich Units were mapped as lapillistones, lapilli-tuffs or tuffs, depending on the size and percentage of fragments. Carbonaceous (black matrix), predominantly conductive Shard-rich Units were mapped as SMSRC (Unit 5). Except for the occurrence of carbon throughout the matrix, this unit is lithologically the same as the other Shard-rich units. Contacts between carbonaceous and non-carbonaceous Shard-rich Units are gradational. The Shard-rich Units are thick, conformable, laterally continuous (several km) sheet-like depositional units of massive, non-bedded, densely packed, originally glass-rich breccias. The units may locally have a bomb- and block-rich-base, and/or a finer top. The units are situated throughout the strata of the Sandcherry member and appear locally to pinch and swell along strike. Shard-rich Units overlie, underlie, are intruded by, and grade laterally into Fluidal Fragment Units of the Sandcherry member. Generally, the Shard-rich Units mark the top of the Sandcherry member.

Interpretation

Shards characteristic of the Fluidal Fragment Units formed by relatively passive fragmentation processes (auto-brecciation) caused by the interaction of melt with surrounding water and/or "wet" (water-rich) breccias. Emplacement and deposition of the Fluidal Fragment Units varied from repeated shallow level intrusion and auto-brecciation to explosive eruptions characterized by submarine and subaerial fountaining and spattering. Passive fragmentation appears to have been widespread along the base of the Sandcherry member, where Fluidal Fragment Units occur as "crusts" to underlying bodies of Basal Intrusion, and also higher up section where Aphanitic dykes and pipe-like bodies of Basal Intrusion intruded wet breccias and auto-brecciated. The Fluidal Fragment Units were emplaced contemporaneously with the Shard-rich Units of the Sandcherry member as both discordant, brecciated intrusive bodies and conformable interbedded units. Contacts between these two Units, where gradational, are represented by LMFLtr, a transitional unit. Emplacement of Fluidal Fragment Units continued during and after the deposition of the Lower Units of the Dowling member. In conjunction with the Basal Intrusion and Aphanitic Dykes, the Fluidal Fragment Units record a complex history of continued multiple intrusion, auto-brecciation, and explosion and may spatially represent "vent" areas within the Onaping Formation. The emplacement and deposition of Fluidal Fragment Units are interpreted to be similar to the emplacement of (1) peperites described by Hanson and Wilson (1993), (2) intrusive hydroclastic breccias described by Hanson (1991), and/or (3) vent-facies deposits of hyaloclastic eruptions on seamount summits, described by Smith and Batiza (1989) (Figures 8, 9, and 10).

The Shard-rich Units of the Sandcherry member are interpreted to have formed from the same melt that formed the Fluidal Fragment Units. The Shard-rich Units are the result of more explosive interaction and eruption of large volumes of predominantly juvenile material comprising mostly equant, blocky shards and fine ash-sized material. The Shard-rich Units were deposited throughout the Sandcherry member strata and are the explosive products of the repeated emplacement and brecciation of melt into its own breccia pile. The occurrence of accretionary lapilli indicate that eruption columns associated with the deposition of the Shard-rich Units were, in part, subaerial. The shard-rich Units were deposited rapidly as voluminous, essentially non-bedded, dense (high particle concentration), subaqueous "pyroclastic" falls of slurry-like hyaloclastic flows that likely sloughed contemporaneously down slope as mass flows. The

Figure 4: Stratigraphic column and subdivision of map units of the Onaping Formation, Sudbury Structure (after Gibbins 1994)



ONAPING FORMATION Dowling Area

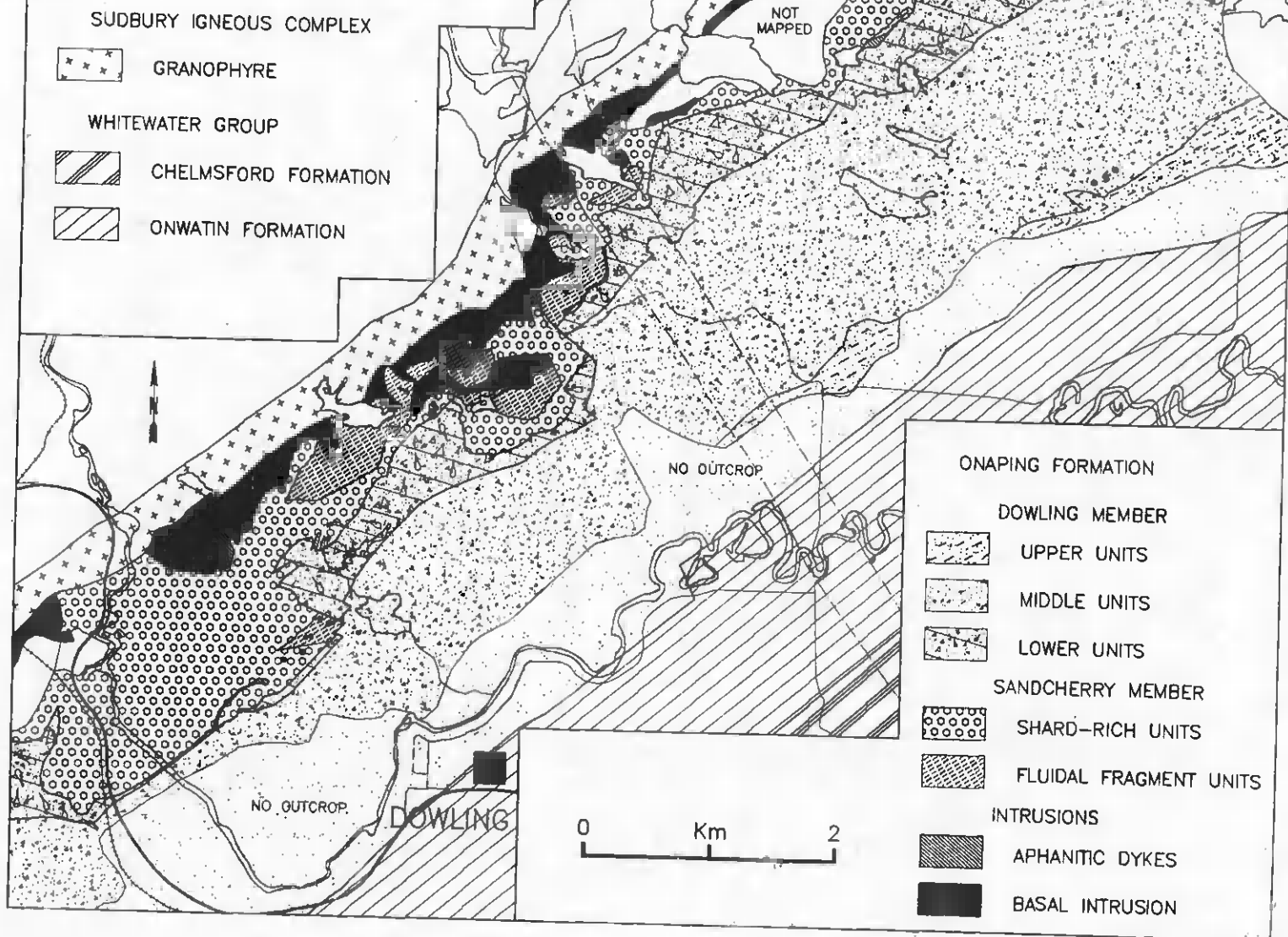


Figure 5:

Geology of the Onaping Formation of the Sudbury Structure

MIDDLE PROTEROZOIC

16 Diabase Dykes (1245–1480 $\pm$ 130 Ma)

EARLY PROTEROZOIC

SUDBURY IGNEOUS COMPLEX (1849.6 $\pm$ 3.4/–3.0 Ma)

15 GRANOPHYRE

WHITEWATER GROUP

CHELMSFORD FORMATION

14 Arkosic to lithic arkosic sandstones (wackee), minor mudstones

ONWATIN FORMATION

13 Black carbonaceous argillites, minor siltstones

ONAPING FORMATION

INTRUSIONS

12 APHYDYLK – APHANITIC DYKES (commonly flow banded, xenolith-poor)

11a BASAL INTRUSION (medium to fine-grained, commonly xenolith-rich)
Bia – Sheet-like bodies

11b B1b – Border phase with Granophyre

11c B1c – Pipe-like bodies

DM–DOWLING MEMBER (lenticular to plate-like shards¹, >80% matrix²)

UPPER UNITS (reworked, black carbonaceous matrix)

10 DMUc – Conductive fine tuff, <3% lapilli-sized fragments (noted in drill hole only)

9b DMUb – Fine tuff, <3% lapilli-sized fragments

9a DMUa – Bedded tuff, interbeds of UMUB and UMMC

MIDDLE UNITS (<3% black-sized fragments, carbonaceous matrix)

8a DMMa – Lapillistone

8b DMMb – Lapilli-tuff

8c DMMc – Tuff

LOWER UNITS (Matrix is locally non-carbonaceous; >3% black-sized fragments)

7a DMLa – Lapillistone/Tuff Breccia

7b DMLb – Lapilli-tuff

7c DMLc – Tuff

6 DMLCT – Contact Unit – Tuff/Lapilli-tuff, subtidal texture, fine matrix, <10% fragments >2cm, locally black³ and bomb⁴-rich base

SM–SANDCHERRY MEMBER (<40% matrix)

SHARD-RICH UNITS (equant, blocky shards)

5 SMSRC – Conductive lapilli-tuff, grades locally to lapillistone and tuff, black carbonaceous matrix (locally non-conductive), <3% accretionary lapilli

4a SMSRa – Lapillistone, non-carbonaceous matrix

4b SMSRb – Lapilli-tuff, non-carbonaceous matrix

4c SMSRc – Tuff, non-carbonaceous matrix

FLUIDAL FRAGMENT UNITS (fluidal, ribbon-like, flow banded fragments common, rarely and locally black carbonaceous matrix)

3 SMFLtr – Lapilli-Tuff/Tuff, <15% fluidal fragments >8cm in size, equant, blocky shards also evident, "transitional" unit between "shard-rich" units and "fluidal fragment" units

2a SMFLa – Autobreccia, <20% matrix, block- and bomb-rich

2b SMFLb – Lapillistone

2c SMFLc – Lapilli-tuff

UNDEFINED UNITS (lower units, significant matrix recrystallization and pervasive silicification)

1a SM—— – Tuff-breccia

1b SM—— – Lapillistone

1c SM—— – Lapilli-tuff

Lower case letters (a, b, c) in unit codes do not necessarily denote time stratigraphic order.

Figure 6: Detailed legend and stratigraphic subdivision of the Onaping Formation of the Sudbury Structure (after Gibbins 1994)

CLASSIFICATION TERMS USED HEREIN ARE
NON-GENETIC TERMS TO DESCRIBE FRAGMENTAL ROCKS

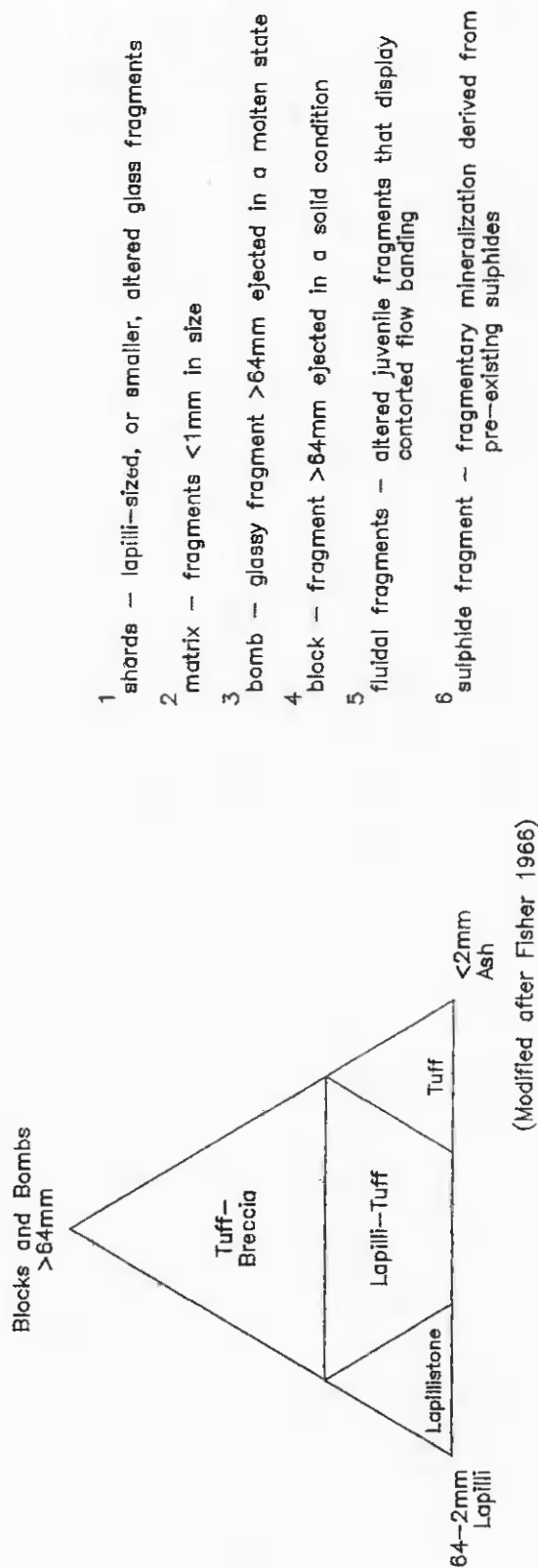


Figure 7:

Classification scheme and terms used in the detailed legend and stratigraphic subdivision of the Onaping Formation of the Sudbury Structure (Figure 6) (after Gibbins 1994).

hyaloclastic debris was likely deposited quenched or cool, as there is no evidence of welding. Fire fountaining, ejection of bombs, and explosive fragmentation of ash-, lapilli- and block-sized material (juvenile, lithic and composite) were ongoing processes during deposition. Emplacement of the Shard-rich Units is interpreted to be similar to hyaloclastic flows on seamount summits, described by Smith and Batiza (1989) (Figure 8). The source of the Shard-rich Units is interpreted to be the same vent sites as for the Fluidal Fragment Units. Eruption and emplacement of both the Shard-rich and Fluidal Fragment Units occurred contemporaneously; the two Units likely represent different vent facies of the same eruptive process that varied in effusion rates and explosivity with time. Unit LMFLtr likely is the product of both the eruption mechanisms characteristic of the Fluidal Fragment and Shard-rich Units.

The Sandcherry member was emplaced due to fragmentation and eruption processes that involved both passive and explosive interaction of water with melt, that was repeatedly emplaced into its own breccia pile. If there was a meteorite impact, "fallback" is not represented by the Sandcherry member, but is possibly represented by some components of the Basal Intrusion (i.e. lithic xenoliths).

Dowling Member

The Dowling member comprises the upper 75% (1000 m) of the Onaping Formation, and consists of at least 10 glass-rich, weakly bedded, fragmental units that are grouped into Lower, Middle, and Upper Units (Figures 5, 6 and 7). Units of the Dowling member define uniform, laterally continuous deposits that characteristically consist of more than 60% fine ash-sized material (matrix) and are essentially carbonaceous, with the exception of the lower Contact Unit (DMLCT - Unit 6)

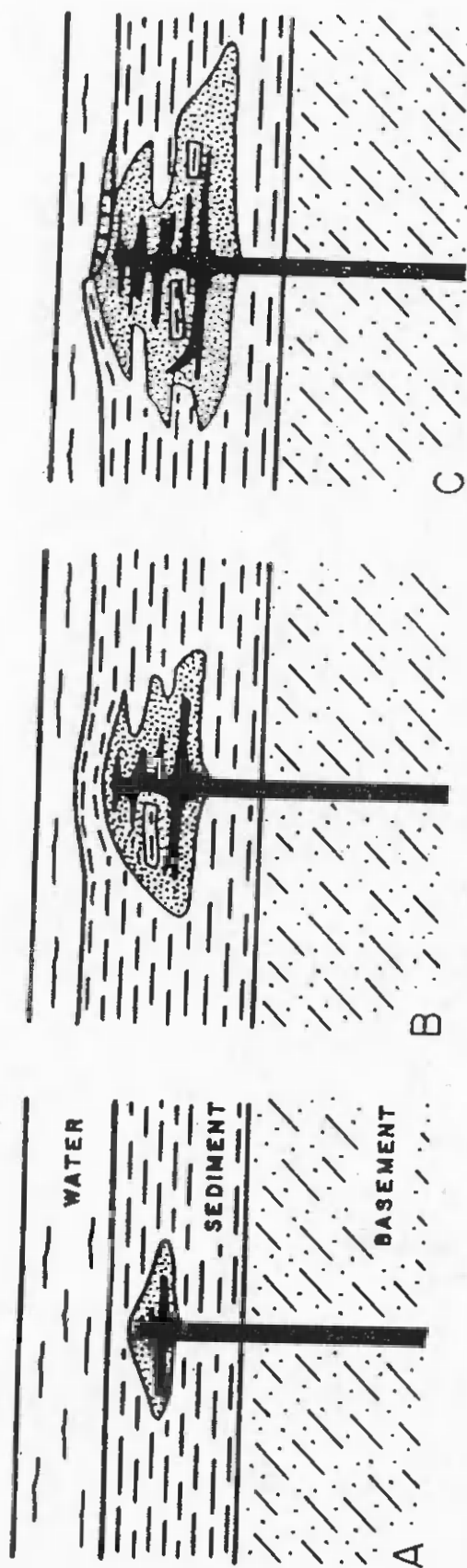
Dowling member rocks contain less than 40% fragments (>1 mm in size) that are predominantly altered "andesitic" glass shards with approximately 15% lithic fragments (Figure 4). Glass shards of the Dowling member, compared to shards of the Sandcherry member, are smaller, contain fewer, but larger vesicles, display less flow banding and have a more wispy, torn-looking, lenticular to plate-like shape. Dowling member depositional units are of considerable strike length (2 to more than 10 km), are uniform in thickness (25 - 300 m), and display conformable to unconformable erosional lower contacts. Sedimentary structures are evident towards the top of the Dowling member.

Lower Units of the Dowling Member

This subgroup of the Dowling member comprises four distinct map units, including the Lower Contact Unit (DMLCT - Unit 6), previously known as the "chloritic shard horizon" or "Green member". The Lower Units are distinguishable from Sandcherry member units essentially by a greater percentage of ash-sized matrix and different shard morphology, and from Middle Units of the Dowling member by the presence of block-sized fragments of country rock and 'andesite' bombs. Collectively, the Lower Units comprise a reverse graded package (increasingly coarser units up section) of thick, non-bedded, crudely channellized units. Individual depositional units are normally graded). The Lower Units have an average true thickness of 200 m, but range locally from less than 5 m to more than 300 m. The Lower Units were mapped as tuffs, lapilli-tuffs, and a considerably coarser lapillistone to tuff breccia.

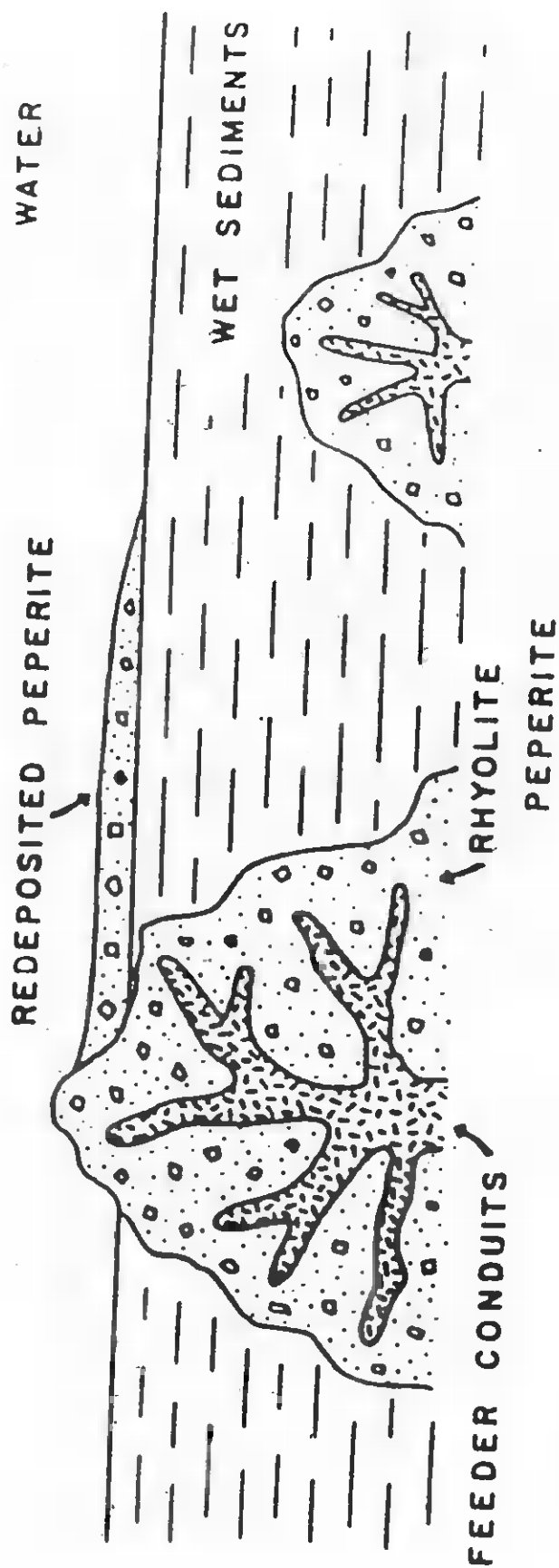
Contact Unit (DMLCT) - 6

The most distinguishing feature of DMLCT unit is the predominance of 20 - 45% green to dark green chloritic shards (less than 5 mm in size) within a very fine matrix. The matrix is normally a pale bluish green, but may be dark gray to black due to fine carbonaceous material,



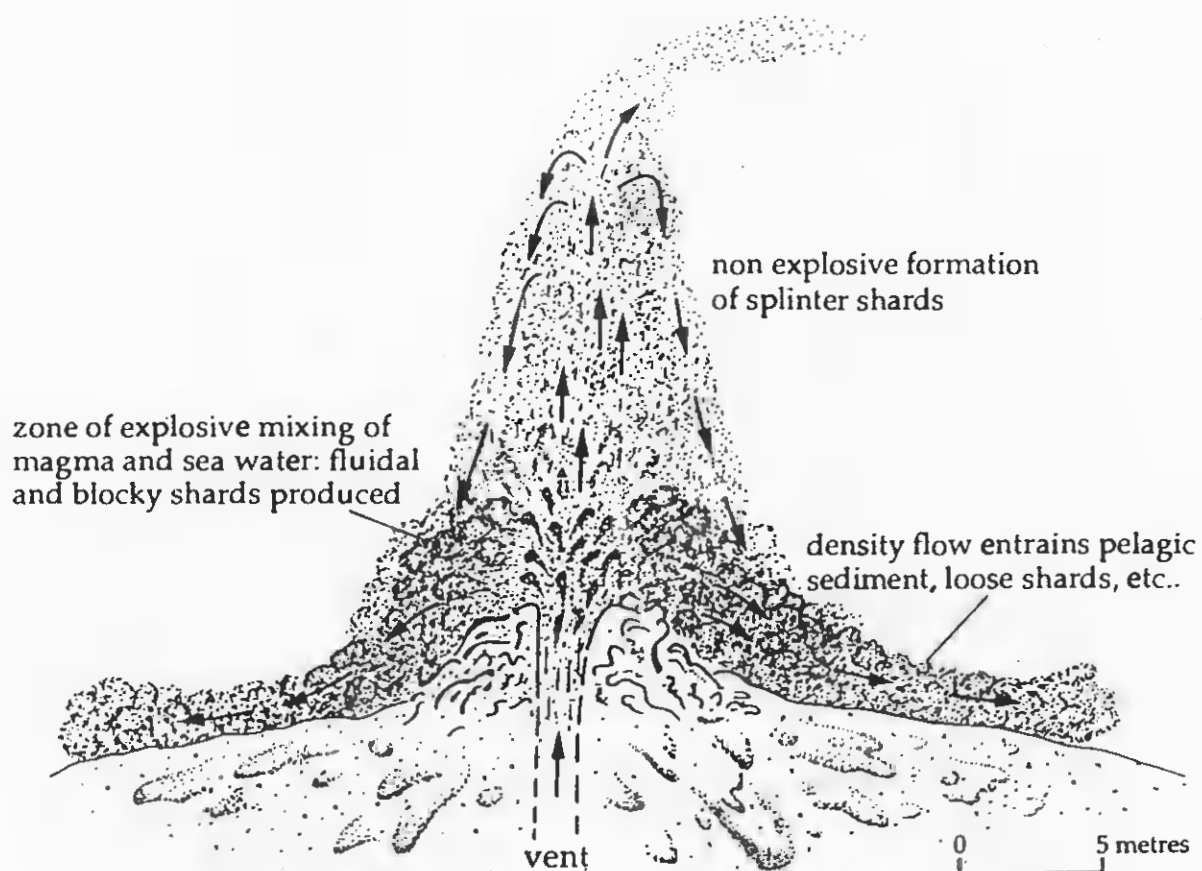
Schematic model for the development of intrusive hydroclastite breccias (Hanson 1991)

Figure 8:



Schematic model for the development of peperites (Hanson and Wilson 1993)

Figure 9:



Schematic diagram illustrating style of eruption envisioned to produce the hyaloclastite deposits on seamount summits (Smith and Batiza 1989)

Figure 10:

which usually occurs towards the top of the unit. The DMLCT Unit contains some (<15%) blocky shards similar to those characteristic of the Sandcherry member, but the majority are finer, angular glass splinters and plate-like shards. The unit commonly displays a eutaxitic-like texture (incipient welding), defined by the alignment of plate-like lenticular shards. Locally, flow features are visible around the margins of blocks and bombs. The unit also contains 5% fluidal lapilli, 5% bombs, <5% lithic fragments, and <3% composite fragments of Sandcherry member units,

This unit outcrops as discontinuous lenses up to several kilometres in length at the contact between the Sandcherry and Dowling members. The lower contact of the DMLCT Unit is commonly marked by an increase in percentage (5 - 45%) of blocks and bombs, 0.5 - 2 m in size, with respect to underlying units. Where a block- and bomb-rich base is not observed, the contact is gradational over a distance of 3 to 5 m and is indicated by a decrease upwards (in section) in shard size and percentage, as well as a change in shard morphology. The upper contact of the DMLCT Unit, though not typically observed, is sharp and marked by an increase (up section) in lapilli-sized fragments and an absence of eutaxitic-like textures. The Contact Unit may extend around the basin but the "welded texture" may only be developed where the unit was deposited above water. Elsewhere, the Contact Unit is not welded or compacted (not deposited hot) and looks like other Dowling member units that were deposited below water (subaqueous deposition). In other words, welding = subaerial deposition and non-welded = subaqueous deposition. Welding is a good paleoenvironment indicator.

The DMLCT Unit is the first stratigraphic occurrence containing depositional features characteristic of the Dowling member. Compared to underlying units of the Sandcherry member, the DMLCT Unit shows an increase in percentage of composite fragments, lithic fragments, bombs, and cored bombs (both simple and complex), locally having a block- and bomb- rich base that clearly separates this unit from underlying Shard-rich Units of the Sandcherry member.

Lower Units (DMLa, DMLb, DMLc) - 7a, 7b, 7c

Differentiated by size and percentages of similar fragments types, these three units, lapillistone to tuff breccia, lapilli tuff, and tuff, represent a discontinuous, crudely interlayered sheet that comprises the bulk volume of the Lower Units. Contacts between the various units are typically indistinct, but can be sharp. Lower contacts are locally channelized. Tuff (DMLc), where preserved, is commonly the lowest of the three units and usually directly overlies the DMLCT Unit (Unit 6). Lapillistone to tuff breccia (DMLa) is normally found near the top of the sequence, intercalated with lapilli-tuff (DMLb). Individually, the units are crudely, but normally graded. Together, the three units define a reversely graded sequence. The units are distinguished from the underlying DMLCT unit by a coarser appearance and the absence of eutaxitic textures in the matrix. Overlying units are better sorted, and lack coarse lapilli and block sized fragments.

The units normally have a dark gray to black carbonaceous fine ash-sized matrix, which represents more than 60% of the rock. The units also contain 15 - 25% wispy, lenticular to cusped shards, 5 - 95% flow banded, tabular and fluidal lapilli of aphanitic 'andesite', 3 - 40% bombs, cored bombs and blocks of aphanitic, poorly vesicular 'andesite', 5 - 10% lithic fragments and blocks, and up to 10% composite fragments of underlying Sandcherry and Dowling member units. Rare discontinuous lenses of fine tuff are locally interbedded with the coarser units. Bedding or layering is not evident at the outcrop scale.

Middle Units (DMMa, DMMb, DMMc) - 8a, 8b, 8c

The Middle Units of the Dowling member consist of similar, thick depositional units of tuff, lapilli-tuff and lapillistone. The three map units that comprise the Middle Units are different only in the percentage of lapilli-sized, dark, chloritic shards and lithic fragments. The units represent the majority (>60%) of the Dowling member, and collectively average 600 m in true

thickness. Contacts with underlying DML Units and overlying DMU Units are mostly gradational. Middle Units are distinguished in the field from underlying DML Units by the absence of block-sized lithic fragments and bombs. Overlying DMU Units are finer grained and more distinctly bedded.

DMM Units contain more than 65% matrix, mostly dark gray to black due to presence of carbonaceous material. The units also contain 15 - 35% wispy, lenticular to cusped shards, 1 - 5% equant, flow banded 'andesite' fine lapilli-sized fragments, <7% lithic fragments (<4 cm in size) and 2 - 8% shiny, dark, rounded quartz grains, <1-2 mm in size. Shards in DMM Units display similar features to shards contained in underlying DML Units. Some shards appear to be coated or surrounded by fine ash-sized material and carbonaceous material. Composite blocks and irregular clumps of coarser and finer underlying breccia units are contained in DMM Units.

Upper Units of the Dowling Member

This subgroup of the Dowling member marks the top of the Onaping Formation and is divided into three map units. In stratigraphic order DMU Units comprise a basal bedded tuff (DMUa - Unit 9a), a fine tuff (DMUb - Unit 9b), and an upper conductive, fine tuff (DMUc - Unit 10). Overall, DMU Units comprise a normally graded sequence that has an average true thickness of 170 m. DMU Units are much finer than underlying units (Figure 4), and display features suggestive of reworking and re-deposition.

Bedded Tuff - (DMUa) - 9a

This bedded tuff (DMUa) occurs at the transitional contact zone between DMM and DMU Units and contains alternating beds of material characteristic of both. DMUa is distinguished from underlying DMM Units by the first stratigraphic occurrence of laterally continuous, shard-poor, fine ash-sized interbeds intercalated with the relatively coarse tuffs and lapilli-tuffs that are characteristic of DMM Units.

DMUa consists of alternating coarse beds of Dowling member Middle Units and fine beds of Dowling member Upper Units. Individual beds vary considerably in thickness, but generally average 5 to 50 cm thick. The average thickness of DMUb beds increases upwards. DMUb beds consist of fine ash-sized fragments of juvenile and lithic material; fragments greater than 2 mm are uncommon. Normal grading within individual beds is absent to weakly developed; contacts between beds are sharp, with uncommon soft sediment slump features and small, channel-like structures.

Fine Tuff - (DMUb) - 9b

Contacts are conformable and gradational, marked by an absence of the DMM Unit-like interbeds common in the underlying DMUa (Unit 9a) and by a generally coarser appearance and lack of conductivity, compared to the overlying DMUc (Unit 10). DMUb is well sorted with greater than 95% of the material finer than 1 mm in size. Much of the fine ash material is sub-rounded lithic fragments and rounded (abraded) shards. Rare, larger altered glass shards may also occur. DMUb is locally inter-layered with beds of angular to rounded argillaceous and cherty fragments, less than 2 cm in size. Individual beds are commonly less than 40 cm thick, and may contain up to 80% of these dark gray to black fine sedimentary fragments. Many of the fragments give the impression of being rip-up clasts.

Conductive Fine Tuff - (DMUc) - 10

This conductive fine tuff (DMUc) was described by Paakki (1992) as "Conductive 'andesite' tuff". Conductivity is attributed to the presence of fine carbonaceous material. Lower contacts with underlying DMUa and DMUb are marked by a gradational fining and the onset of conductivity, associated with a stratigraphic increase in carbonaceous material. The upper contact with overlying sediments and carbonates of the Vermilion Formation is sharp and conformable. DMUc is visually distinguished from the similar looking Onwatin Formation by the absence of fine laminations and siltstone interbeds.

The upper 5 to 10 m of DMUc is black, fine, poorly bedded to massive, and strongly conductive. Towards the base of DMUc conductivity decreases and wispy lenses of lighter and slightly coarser, dark gray tuff become apparent.

Interpretation

The morphology and internal characteristics of shards within the Dowling member indicate that vesiculation (volatile exsolution) played a role, though a minor one, in the predominantly hydroclastic fragmentation and eruption of the Dowling member. The Dowling member Lower Contact Unit represents a deposit formed by fragmentation processes that changed from the relatively passive to moderate explosive generation of Fluidal Fragment Units (proximal, intrusive/extrusive auto-breccia deposits) and co-genetic Shard-rich Units (more widespread hyaloclastic deposits) to more explosive activity and basin-wide deposition of voluminous falls, flows and subsequent mass flows. Consistent with the greater explosivity is a fine grain size and minor (10%) enrichment in the lithic fragment content of depositional units. The Sandcherry member/Dowling member contact is suggestive of an evolving hydroclastic eruption that was initially relatively passive, but with time became more explosive.

The Contact Unit (the DMLCT Unit) is interpreted to have been deposited relatively hot, possibly in a subaerial to shallow subaqueous environment, and is incipiently welded (where deposited subaerially). The DMLCT Unit is the product of the explosive introduction of new melt at surface.

The majority of the Dowling member units are interpreted to have been deposited subaqueously as a prolonged, explosively erupted series of "pyroclastic" falls, flows and subsequent debris or mass flows. Nearly contemporaneous slumping and sloughing resulted in the transportation and re-deposition of tuffaceous material down slope in the form of pyro-turbidite and debris-like mass flows (Figure 11). Cored, aerodynamic bombs indicate that eruption columns were, in part, subaerial and associated with lava fountaining during the deposition of the Lower Units. Lower Units were deposited on fairly irregular paleo-topography as poorly sorted, channellized sheets of significant thickness. In contrast, the Middle Units are interpreted to have been deposited as a series of frequent, thin (1 - 10 m) "pulses" of generally better sorted, finer (block- and bomb-poor), possibly graded material; there is no evidence of significant sedimentary re-working. Deposition was rapid and mass slumping destroyed primary depositional features. The "pulses" are typical of hydroclastic explosions where water intermittently has access to melt. Deposition of the laterally continuous and uniform Middle Units of the Dowling member marks a change to a more tectonically stable depositional environment, compared to that of the Lower Units of the Dowling member. The Upper Units represent the final deposition of fine ejecta and subsequent sedimentary reworking.

Basal Intrusion

The Basal Intrusion is subdivided into three separate map units. These are (1) Sheet-like bodies (B1a), which occur as discontinuous sheets or sills, up to 300 m thick, at the base of the

Sandcherry member, (2) Pipe-like bodies (BIc), which occur as irregular- to ovoid-shaped intrusive masses within fragmental units of the Sandcherry and Dowling members (pipe-like bodies are commonly exposed in clusters, and range in size from less than 2 x 2 m to over 50 x 100 m), and (3) Border phase with Granophyre (BIb), which represents a transitional contact zone up to 65 m thick between sheet-like bodies of Basal Intrusion and Granophyre. The border phase was not noted where Granophyre and fragmental units of the Sandcherry member are in direct contact.

Sheet-like (BIa) - 11a and Pipe-like Bodies (BIc) - 11c

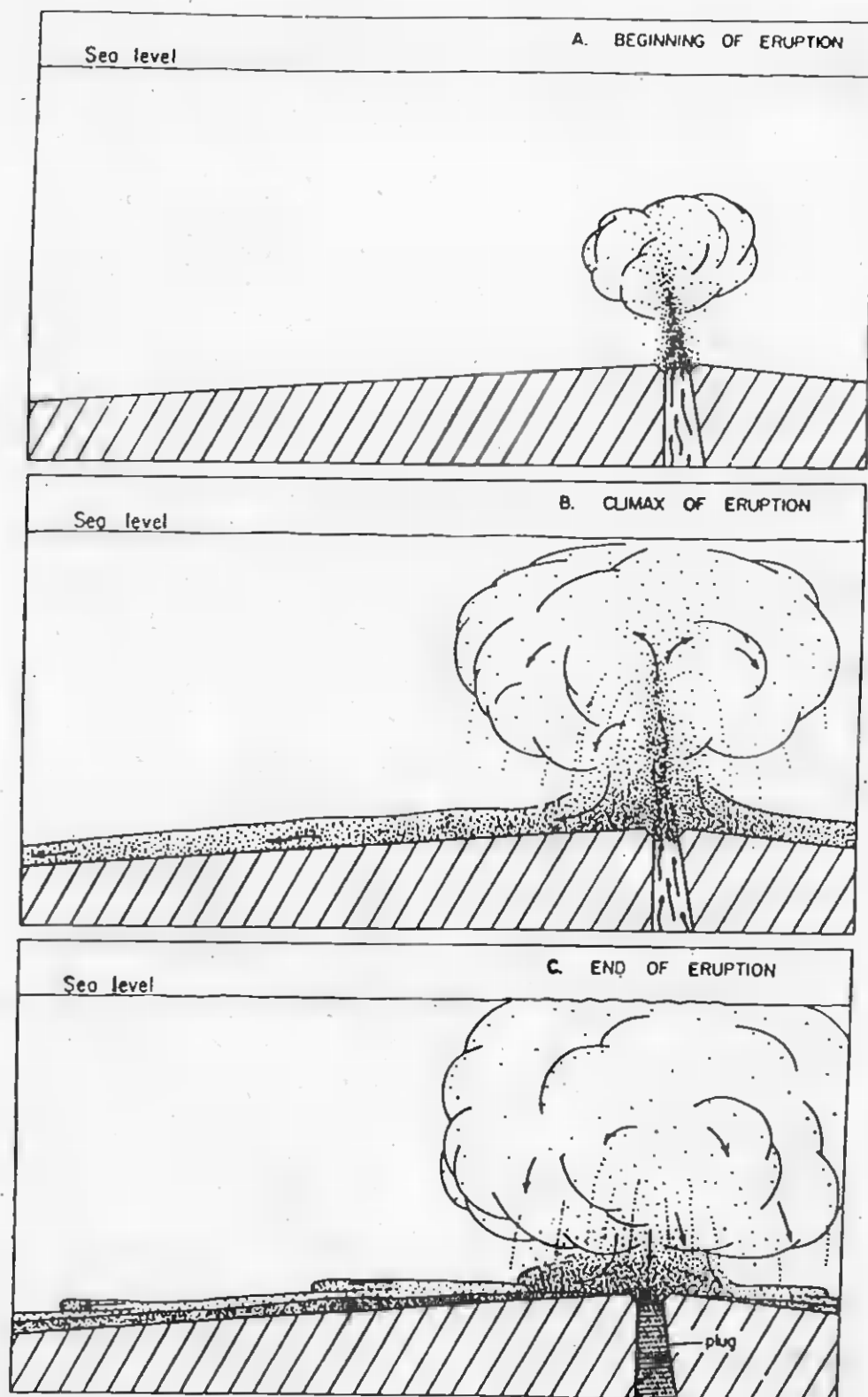
Sheet-like and pipe-like bodies of Basal Intrusion are igneous-textured phases of the same unit, and are different only in their morphology and stratigraphic level of exposure. The most distinguishing feature of the Basal Intrusion is 5 - 85% (ave. 35%) xenoliths of a variety of leucocratic basement rock types (quartzites, granitoids). Xenoliths are randomly oriented, subangular to rounded, sub-equant, and range in size from <5 mm to 30 m, but average 30 - 40 cm. Locally, xenoliths are well sorted and well rounded. The xenoliths decrease in size and are better sorted in bodies of Basal Intrusion exposed higher in strata. Pristine to corroded (melted) textures are common, with xenoliths showing minor bleaching, recrystallization, assimilation and/or partial melting, the last of which is demonstrated by embayments, rounded margins, cavities, apophyses, and annealed margins with other fragments. This "melting" indicates melting and assimilation at "depth" and then transportation to surface and this is further evidence of the Onaping melts being emplaced from below and not as fall back.

The matrix is medium greenish-gray, fine- to medium-grained, and has a massive, salt-and-pepper texture. Fine prisms of amphibole are typically visible in the coarser-grained bodies. Generally, there is a decrease in matrix grain size in intrusive bodies exposed higher in stratigraphy. Pipe-like bodies higher in strata also contain 5 - 10% quartz-, chlorite-, and/or sulphide-filled amygdulcs, that range from 2 - 5 mm in size.

Contacts with all but the Fluidal Fragment Units are intrusive, sharp, vertical to horizontal and usually obvious on outcrop surfaces. The large sheet-like bodies display chilled, fine-grained to aphanitic, xenolith-poor margins. The smaller pipe-like bodies generally have a thin chilled margin. Contacts with the Fluidal Fragment Units are gradational, marked by an aphanitic, brecciated and xenolith-poor margin. Where these brecciated contact margins are relatively large or extensive they have been mapped as Autobreccia (SMFLa). Contact relationships suggest emplacement of Basal Intrusion is contemporaneous with, pre-date and post-date the emplacement of the fragmental units. Locally, where the Basal Intrusion intrudes carbon bearing fragmental rocks, a 2 to 15 m contact zone of carbon-poor tuffs surrounds the intrusive body.

The Basal Intrusion is envisioned to represent an xenolith-bearing melt that intruded the fragmental rocks of the Onaping Formation. Bodies of Basal Intrusion were emplaced before, during, and shortly after, the deposition of the Sandcherry and Dowling members. During intrusion most of the fragmental units were unconsolidated and, at least locally, bodies of the Basal Intrusion are interpreted to be the melt source for the Fluidal Fragment Units (SMFL), in similar fashion to peperites.

Xenoliths within the Basal Intrusion are interpreted to be remnants of basement rocks. The variety of xenolith rock types indicates mixing of basement fragments before and during their assimilation into, or transportation by, the Basal Intrusion. Locally, xenoliths were rounded and sorted according to size before or during emplacement. Because of the high percentage of xenoliths and relative small size of the intrusions, partial melting of the xenoliths is interpreted to have occurred before incorporation into the intrusive bodies that transported them to their present site. Other xenoliths are fresh and unmelted, suggesting variation in melt temperatures or, more likely, in the timing of incorporation. The cataclastic event that formed the Sudbury Structure is interpreted to have formed the xenoliths, that are presently found within the Basal Intrusion, by



Schematic diagram of inferred submarine eruption
(Fiske and Matsuda 1964)

Figure 11:

brecciation of the basement rocks. The "melted" appearance of some xenoliths may be evidence of impact melting.

Border Phase of the Basal Intrusion (BIb) - 11b

BIb represents a gradational contact zone between Granophyre and bodies of the Basal Intrusion. BIb has features of both these units, in varying percentages. The contacts between the border phase of the Basal Intrusion (BIb) and both the sheet-like bodies of Basal Intrusion (BIa) and Granophyre are gradational over 1 - 5 m. Close to the Granophyre, the matrix of BIb is similar to Granophyre. The sole difference between the two being the presence of 5 - 10% xenoliths. Near the centre of BIb, the matrix is increasingly fine-grained, but commonly displays aggregates of coarser and/or finer crystals within it. Rare amphibole needles are visible. Lithic xenoliths account for 15 - 65% of the rock, and commonly have a mafic reaction rim that extends 2 - 7 mm into the surrounding matrix. Close to BIa, the matrix is fine-grained and homogeneous, and except for rare long needles of amphibole, is indistinguishable from BIa.

BIb is interpreted to be the lower border phase/contact zone of the sheet-like bodies of Basal Intrusion and Granophyre. No sharp intrusive contact between Granophyre and BIb has been noted. BIb may represent a zone of mixing between two nearly contemporaneous melts.

The Basal Intrusion has been described as a conglomerate (Coleman 1905), a rhyolite breccia (Thompson 1957; Williams 1957), a tectonic quartzite breccia (Stevenson 1972), a meteorite fall-back breccia (Peredery 1972a, 1972b), and part of an impact melt system also comprising the Sudbury Igneous Complex (Brockmeyer 1990). Stevenson (1961a) proposed that the matrix was originally a highly pulverized mixture of country rock fragments, subsequently recrystallized by the intrusion of the upper phases of the SIC. Alternatively, the matrix has been interpreted to have been initially igneous-textured and intrusive (Brockmeyer and Deutsch 1989; Paakki 1990).

Aphanitic Dykes (APHDYK) - 12

Aphanitic dykes (APHDYK) are narrow, to irregular-shaped, intrusive aphanitic 'andesite' dykes that are xenolith poor, commonly display regular to contorted flow banding, and are similar in appearance and composition to fluidal fragments and bombs within the fragmental units of the Sandcherry and Dowling members. APHDYK occurs spatially associated with the margins of sheet-like bodies of Basal Intrusion, as narrow, or lens-shaped intrusions within the Sandcherry member, and uncommonly as small, thin dykes within the Lower, Middle, and Upper Units of the Dowling member. Contacts between APHDYK and the fragmental units may be locally knife-sharp, intrusive, and normally steeply dipping. Elsewhere, these contacts tend to be highly irregular and brecciated, with numerous apophyses extending outwards from the main body in lobe-shaped structures, surrounded by hyaloclastite, in similar fashion to the emplacement of peperites. Contacts of APHDYK with bodies of Basal Intrusion are gradational over 10 cm and are characterized by a coarsening of grain size towards the Basal Intrusion. The margins of APHDYK are typically strongly flow banded parallel to contacts. Conchoidal fractures and sharp flinty to cherty-like broken edges are characteristic of the unit.

APHDYK contains less than 5% subrounded quartz-rich lithic fragments (1 - 10 cm in size), up to 10 % quartz/chlorite-filled amygdules, and 1% pyrrhotite and chalcopyrite. Spherulitic textures are also locally common. Higher in stratigraphy the unit is more vesicular and spherulitic. APHDYK is similar in appearance to bombs and fluidal fragments within the fragmental units.

Aphanitic dykes are interpreted to be the less contaminated, lithic-poor, more rapidly crystallized equivalents (end members) of the Basal Intrusion. Aphanitic dykes and pipe-like bodies of Basal Intrusion may represent different phases of the same intrusion. Aphanitic dykes

are interpreted to represent small hypabyssal intrusions of non-brecciated melt of 'andesite' composition that intruded the fragmental rocks of the Onaping during and shortly after their deposition. The occurrence of Aphanitic Dykes may define "vents" and structures that controlled emplacement of the Onaping breccias, fluid migration, alteration, and mineralization. Locally, APHDYK represents sites where massive 'andesite' locally intruded and flowed, tongue-like, into unconsolidated, wet piles of glass-rich fragmental rock, interacted with water and passively to explosively fragmented. Aphanitic dykes represent feeders, at least locally, for the fragmental units of the lower Onaping Formation. The dykes show many features similar to "peperites" described by Hanson and Wilson (1993) (Figure 9) and "intrusive hydroclastic breccias" described by Hanson (1991) (Figure 8). Aphanitic dykes are likely representative of the original melt from which the fragmental rocks of the Onaping Formation were derived.

Carbon Contact

Carbonaceous material occurs locally within the Sandcherry member and is pervasive through much of the overlying Dowling member. The contact between carbon-poor and carbon-bearing fragmental rocks transects lithological contacts and is gradational over 5 to 20 m. Where carbonaceous material occurs within the Sandcherry member Shard-rich Units, the rocks are conductive. The Dowling member, though significantly more carbonaceous than the Sandcherry member, is conductive (due to high amorphous carbon contents) only in its upper 50 m, directly beneath the Vermilion Formation. Conductivity within the Shard-rich Units of the Sandcherry member, however, is not attributed solely to high amorphous carbon contents.

Carbonaceous Sandcherry and Dowling member fragmental rocks support subaqueous deposition for both members. Carbonaceous material must have been relatively abundant within the water column and on the depositional floor during the emplacement of both the Sandcherry and Dowling members. This suggests the early incorporation of carbonaceous material, locally at least, during deposition of the Onaping Formation.

The carbon contact is interpreted to mark either (1) the boundary between oxic and anoxic depositional environments, or (2) an alteration front, or contact, between lower rocks (carbon-poor) and upper rocks in which the carbonaceous material has been preserved. All of the Sandcherry member depositional units may have been initially carbonaceous. Deep circulation of fluids, presumably marine water, driven by the heat of the Basal Intrusion and SIC, may have been responsible for the removal of the carbonaceous material out of much of the Sandcherry member. Later cooling of the SIC may have subsequently caused the "drawing down" and redistribution of carbonaceous material.

Peredery (1972a, 1972b), Peredery and Morrison (1984), Avermann (1992), and Avermann and Brockmeyer (1992) proposed that the carbonaceous material within the fragmental units is fine organic material, derived from surrounding pelagic sediments, that was washed into the crater and redeposited along with reworked meteorite fallout material. Alternatively, Whitehead et al. (1990) proposed that the source of the carbon is the result of a mass killing of organisms within the Basin - the dead organisms subsequently settled through the water column and were incorporated into the initially glassy breccias being deposited on the crater floor.

Alteration

The Onaping Formation displays pronounced stratigraphic lithogeochemical variation, illustrated by progressive apparent losses upwards in wt.% SiO_2 , TiO_2 , Al_2O_3 , Na_2O , K_2O and MgO , and progressive apparent gains upwards in wt.% CO_2 , CaO , Fe_2O_3 , MnO , C_{org} , and S (Table 2, Figures 12, 13, 14, and 15). The base of the Sandcherry member shows a marked apparent increase in SiO_2 . Variations in composition, except for the occurrence of particulate organic carbon (C_{org}), are attributed largely to alteration. All fragmental units of the Sandcherry member

are interpreted to have initially been of a similar andesitic composition (Gibbins 1994). Aphanitic dykes best represent the precursor composition of the glass-rich breccias.

Glass composition heterogeneity and lithogeochemical stratigraphic variation (zonation) displayed by the fragmental rocks of the Onaping Formation is attributed largely to various types of alteration. These consist of (1) a basal silicification, (2) an overlying, lower semiconformable feldspar (albite + orthoclase) alteration (similar to spilitization), (3) an overlying, upper semiconformable calcium carbonate alteration that increases in intensity upwards, toward the contact with the overlying Vermilion Formation, and (4) a low temperature, (semiconformable?) potassic alteration, at the top of the Onaping Formation.

Sulphide Showings

Base metal sulphide occurrences within Onaping Formation area are predominantly fragmental in nature and, in decreasing order of mineral abundance, consist of pyrrhotite, sphalerite, chalcopyrite and pyrite. Stringer-like vein mineralization has been observed. All sulphide occurrences are nickel-poor. In stratigraphic order, sulphide showings occur at four main "horizons". These are: (1) in the silicified Undefined Units of the Sandcherry member; (2) at the carbon contact; (3) within coarse Lower Units of the Dowling member, and (4) 100 - 200 m above the carbonate contact within the Middle Units of the Dowling member. Mineralization also occurs adjacent to pipe-like bodies of Basal Intrusion and in calcite veins associated with faults. Most of the sulphides occur as fine disseminations and replacement of glass shards, but some of the mineralization may be the result of brecciation and reworking of older intra-Onaping Formation sulphide occurrences.

Concluding Remarks

The Sandcherry and Dowling members constitute a sequence of initially glass-rich fragmental rocks (breccias) of intermediate composition. The two members, distinguished from each other by percentage, size, and morphology of glass fragments consist of numerous distinct depositional units that show an overall fining upwards along with an increase, first, in fine carbonaceous material followed by an upwards increase in calcium carbonate. Both carbon and carbonate boundaries transcend (overprint) lithological contacts. The upper 170 m of the Onaping Formation, compared to the rest of the sequence, is characterized by a pronounced decrease in grain size, greater internal stratification, and stronger evidence of sedimentary reworking.

In terms of the interpretation of mechanisms of emplacement of the Onaping Formation, the origin or source of the melt is inconsequential. The assumption is made, simply, that the emplacement and deposition of the breccias of the Onaping Formation was preceded and initiated by the emplacement of a high level, "shocked" lithic clast-bearing melt of an intermediate composition. This melt may represent (1) a meteorite impact melt sheet, (2) a melt generated by intracrustal bulk melting beneath an impact crater ("impact-induced anatexis", Lowman 1993), or (3) a hypabyssal intrusion of contaminated magma. The occurrence of shock features within lithic fragments and zircons (both of basement origin) within the glass-rich of the Onaping Formation suggests the source melt for the breccias was at least partially produced by a meteorite impact. The Basal Intrusion and, particularly, Aphanitic dykes are interpreted to represent the remnants of the melt source for the fragmental rocks.

The morphology of glass fragments within the Onaping Formation indicates that the fragmental rocks (breccias) formed by the rapid cooling and fragmentation of melt upon interaction with water. "Magmatic" degassing (vesiculation) played only a minor role in clast fragmentation and emplacement of the Onaping Formation. Deposition and emplacement of the Onaping Formation is the result of prolonged passive to explosive fragmentation of melt, which was continuously fed from below, upon interaction with water. Deposition and emplacement involved repeated brecciation,

ejection, and re-deposition of earlier deposited, altered, and lithified breccias. Deposition of the Onaping Formation occurred over a prolonged period of time, too long of a period to accommodate "simple" meteorite impact fallback models. "Secondary" and renewed eruptive processes must have occurred during emplacement and deposition.

Assuming a meteorite impact, fallback breccias were either (1) deposited beneath the Sandcherry member and subsequently "eliminated" or assimilated by the underlying Basal Intrusion and SIC, or by the emplacement of the Sandcherry member, or (2) were never actually deposited within the crater defined by the Sudbury Basin.

The upper contact of the Onaping Formation with the overlying argillites of the Onwatin Formation has been described as gradational and conformable (Muir and Peredery 1984; Rousell 1984a; Avermann 1992; Avermann and Brockmeyer 1992) to geochemically and lithologically sharp (Whitehead et al. 1990; Paakki 1992, Gibbins 1994, Grey 1995). The upper 40 metres of the Onaping Formation is fine-grained, rich in organic carbon, and as stated by Martin (1957) can be difficult to distinguish visually from the pelagic sediments of the Onwatin Formation.

Vermilion Formation

The Vermilion Formation (Martin 1957, Stoness 1994), previously known as the Vermilion member of the Onwatin Formation (Rousell 1982a), is situated at the contact between the Onaping and Onwatin Formations. Stoness (1994) upgraded the member to formation status because of its Basin-wide occurrence and distinct geological character. The Vermilion Formation hosts the Vermilion and Errington Zn-Cu-Pb-Au-Ag Deposits, located in the south-west quadrant of the Sudbury Basin. While diamond drilling has intersected Vermilion Formation rocks, 1 to 30 m thick, elsewhere in the North and South Ranges, the continuity of the formation is unknown (Arengi 1977; Gibbins et al. 1992). In the vicinity of the deposits the Vermilion Formation has an average thickness of 43 m (Martin 1957; Rousell 1982a).

The Vermilion Formation comprises fine- to coarse-grained, commonly pyritiferous and base-metal-bearing carbonate; cherty carbonate, chert breccia, interbedded fine-grained gray argillite, and fine- to coarse grained granular to pisolitic carbonate. Rapid lateral lithological variation within the Vermilion Formation in the vicinity of the deposits is common. The Vermilion Formation has been described as a syngenetic stratabound deposit (mainly recrystallized, altered micritic limestone) by Card and Hutchinson (1972), a sedimentary-exhalative deposit (Rousell 1984b; Davies et al. 1990; Whitehead et al. 1990; Paakki 1992), and an epigenetic vein deposit (Martin 1957). Most recently, the Vermilion Formation has been subdivided into turbiditic argillite deposits (Stoness 1994) and carbonate exhalite sinter deposits (Gray 1995). The exhalites comprise the Lower Carbonate member of the 50 m thick Vermilion Formation. The middle member is the Grey Argillite member and consists of fine-grained grey turbidites that have basin-wide continuity; and the Upper Carbonate member is a thin hydrothermal concretionary carbonate (Gray 1995).

Onwatin Formation

The Onwatin Formation (Coleman 1905; Burrows and Rickaby 1930; Martin 1957; Thomson 1957; Sadler 1958; Beales and Lozej 1975; Rousell 1984a) consists of laminated carbonaceous and pyritic argillites and siltstones, with minor fine-grained carbonates and wackes. The Onwatin Formation is poorly exposed in the Sudbury Basin, but where present, a well developed slaty cleavage predominates (Paakki 1992). Carbonate concretions, though rare, are also evident. The formation, based on drill hole data and stratigraphic reconstruction (Gibbins et al. 1992), is interpreted to have an original thickness of 600 m. The formation has been

ARG-ILLITE		ONAPING FORMATION																			SIC
		DOWLING MEMBER									SANDCHERRY MEMBER				INTRUSIONS						GRANO-PHYRE
		UPPER UNITS			MIDDLE UNITS			LOWER UNITS			SHARD-RICH UNITS		FLUIDAL FRAGMENT UNITS		BASAL SAND-CHERRY	APHAN-ITIC DYKES	BASAL INTRUSION				
																	PIPES	SHEETS	BORDER PHASE		
		ONW	DMUc	DMUb	DMUa	DMMb,a	DMMc	DMLa	DMLb	DMLc	DMLCT	SMSRC	SMSR	SMFLr	SMFL	SM---	APHDYK	B1c	B1a	B1b	
wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %		
SiO ₂	55.97	52.32	57.50	59.00	60.36	60.76	61.33	61.00	61.22	61.62	62.04	63.00	62.88	63.12	66.13	63.44	65.01	66.40	68.81	69.08	
TiO ₂	0.63	0.44	0.40	0.43	0.48	0.49	0.56	0.55	0.55	0.56	0.55	0.56	0.56	0.57	0.48	0.58	0.57	0.49	0.45	0.78	
Al ₂ O ₃	14.33	8.77	8.64	9.52	10.61	10.77	11.88	11.88	11.91	12.07	11.98	12.37	12.71	12.82	11.61	12.94	13.21	12.62	13.12	12.31	
Na ₂ O	0.90	0.42	0.59	1.17	1.84	2.22	3.56	3.79	3.70	4.38	4.21	5.07	4.41	4.78	3.94	3.68	4.00	4.00	4.04	3.04	
CaO	0.78	4.04	6.27	5.23	3.87	3.70	3.69	3.98	4.08	3.85	3.45	3.54	3.75	3.44	3.03	2.21	1.70	2.23	1.55	1.59	
P ₂ O ₅	0.12	0.16	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.14	0.15	0.15	0.14	0.11	0.15	0.13	0.11	0.12	0.18	
K ₂ O	3.62	3.32	1.23	2.00	2.10	1.89	2.04	2.32	2.25	1.64	2.21	1.31	1.84	1.61	1.58	2.39	2.41	1.87	2.31	3.77	
MgO	2.32	3.83	3.86	3.95	4.00	4.13	4.21	4.33	4.28	4.36	4.12	4.07	3.79	3.82	3.64	3.37	3.29	2.76	1.35	0.86	
Fe ₂ O ₃	8.09	12.75	11.10	10.24	9.02	9.26	8.28	8.60	8.79	8.77	8.04	7.43	7.08	6.97	6.21	6.53	5.99	5.66	4.04	5.79	
MnO	0.23	0.58	0.59	0.54	0.40	0.39	0.26	0.26	0.27	0.23	0.20	0.19	0.17	0.16	0.18	0.15	0.13	0.13	0.09	0.11	
Cr ₂ O ₃	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	
LOI	8.93	9.39	6.99	6.11	5.81	4.38	2.67	2.03	2.15	1.51	2.15	1.32	1.46	1.36	1.47	1.50	1.63	1.83	1.38	1.20	
C _{tot}	3.19	6.11	2.34	2.04	1.84	0.78	0.69	0.80	0.19	0.09	0.47	0.08	0.07	0.08	0.04	0.05					
C _{org}	0.65	4.28	1.01	0.89	0.99	0.49	0.36	0.50	0.14	0.06	0.37	0.03	0.03	0.04	0.03	0.03					
CO ₂	6.81	6.49	4.46	3.92	2.94	0.94	0.79	0.33	0.10	0.09	0.31	0.17	0.13	0.13	0.32	0.03					
S	0.37	1.25	0.72	0.43	0.28	0.48	0.26	0.41	0.23	0.16	0.38	0.10	0.05	0.11	0.35	0.02					
Cu	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
Zn	83	54	165	12	24	34	31	33	35	26	33	28	23	16	33	24	19	30	22	11	
Pb	157	124	89	82	82	74	61	50	56	49	52	42	49	45	56	44	50	50	48	52	
Ni	25	22	9	8	11	12	8	9	8	7	11	9	9	7	14	8	14	12	9	10	
Ba	70	68	44	47	60	59	59	62	61	63	53	62	59	60	52	46	51	49	18	4	
Rb	710	856	626	807	861	804	782	818	847	597	773	404	552	457	413	849	772	674	860	1198	
Sr	149	119	46	54	60	52	61	80	77	58	81	50	66	59	51	81	100	64	83	121	
Zr	120	180	142	111	97	80	108	99	91	74	117	85	138	135	121	161	210	215	238	138	
Y	131	115	130	132	126	129	130	126	135	139	138	133	132	138	115	140	127	121	146	217	
Nb	22	14	12	11	13	12	10	12	15	15	16	13	13	14	12	14	11	11	12	23	
	18	23	16	19	14	15	10	15	14	14	16	14	12	13	13	12	12	12	10	16	
Pts.	202	38	27	45	213	468	11	64	111	115	124	205	57	86	54	51	18	79	15	9	

Table 2: Average lithochemical composition of Onaping Formation units (after Gibbins 1994)

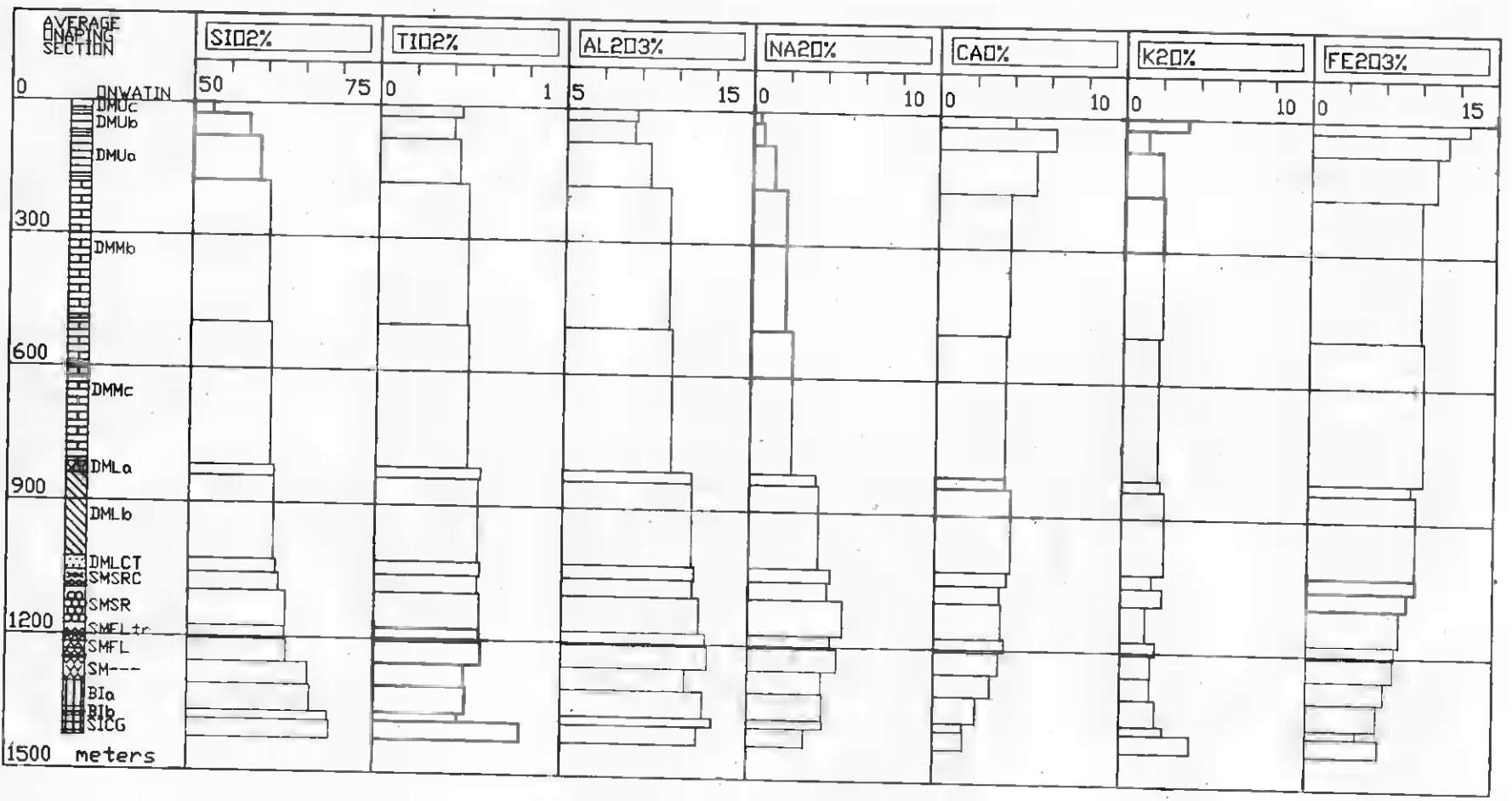


Figure 12: Lithogeochemical stratigraphic column - Average compositions (major oxides) and thicknesses of units (after Gibbins 1994).

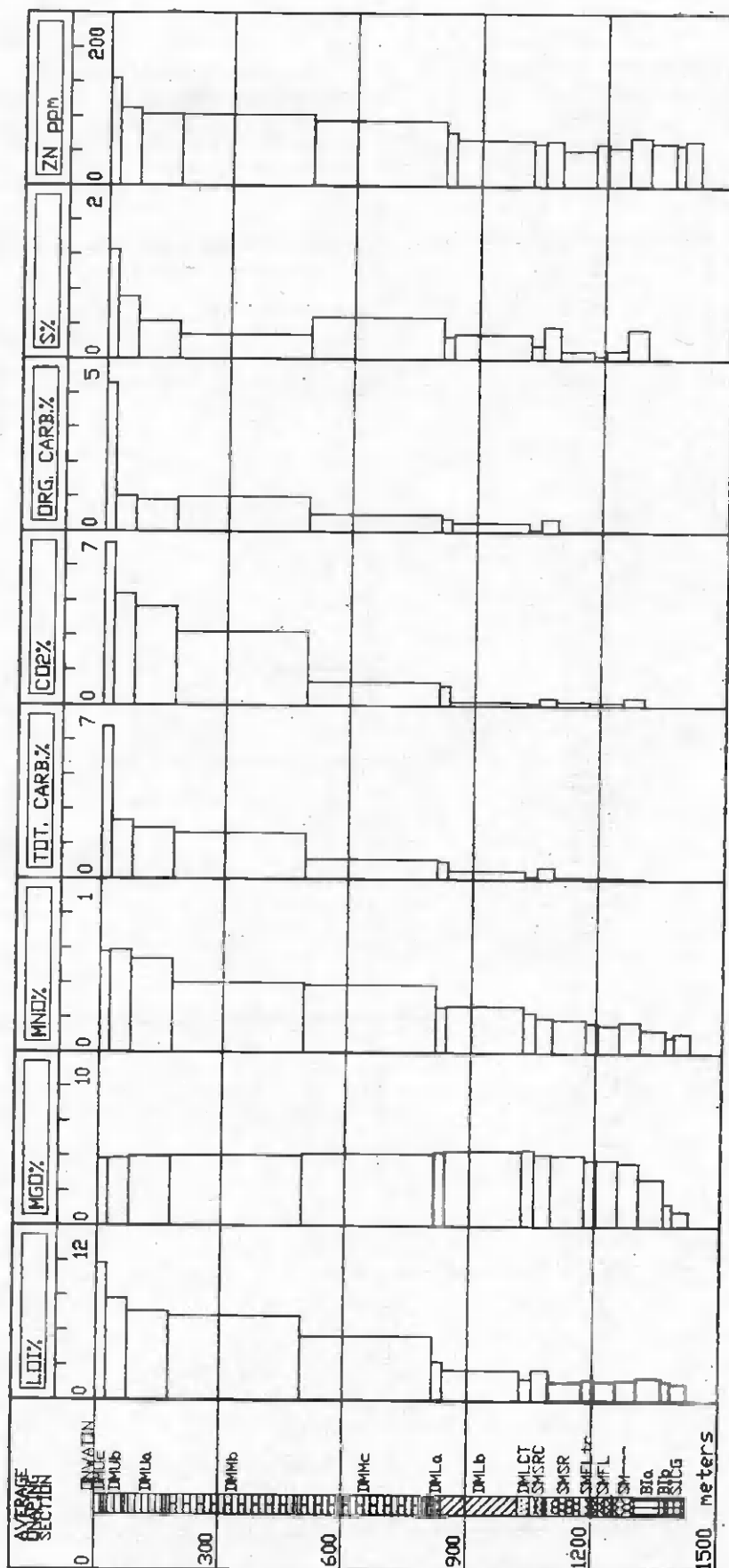


Figure 13: Lithogeochemical stratigraphic column - Average compositions (major oxides#2 + Corg, CO₂, S, Zn) and thicknesses of units (after Gibbins 1994).

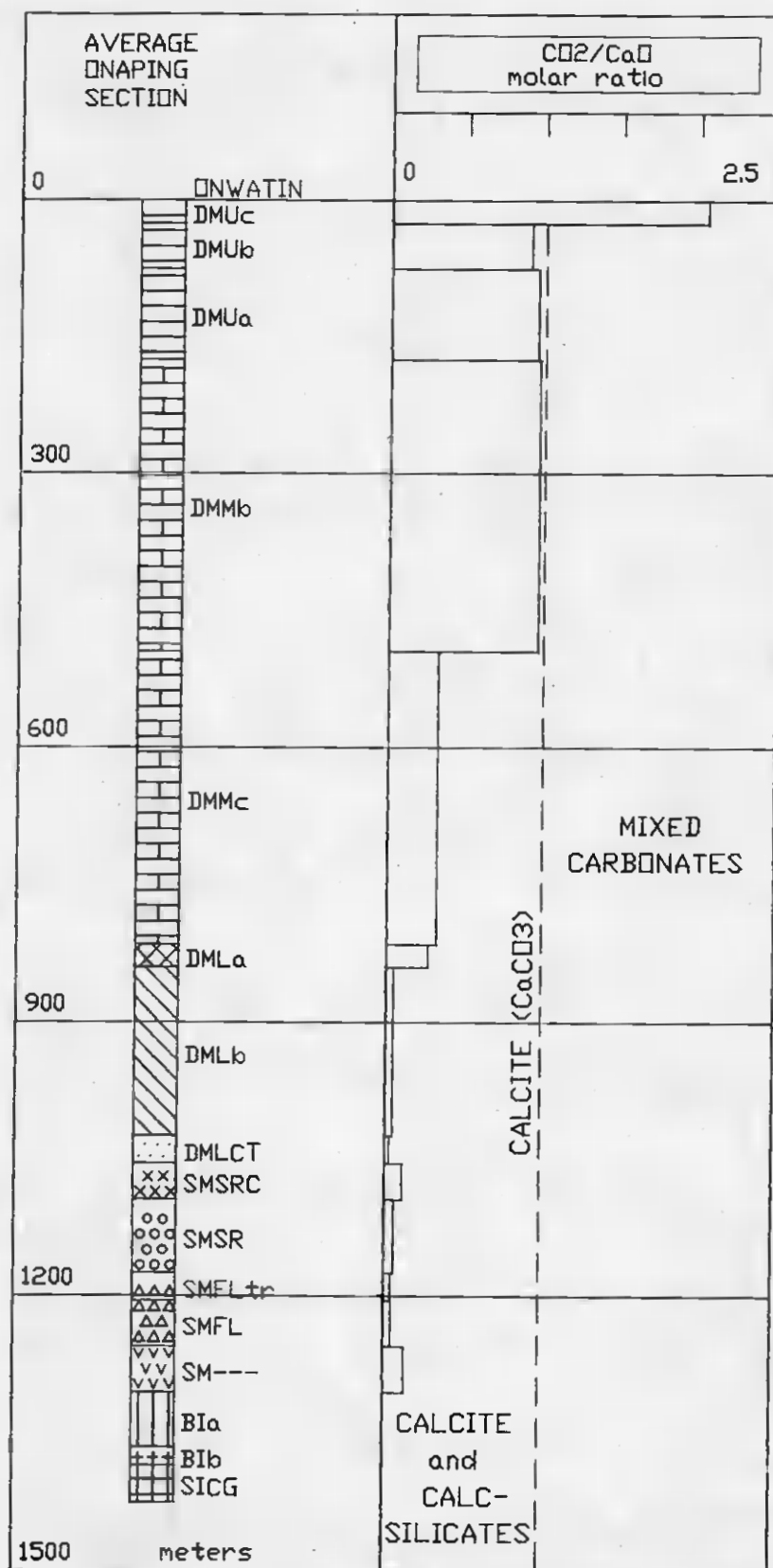
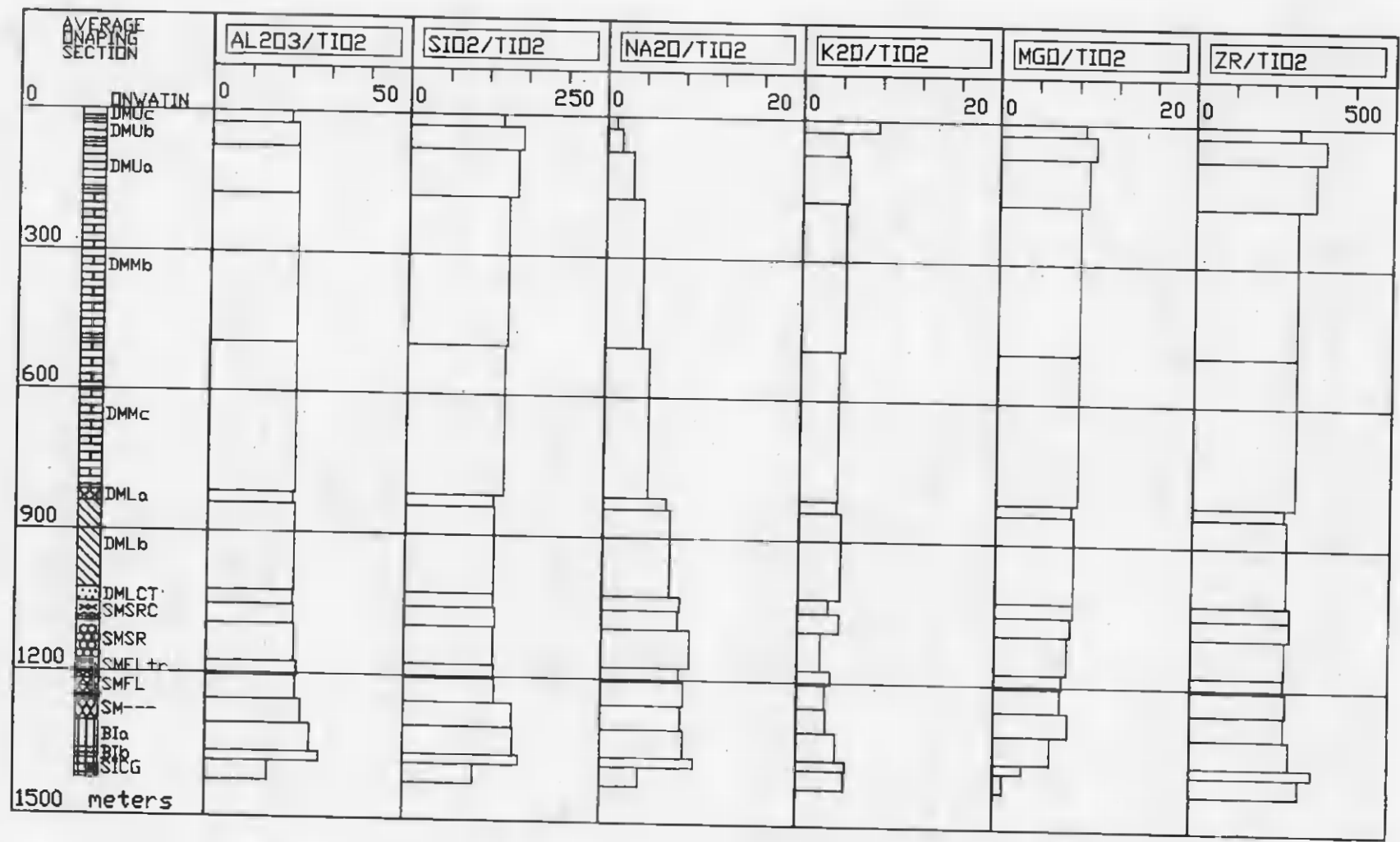


Figure 14: Lithogeochemical stratigraphic column - Average CO₂/CaO molar ratio and thicknesses of units (after Gibbins 1994).

Figure 15: Lithogeochemical stratigraphic column - Average compositions (TiO₂ ratios) and thicknesses of units (after Gibbins 1994)



structurally thickened, particularly in the South Range. Whitehead et al. (1990), Paakki (1992), Stoness (1994), Gibbins (1994) and Gray (1995) showed the Onwatin Formation (and Vermilion Formation) to be chemically and lithologically distinct from the underlying Onaping Formation (Table 2). The upper contact is gradational with the Chelmsford Formation and is considered to be at the base of the first thick wacke bed.

The pelagic rocks of the Onwatin Formation were deposited in a restricted basin with anoxic bottom conditions (Rousell 1984a). They grade upwards into the coarser sediments of the Chelmsford Formation, indicating a transition to a higher energy depositional environment (Dressler et al. 1991).

Chelmsford Formation

The Chelmsford Formation (Burrows and Rickaby 1930; Williams 1957; Cantin 1971; Cantin and Walker 1972; Rousell 1972; Vezina 1992) is the uppermost formation of the Whitewater Group and has a preserved thickness similar to that of the underlying Onwatin Formation, approximately 600 m. The Chelmsford Formation is a turbidite succession of massive to normally graded lithic wackes, siltstones, and carbonaceous mudstones. Sedimentary structures include carbonate concretions, rip-up clasts, U-shaped channels, climbing ripples and cross-bedding, convolute laminations, and load structures. Paleocurrent studies indicate that the predominant flow direction was to the south-west, parallel to the long axis of the Sudbury Basin (Cantin and Walker 1972; Rousell 1972).

Errington and Vermilion Deposits

The Errington and Vermilion Deposits are Paleoproterozoic carbonate-hosted Zn-Cu-Pb-Au-Ag massive sulphide deposits located in the southeast corner of the Sudbury Basin. The deposits occur at the top of Onaping Formation and partially within the Vermilion Formation. The Errington deposit contains an undiluted mineral inventory of 6.27 M tonnes grading 4.21% Zn, 1.22% Cu, 1.09% Pb, 0.86 g/tonne Au and 62.06 g/tonne Ag (Severin and Gates 1981). The Vermilion deposit contains an undiluted, proven-probable-possible mineral inventory of 2.44 m tonnes grading 5.11% Zn, 1.49% Cu, 1.37% Pb, 1.10 g/tonne Au and 66.17 g/tonne Ag (Severin and Gates 1981). The two deposits, 8 km apart, were discovered in the mid to late 1920's and later developed for production. Attempts to exploit the deposits were unsuccessful due to poor metal recoveries, low metal prices and overall marginal grades.

Gray (1995) described the deposits to be hosted by the Vermilion Formation within a Ca-Mg carbonate exhalite sinter vent complex that grades laterally into Mn-Fe-rich carbonates (up to 9.5 wt% MnO and 33 wt% Fe₂O₃). The Vermilion Deposit is underlain by lower discordant chlorite zone and an upper discordant silicification and stratiform Ca-Mg carbonate stockwork zone. Gray (1995) proposed the deposits formed in a sub-seafloor environment by the initial low temperature pyrite-sphalerite infilling of carbonate porosity within sinters followed by later higher temperature chalcopyrite-rich mineralization that replaced earlier pyrite and sphalerite and secondary porosity from hydrothermal dissolution leaching of the carbonates. The carbonate sinter host is attributed to sub-seafloor boiling and carbonate precipitation by venting into an alkaline, anoxic basin and by successive replacement events that enabled the sinter mounds to grow. Carbonates were preserved from dissolution by the emplacement of turbidites. The hydrothermal system responsible for the Vermilion Deposit was long-lived, the underlying Sudbury Igneous Complex, or precursor melt provided the thermal energy to drive and sustain convection cells within the Onaping Formation (Gray 1995).

LOCATION AND DESCRIPTION OF GEOLOGICAL TOUR STOPS

Tour stops are indicated on Figures 16 - 22.

STOP 1

SUDBURY BRECCIA

An easily accessible outcrop of Sudbury Breccia is located on Highway 144, 3.2 km north of the junction of Highway 144 and Regional Road 8 (Levack turnoff).

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. Fragments in the breccia generally consist of the same material as the wall rocks and are rounded to varying degrees. The matrix of the breccia consists of finely comminuted wall rock material that has been recrystallized to a coherent mass.

STOP 2

FELSIC NORITE

This stop is located 1.4 km north of the junction of Highway 144 and Regional Road 8 (Levack turnoff), near the Elk's Club Road.

Felsic norite is the main member 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 "cryptic layering".

STOP 3

QUARTZ GABBRO AND GRANOPHYRE

Stop 3 consists of rock outcroppings on either side of Regional Road 8 at the junction of Highway 144. Quartz gabbro can be seen in the road cuts to the north and south of the road; the granophyre is further to the southwest.

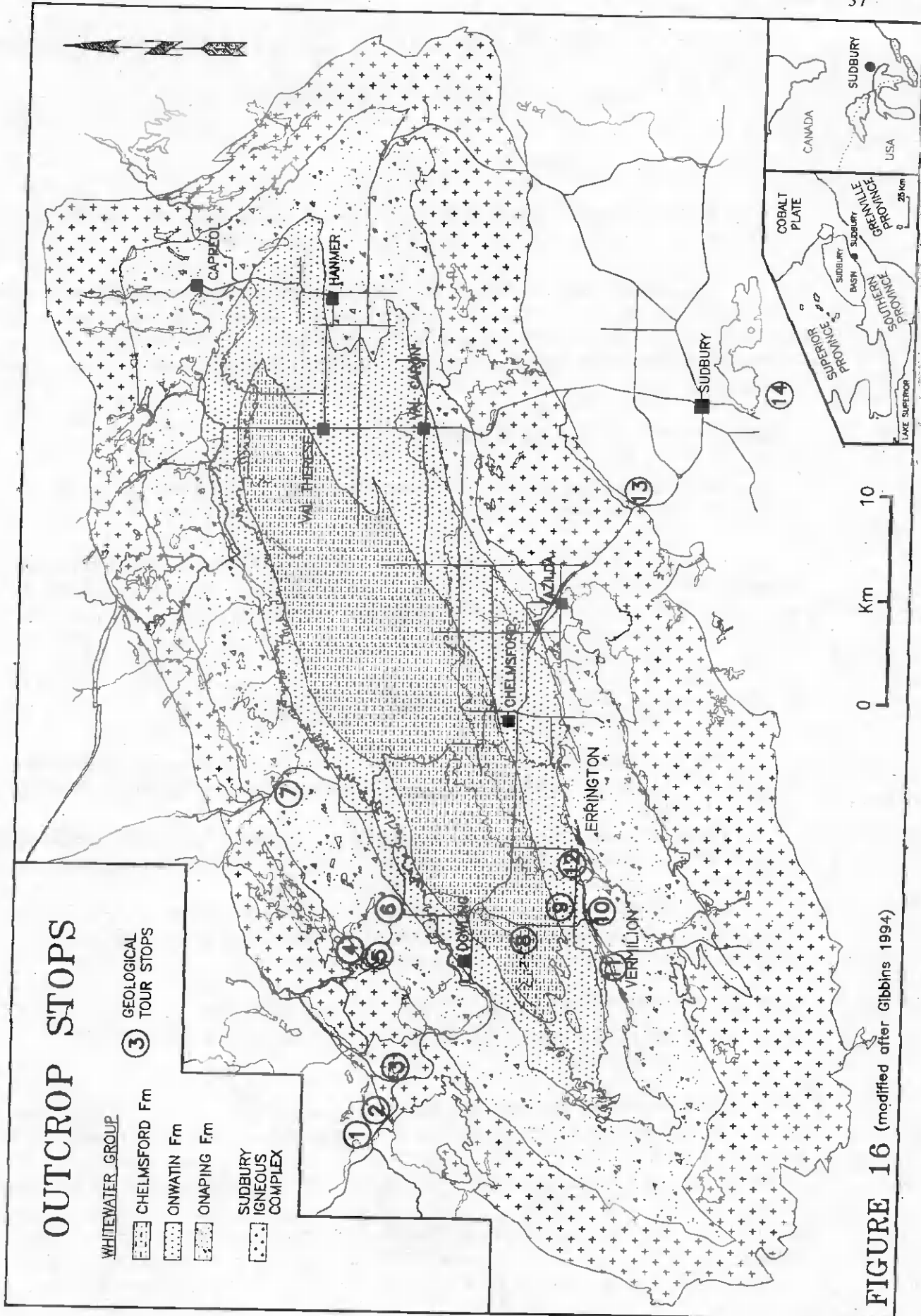
The upper member of the Sudbury Igneous Complex consists of granophyre, which is pink in colour and comprises about three parts micrographic intergrowth to one part plagioclase. Quartz, biotite, amphibole, chlorite and opaques are also present.

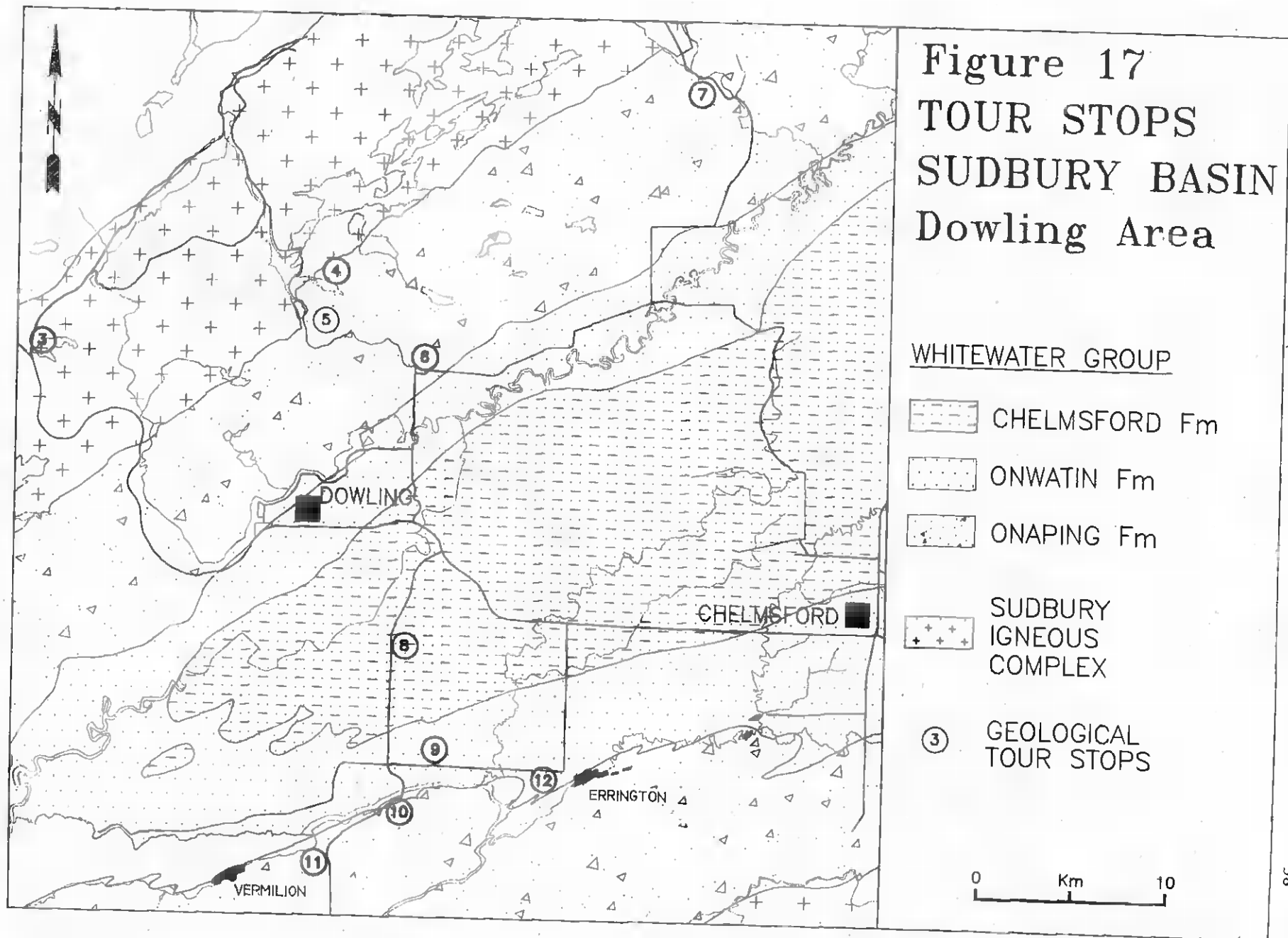
Below the granophyre, occurs a thin member known as quartz gabbro (or transition zone), which is more mafic than the granophyre and consists principally of plagioclase, clinopyroxene, amphibole and intercumulus micrographic intergrowth and quartz.

STOP 4

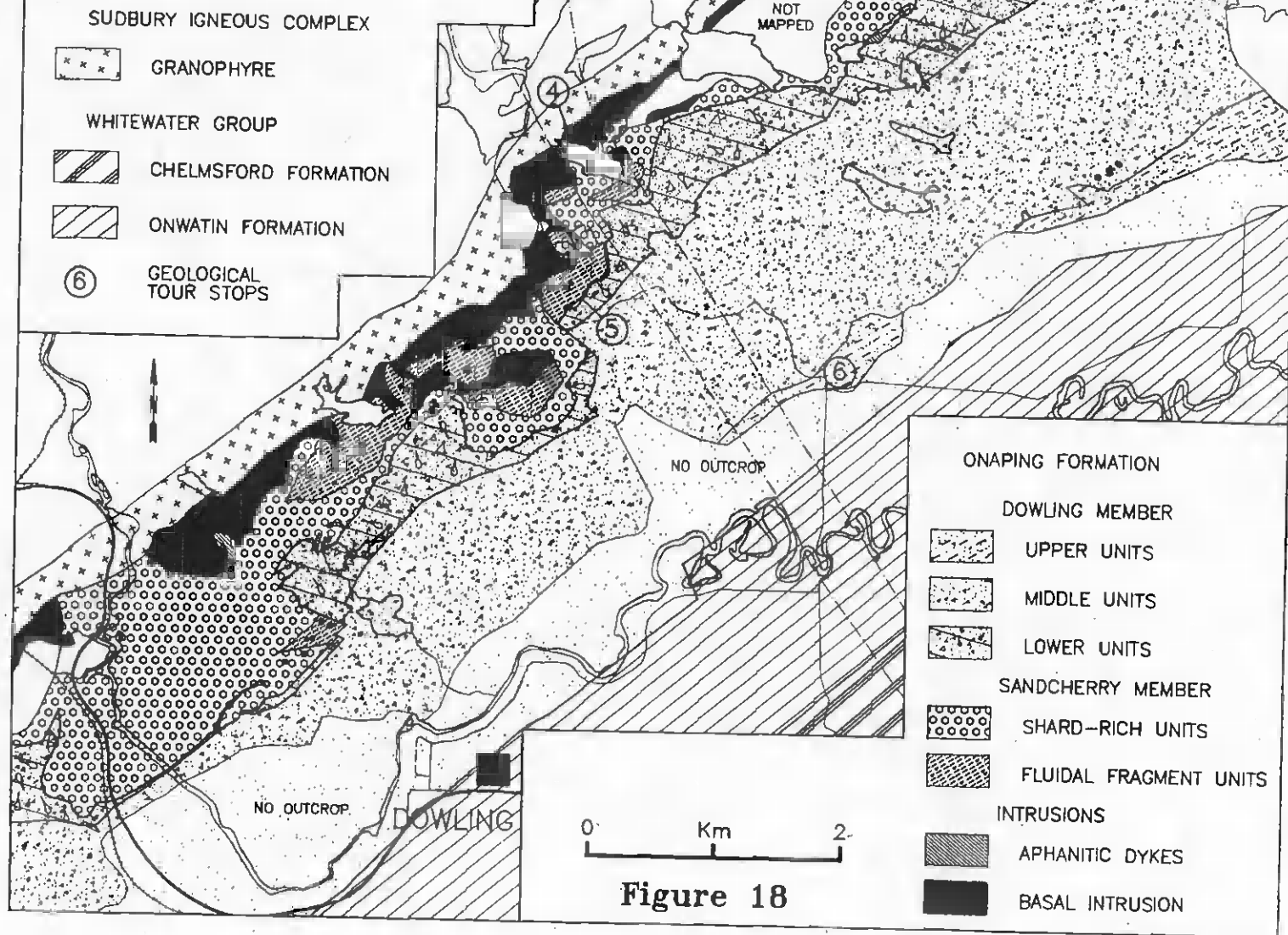
CONTACT BETWEEN GRANOPHYRE AND BASAL INTRUSION, APHANITIC DYKES, AND THE BASE OF THE SANDCHERRY MEMBER

Stop 4 is a walking tour over the contact zone between Granophyre and the Basal Intrusion and over a variety of exposures of Basal Intrusion, Aphanitic Dykes, and glass-rich breccias at the base of the Sandcherry member of the Onaping Formation. Access to the area is gained from a private dirt road (Gravel Lake Road), which extends south of Falconbridge Limited's main access road to Strathcona Mine, approximately 4.8 km past the main gate entrance. Permission to use the road and to view the outcrops is required from Falconbridge Limited, as the area is on mine property. Turn right off the mine access road on to Gravel Lake Road, which parallels the eastern shore of a nearby lake, and continue south along the shore of the lake until a yellow road gate is





ONAPING FORMATION Dowling Area TOUR STOPS



reached (≈ 2 km). The walking tour begins 200 south of the gate by leaving the gravel road and following a stream eastwards for 600 m to reach exposures of granophyre along the north shore of a small lake. The walking tour route is marked in detail from this point onwards on Map A, Figure 19.

During the tour the following exposures will be seen: granophyre, xenolith-bearing granophyre, both coarse grained xenolith-rich basal intrusion and fine-grained, well sorted, xenolith-poor basal intrusion, flow banded Aphanitic Dykes and various 'glass'-rich units of the Sandcherry member. Although a bit of a hike, the walking tour offers one of the best exposures of the base of the Onaping Formation and of flow banded Aphanitic Dykes. The walking tour begins and ends at the same spot.

STOP 5 FLUIDAL FRAGMENT-RICH AND SHARD-RICH BRECCIAS OF THE SANDCHERRY MEMBER, THE CONTACT BETWEEN THE SANDCHERRY MEMBER AND LOWER UNITS OF THE DOWLING MEMBER, AND PIPE-LIKE BODIES OF THE BASAL INTRUSION

Stop 5 is a walking tour that extends eastward from Gravel Lake Road, 200 m south of a gravel pit, which is approximately 1.5 km further along Gravel Lake Road from the yellow gate described in the previous stop. After a walk of 200 m eastward from Gravel Lake Road, a small ridge of rock is reached which marks the beginning of a geological traverse over (1) Fluidal Fragment-rich and Shard-rich units of the Sandcherry member, (2) a rare well exposed contact (running along the top of a steep, large ridge) between the Sandcherry and Dowling members, with both sharp and gradational characteristics over its 400 m length, and (3) pipe-like bodies of the Basal Intrusion. The walking tour is marked in detail on Map B, Figure 20. The Lower Contact Unit of the Dowling member ("chlorite shard horizon") and the carbon boundary are also well exposed locally along the southern flank of the ridge. Alteration (silicification and albitization) of the 'glass' shards at the top of the Sandcherry member is well featured within the vicinity of the pipe-like bodies of Basal Intrusion, near the western end of the ridge of outcrop. From this area, return to Gravel Lake road by walking 150 m due west through the bush.

STOP 6 MIDDLE AND UPPER UNITS OF THE DOWLING MEMBER

Stop 6 is located at the south end of Gravel Lake Road at the junction with Morgan Road. Unfortunately due to a wash-out south of Stop 5 in Gravel Lake Road, Stop 6 must be reached from the south. To get there, return to Hwy. 144, by the same route taken in, and travel south, through the town of Dowling and turn left onto Morgan Lake Road, just before the bridge on Hwy. 144 that crosses over the Vermilion River near Larchwood. Stop 6, at the junction between Gravel Lake Road and Morgan Road is approximately 3.5 km north of Hwy. 144.

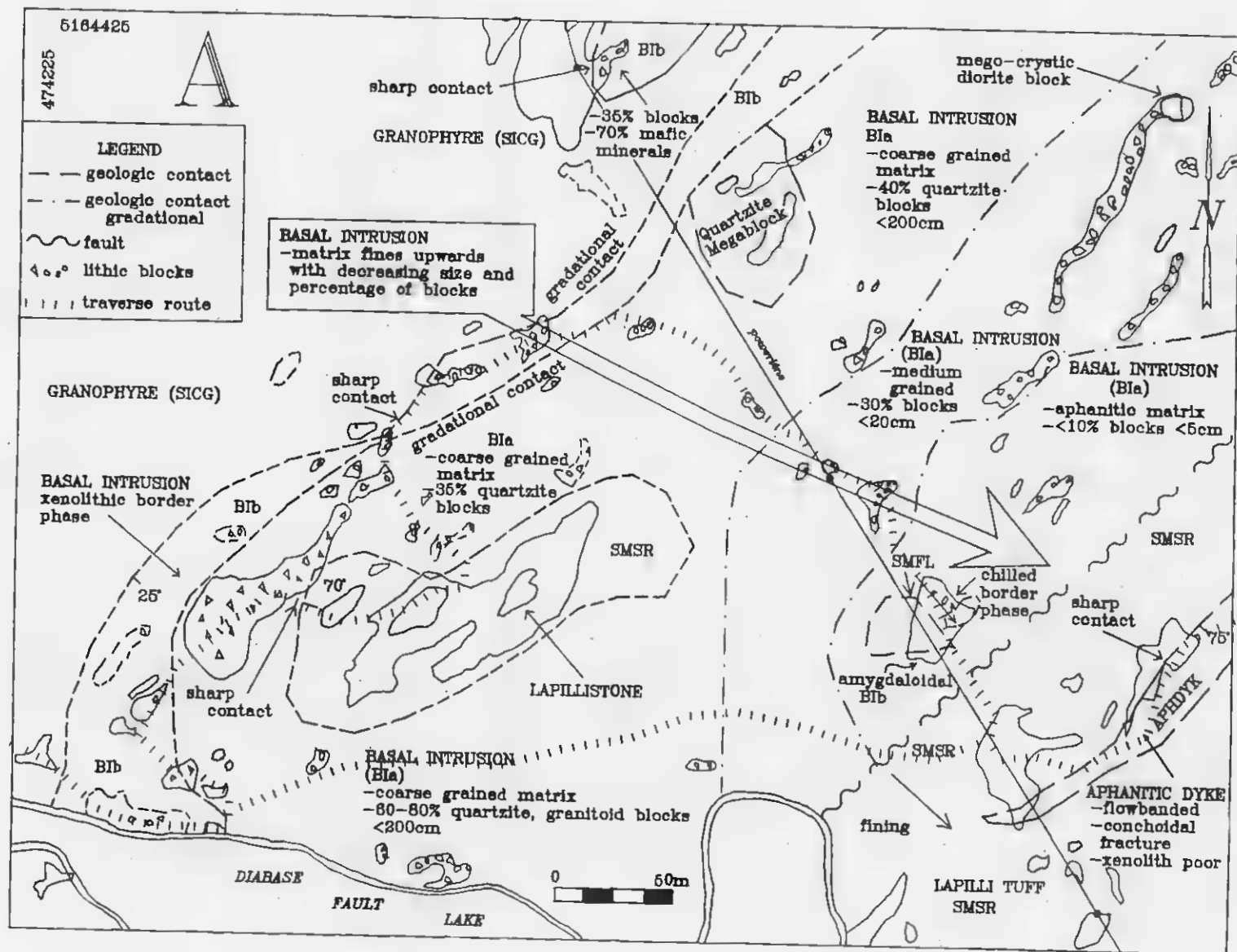
Stop 6 is shown in detail on Map C, Figure 21. Representative units of the Middle and Upper Units of the Dowling member are well exposed at this stop, including rarely exposed characteristic features of reworking and bedding within the Upper Units. The stop provides a good example of the unaltered and undeformed equivalents of the immediate footwall rocks to the Errington and Vermilion deposits located at the top of the Onaping Formation along the southern margin of the Sudbury Basin.

STOP 7 CARBON BOUNDARY WITHIN SHARD-RICH UNITS OF THE SANDCHERRY MEMBER AND AN INTRUSIVE FLUIDAL BRECCIA COMPLEX

Located near Sandcherry Creek, Stop 7 is accessed via Nickel Offset road that extends northwards from Morgan Road (Montpellier Road). The Nickel Offset Road is located 5.75 km

Figure 19:

Detailed geology of Stop 4 (after Gibbins 1994).



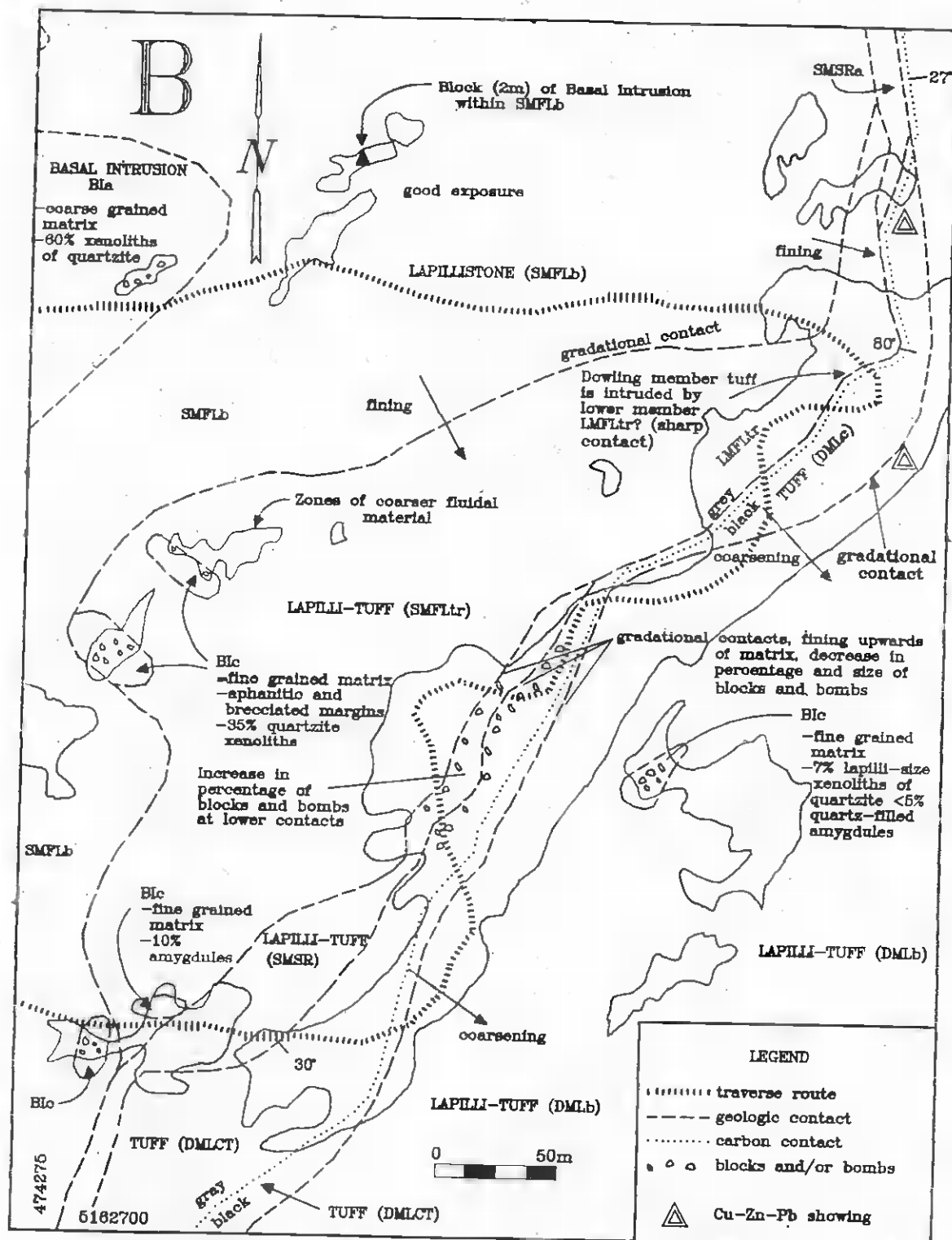


Figure 20: Detailed geology of Stop 5 (after Gibbins 1994).

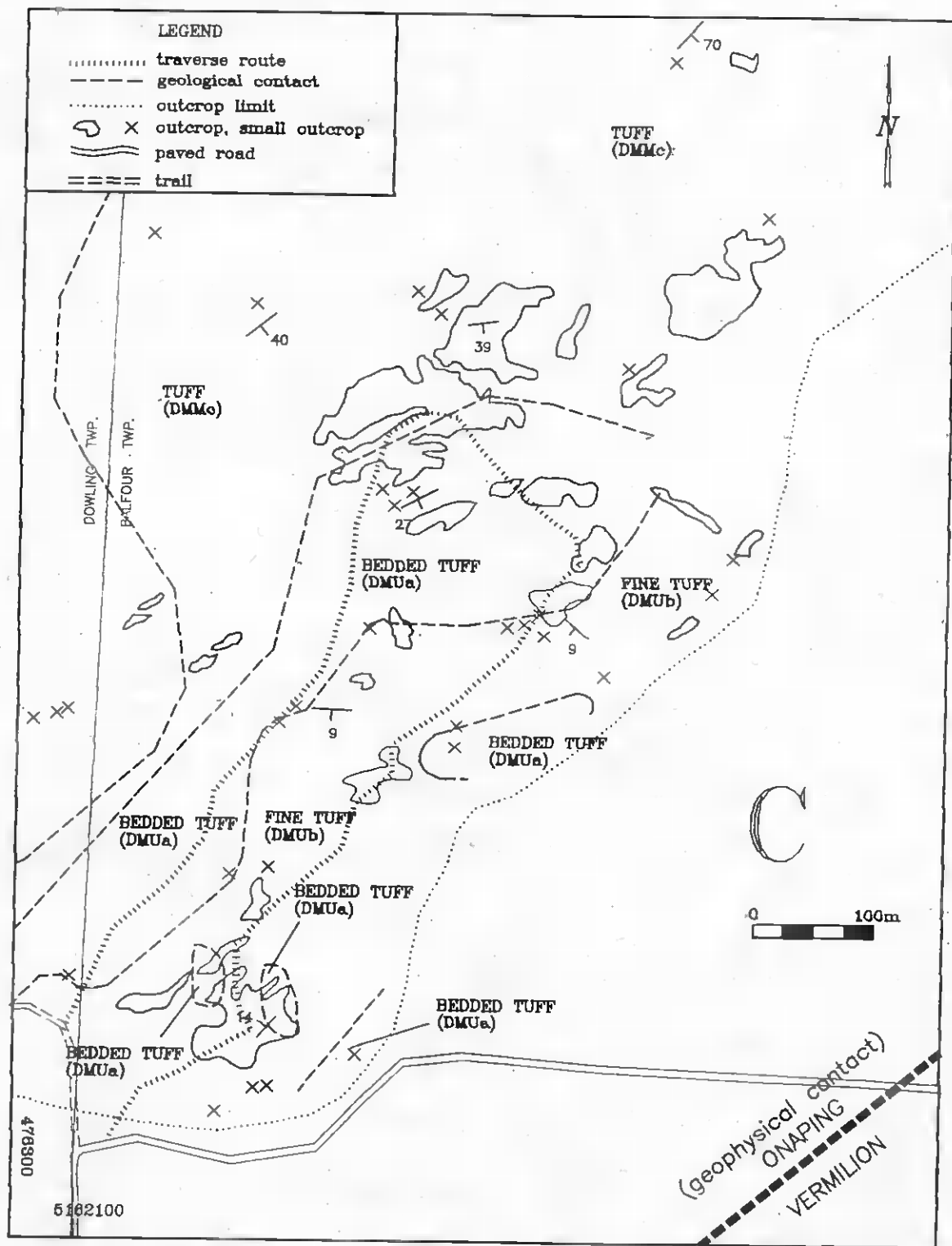


Figure 21: Detailed geology of Stop 6 (after Gibbins 1994).

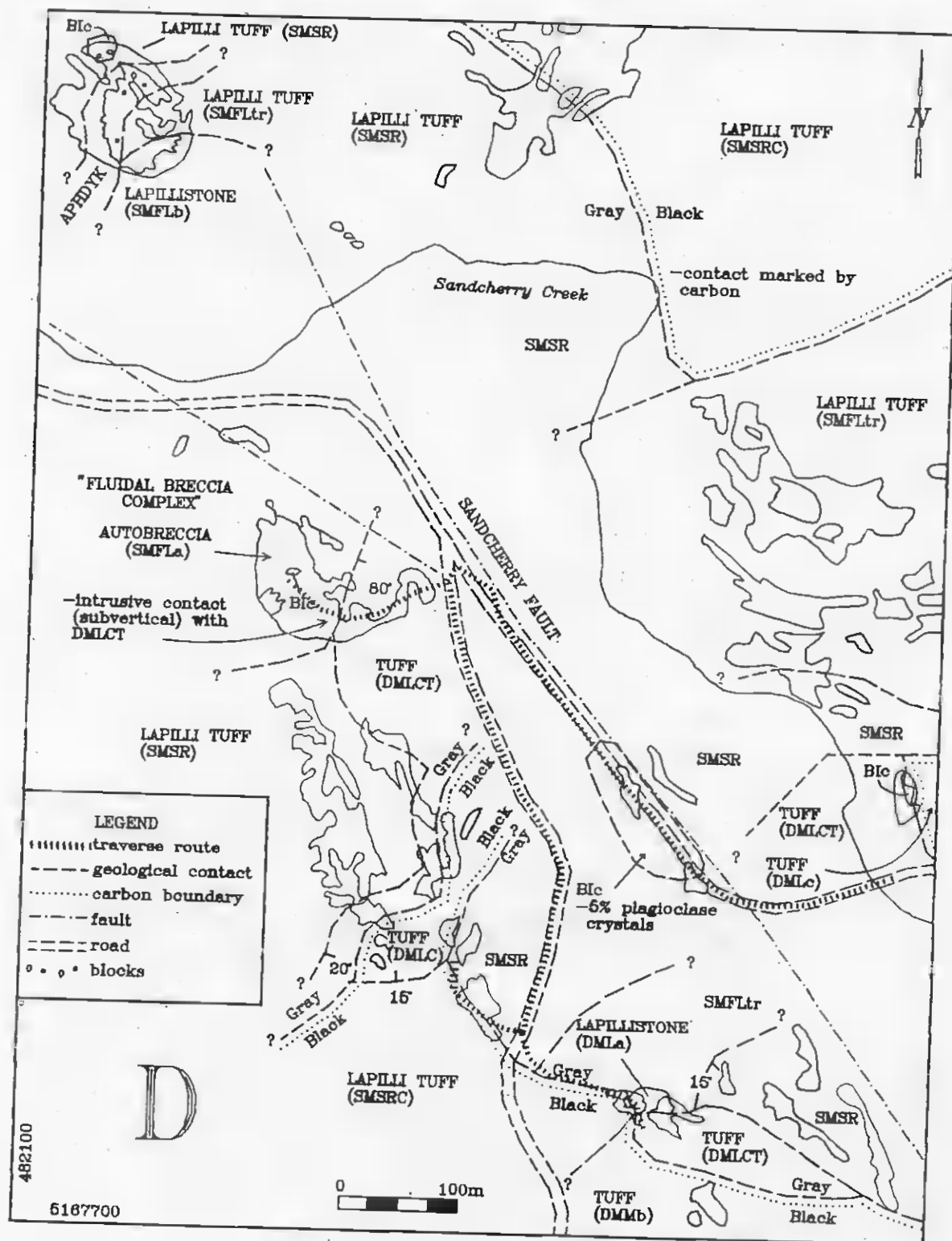


Figure 22: Detailed geology of Stop 7 (after Gibbins 1994).

east of Stop 6, further along Morgan Road. Drive 5.5 km north on Nickel Offset Road until the second of two bridges that cross Sandcherry Creek is reached. Park the vehicle before crossing the 2nd bridge and walk 500 m further up Nickel Offset Road to a junction with a second, but less traveled dirt road, as indicated on Map D, Figure 22. Though a bit of bush crashing and climbing is involved (50 m), Stop 7 provides an excellent exposure of Fluidal Fragment Units and Pipe-like bodies of Basal Intrusion (Fluidal Breccia Complexes) intruding into the Lower Contact Unit of the Dowling member. Only 350 m to the south is a representative exposure of the carbon boundary/contact within Shard-rich units of the Sandcherry member.

STOP 8 CHELMSFORD FORMATION

Easily accessible road cuts of the Chelmsford Formation are to be found on both sides of the Gordon Lake road approximately 3.5 km south of the junction between Hwy. 144 and Gordon Lake Road. The Gordon Lake Road turn off from Hwy. 144 is located 200 m south of the bridge that crosses over the Vermilion River near Larchwood. The Chelmsford Formation is the youngest member of the Whitewater Group and occupies the central portion of the Sudbury Basin. The Formation consists of turbidites, with partial to complete Bouma sequences, which mark a change in the pattern of sedimentation within the Basin (the underlying Onwatin Formation is a series of carbonaceous and pyritic siltstones and mudstones). Rusty weathering concretions and lenses are common and represent concentrations of ferruginous carbonate. At this locality, a partial Bouma sequence is present with cross bedding and dewatering structures also present.

STOP 9 ONWATIN FORMATION

Stop 9 is located on Vermilion Lake Road, 1 km east of the junction between Vermilion Lake Road and Gordon Lake Road. At this locality, in the hangingwall to the Errington and Vermilion deposits and in the mid-zone area between the two deposits, the carbonaceous Onwatin Formation contains elevated amounts of pyrite and rare pyritic carbonate concretions.

STOP 10 VERMILION FORMATION

Stop 10 is located on the south side of Gordon Lake road, approximately 75 m south of the bridge over Vermilion River. Varved-looking, 1-2 cm thick bands of carbonate and grey argillite representative of the non-carbonaceous Vermilion Formation, and host to the Errington and Vermilion deposits, can be seen at this rare exposure.

STOP 11 LOBATE PEPPERITE-LIKE INTRUSIVE BODIES OF SPHERULITIC APHANITIC DYKES WITHIN UPPER UNITS OF THE DOWLING MEMBER

Stop 11 is located on the west side of Gordon Lake road, approximately 200 m south of the Vermilion Mine road turn off, which is 2 km southwest of the Gordon Lake road bridge over the Vermilion River. Exposures such as these strongly altered (silicified) and spherulitic devitrified lobes of aphanitic 'andesite' are extremely rare at this level of the Onaping Formation. They have not been related to the mineralization at the Vermilion or Errington deposit, but they may define structures that also controlled the location of the deposit.

STOP 12 VERMILION FORMATION

Stop 12 is located within the vicinity of the Errington #1 shaft, 700 m east of the Stobie Dam on Vermilion River. Though reclamation activities have been recent in the area, trenches

showing folding of the Vermilion Formation, weak mineralization and strong carbonate alteration can still be observed. The folding is representative of the structure pattern in the deposit area.

STOP 13 DISCOVERY SITE

Stop 13 is located on the east side of Highway 144, 1.9 km north Godfrey Drive, or 4.4 km north of the Big Nickel Mine Road. Look for a small paved area with an Heritage Foundation historical plaque and an American Society of Metals commemorative plaque marking the site. Be careful! Train traffic on the railway can be heavy.

Though Nickel was first reported in 1856 near the Creighton Mine site by A. Murray of the Geological Survey of Canada, it was not until 1883, during the construction of the Canadian Pacific Railway, that a railway rock-cut near the site exposed nickel-copper mineralization, which was subsequently developed as the Murray Mine ore body. 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, when 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, across the highway.

Thirty meters from the paved area, toward the railway tracks is a rust-covered outcrop of weakly mineralized Sublayer of the Sudbury Igneous Complex and host for the nickel-copper ore minerals (pyrrhotite, pentlandite, and chalcopyrite). The outcrop is the eastern continuation of the mined-out ore body. 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. The quartz-rich norite differs from the Sublayer, in that it contains few ore minerals or inclusions, it is homogeneous and the quartz has a distinct blue tint. The Sublayer dips northward at about 60° beneath the norite.

STOP 14 SHATTER CONES

Stop 14 is located on Ramsey Lake Road, on the south side in a rock cut about 200m long, 1.4 km east of Paris Street. The shatter cones, feathery-looking conical striated fracture structures in the host quartzite and greywackes of the Mississagi Formation of the Huronian Supergroup, are best observed when obliquely illuminated by the late afternoon light. The site on Ramsey Lake Road is one of the best and most easily accessible. There are numerous shatter cones in these exposures, most being 20 to 30 cm in size. Please do not break samples from this site.

First noted in the early 1960's by Dr. Robert Dietz, the shatter cones, which were produced by strong shockwave(s) traveling through the rock, occur in all rocks outside of the Sudbury Basin, but not within, and have been attributed to the Sudbury Event which formed the Sudbury Structure. The shatter cones are widely accepted as evidence of a meteorite impact.

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