**GEOLOGY AND REGIONAL HYDROTHERMAL ALTERATION OF THE
CRATER-FILL, ONAPING FORMATION: ASSOCIATION WITH Zn-Pb-Cu
MINERALIZATION, SUDBURY STRUCTURE, CANADA**

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the requirements for the degree of Doctor of Philosophy

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ABSTRACT

This study of the impact crater-fill sequence (Onaping Formation) in the Sudbury Structure reveals significant features critical to our understanding of modification processes and water-rock interaction in large (~200 km) impact structures. The crater-fill sequence has a distinct mappable stratigraphy and consists of three informal members, the Garson, Sandcherry and Dowling, that have different vitric morphologies, percentage of matrix and lithic fragments and depositional characteristics. A distinct, coeval set of aphanitic dykes occupy syn-depositional faults and fractures.

Similarities of trace, REE and isotopic data of least altered andesitic Onaping Formation melt, felsic norite and quartz diorite of the Sudbury Igneous Complex (SIC) supports the interpretation that they represent an initial melt composition. The Onaping Formation was emplaced early, prior to differentiation and/or emplacement of the SIC in its present position.

Stratigraphy, morphology, structural controls and geochemistry of the Onaping Formation constrains the timing and evolution of the Sudbury Structure. A two stage history of crater-fill is recorded. Stage 1 involves, the emplacement of Garson and Sandcherry member units as products of slumping and fallback followed by intrusion of andesitic melt into crater floor-fractures. Stage 2 involves, large-scale, crater wall collapse along superfaults outside of the transient crater followed by melt-water interaction that resulted in “phreatomagmatic” explosive eruptions to produce the Dowling member. The basal intrusion was then injected along pre-existing fractures formed in Stage 1.

The crater-fill succession records a major impact-induced, hydrothermal system at $1848.4 \pm 3.8/-1.8$ Ma that produced low temperature, ($<250^{\circ}\text{C}$) carbonate-hosted Zn-Cu-Pb subseafloor replacement-type deposits within the crater-fill. Mineralogical, geochemical and mapping data show a complex hydrothermal history controlled by the structural, magmatic and stratigraphic history of the impact crater. Alteration zones include a regional, upper calcite zone, transition zone, chlorite zone, albite zone and lower silicification zone. Field, textural, stable and radiogenic isotope data for the regional carbonate zone are compatible with magmatic CO_2 diluted by Proterozoic seawater. The Sudbury Structure is the largest, well preserved example of a terrestrial impact crater and records a distinct history of crater-fill emplacement and a productive hydrothermal system that is unparalleled in other impact craters on Earth.

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STATEMENT OF ORIGINAL CONTRIBUTION

This thesis is based on over 6 months of detailed mapping in the Onaping Formation by the author in 1993, 1994 and 1995. Ten original maps of the stratigraphy, alteration and structure in the Onaping Formation are presented at 1:2000 to 1:5000 (pocket) as well as page-sized maps. The stratigraphy of the Onaping Formation was revised and the link recognized between stratigraphic, structural, magmatic and alteration events in the Onaping Formation. This represents the first systematic mapping of alteration assemblages and paragenetic sequence in the Onaping Formation.

The geochemical data of least altered and altered Onaping Formation is original and this is the first definition of a least altered glass composition in the Onaping Formation. Original geochemical data includes over 250 analyses of whole rock, trace element and rare earth element data. Original mineral chemical data includes 1,993 analyses of silicate, carbonate, oxide and sulphide minerals in the Onaping and Vermilion Formations and Errington Zn-Pb-Cu deposit. First systematic stable and radiogenic isotope study of alteration in the Onaping and Vermilion Formation including C, O, Sr and U-Pb data with the data analyzed by others noted in the text. First direct dating of hydrothermal system in Onaping Formation or any meteorite impact crater. The U-Pb work was published in *Geology* in the paper "Dating of a regional hydrothermal system induced by the 1850 Ma Sudbury Impact event", May, 1998, v. 26, no. 5 p. 447-450, authored by D.E. Ames, D.H. Watkinson and R.R. Parrish.

Data sources for figure compilations or modifications to previous studies are acknowledged in the text and/or figure captions. Major, trace and rare earth element geochemical analyses for this study were performed by employees in the analytical labs at the Geological Survey of Canada. Sr isotopic analyses of carbonates were determined by Dr. Brian Cousens at Carleton University; C-O data of carbonates by the Ottawa-Carleton Isotopic laboratory at Ottawa University and O-isotope data from Saskatchewan University. U-Pb geochemistry of zircon and titanite was done by the isotope lab at the Geological Survey of Canada with picking done by the author and regression of data by Dr. R. Parrish. Mineral chemical data was collected predominantly by the author with less from Dr. I. Kjarsgaard.

Collectively, this research has led to the development of a new model for deposition and alteration of the impact crater-fill sequence with implications for the evolution of the Sudbury Structure as a whole. This dissertation provides the first comprehensive investigation of regional-, local- and deposit-scale hydrothermal alteration with respect to stratigraphy in the Onaping Formation, illustrates their interrelationships and significance to ore-forming processes in the Sudbury Structure.

DEDICATION

With love, to my family.

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Chapter 1

INTRODUCTION

Regional-scale semiconformable alteration zones are recognized as an important component of subseafloor convective hydrothermal systems (Eastoe et al., 1987; Franklin 1996; Galley, 1993) that are commonly linked to the formation of volcanogenic massive sulphide (VMS) deposits, although their exact role in the ore-forming processes is not well understood. The Sudbury Structure presents a unique opportunity to examine extremely well preserved and exposed, semiconformable alteration zones within a 1.4 km thick succession of vitric breccias, the Onaping Formation, that constitute the footwall to 6.4 Mt of replacement type Zn-Cu-Pb massive sulphide at the Errington and Vermilion deposits (Figure 1-1), (Jonasson and Gibson, 1993; Ames and Gibson, 1995; Ames et al., 1998). What makes this study truly unique is that the hydrothermally altered breccias and the ore deposits occur within a meteorite impact crater. The possibility that the underlying Sudbury Igneous Complex (SIC) may be the heat engine for this large hydrothermal alteration system raises the question of the temporal and/or genetic relationship between the alteration in the crater-fill sequence and Cu-Ni-PGE mineralization. The knowledge and research on the ore deposits and occurrences within the Whitewater Group of the Sudbury Structure is vastly overshadowed by the voluminous literature on the famous Cu-Ni-PGE deposits located in the footwall and along the outer rim of the SIC.

Although the Sudbury Structure is an atypical setting for a VMS camp, the basic components are present. These include; 1) a heat source (SIC, and impact event), 2) a 1.4

km thick vitric fragmental sequence of andesitic composition (Onaping Formation), 3) hydrothermal alteration (silicification, alkali metasomatism, chloritization, carbonatization), and 4) Zn-Cu-Pb deposits and occurrences. These alteration types have been observed in conventional VMS camps but in no one camp are all types present as they are in the Sudbury basin. The volume of altered rock in the Sudbury Structure hydrothermal system (minimum 3600 km³ -9000 km³) is vastly greater than that in many classic VMS camps such as Noranda (225 km³; Gibson and Watkinson, 1990; Hoy, 1993; Cathles, 1993), Sturgeon Lake (400 km³, Franklin pers. comm.), Snow Lake (2000 km³, Galley, 1993) and is more similar in size to large-scale semiconformable alteration systems in intracontinental and epicontinental rift systems such as, the Iberian pyrite belt and Bergslagen VMS districts (Galley, 1993).

This dissertation focuses on the Onaping Formation, a crater-fill sequence that forms the footwall to, and hosts Zn-Cu-Pb deposits within the Sudbury Structure. The purpose is to determine a) the stratigraphic and/or structural controls on hydrothermal alteration zones b) the spatial distribution, mineralogy, mineral-chemical characteristics, timing and origin of the alteration types and c) the relationship between regional-scale hydrothermal alteration with intra-Onaping base metal occurrences and the overlying Zn-Cu-Pb massive sulphide deposits.

More than six months of mapping by the author mainly in 1993-1995 provided the framework for detailed stratigraphic and alteration analysis in the Onaping Formation (Figure 1-2; Appendix 1). Mapping was facilitated using 1:2000 scale enlargements of airphotos with initial map area selections based on discussions with H.L. Gibson

(Laurentian University), S. Gibbins and L. Nunes, (Falconbridge Ltd.). Logging and sampling of Falconbridge Ltd. drillcore enhanced the coverage of the Errington deposit, Cow Lake base metal, and Azilda peperite showings. Detailed mapping areas (~1:2000 scale) were selected to include A) control stratigraphic/alteration sections across the entire Onaping Formation (Morgan Township, North Range, Map 1) Garson powerline, South Range B) areas of intense alteration (albitization; Joe Lake, Map 2 and Nelson Lake, Figure A2-4.1; fracture-controlled silicification, Hanmer powerline; actinolite veining, Capreol, Map 3), C) regional carbonatization (Maps 1 and 4), D) peperite (A&M, Gordon Lake road, Azilda) and E) intra-Onaping base metal showings (Simmons (Map 5), Cow Lake (Map 4), McNunes, Ryan, Limerick). Studies of the Zn-Cu-Pb deposits and alteration along the Vermilion/Onaping formations contact were based on mapping by Gray, (1995; LW showing) and Paakki, (1992; Errington deposit). Re-mapping of the A&M peperite involved use of a base map of M. Gray and H. Gibson, Falconbridge Ltd/Laurentian University. The significance of each map area is summarized in Appendix 1.

This thesis is basically divided into 3 components: 1) stratigraphy, structure and “primary” geochemistry; 2) alteration characteristics and age relationships; and 3) isotope geochemistry of alteration minerals and rocks.

In Chapter 2, the stratigraphic framework outlining the complex depositional features of the Onaping Formation is examined. Detailed studies defined syn-depositional structures through facies analyses, architecture of the fragmental pile and structural analyses of dykes. These syn-depositional structures controlled the emplacement of units

in the Onaping Formation, focused hydrothermal fluids and defined the orientation and distribution of the paleo fault-fracture system. U-Pb geochronology of xenocrystic zircon within these dykes provides information on the source and or pathway of the melt.

In Chapter 3, the precursor composition of least altered Onaping Formation is determined as a background for superimposed hydrothermal alteration. The significance of the revised stratigraphic and new structural and geochemical data presented here to the interpretation of the Onaping Formation as it relates to the Sudbury Structure is summarized and discussed at the end of Chapters 2 and 3.

Chapter 4 defines the hydrothermal metasomatic effects that are widespread in the Onaping Formation; these are divided into regional and local alteration zones and discordant alteration zones associated with base metal mineralization. The morphology, contact relationships and controls on the distribution of various alteration zones were determined through detailed mapping and followed up by petrography, scanning electron microscopy and mineral chemistry. The emphasis in the detailed alteration study was on mineralogical rather than bulk geochemical processes. Mineral assemblage, mineral chemical data as well as bulk rock chemical changes during alteration help define the nature of the hydrothermal system and conditions of alteration. The temporal relationships of various alteration types are important in order to determine a syn-depositional or syn-kinematic origin or an even later event. The relative timing of alteration was deduced through macroscopic field relationships and petrographic observations of textural and paragenetic features with two hydrothermal systems defined. U-Pb geochronology of hydrothermal titanite links the age of regional albitization in the

Onaping Formation with the 1850 Ma Sudbury event (Ames et al., 1998) and thus provides a marker age for the relative timing observations determined for other alteration types.

In Chapter 5, the sulphide and alteration mineral chemistry of the 4.36 Mt, Errington Zn-Cu-Pb-Ag deposit at the Onaping/Vermilion Fm. contact and the Cu-Zn-Pb showings throughout the Onaping Formation, characterize and contrast the base metal-producing hydrothermal fluid chemistry from regional, more diffuse, low temperature hydrothermal fluid signatures. This has implications in unravelling the regional alteration associated with syngenetic Cu-Zn deposits in more typical VMS settings.

Chapter 6 defines the stable isotopic signature of the regional alteration zones, focused discordant alteration zones and the Errington massive sulphide deposit in order to provide further constraints on the interpretation of the source, composition and temperature of fluid that altered the Sudbury Structure crater-fill sequence. These include $\delta^{18}\text{O}$ of alteration minerals and whole rocks and C-O-Sr isotopic data for the carbonates. Preliminary oxygen isotope data was collected to determine the feasibility of defining paleoisotherms. In typical VMS settings, main sources of carbon proposed for regional semiconformable carbonate alteration zones are seawater, magma/mantle degassing and oxidation of organic carbon. Sources proposed for carbon in the Onaping Formation include degassing of the SIC (Paakki, 1992) and/or transformation of the organic carbon in the Onaping Formation (Gray, 1995). These and other possible sources of carbon as well as possible Sr sources for the regional zone of carbonatization are examined. Ore deposition commonly accompanied by siderite precipitation may overprint regional

alteration zones, and the source of carbon in the ore deposits could be different than the regional source. The C-O isotopic signature of carbonate in the Errington massive sulphide deposit was studied to observe changes in hydrothermal conditions possibly preserved in the various paragenetic and compositional phases of carbonate (calcite-dolomite-siderite). A possible link between regional-scale and deposit-scale carbonatization is addressed.

This research therefore contributes not only to the understanding of the Sudbury Structure but also to the fundamental knowledge of the nature of subsurface processes in base metal producing hydrothermal systems.

Figure 1-1: Regional geology of the Sudbury area, Ontario (modified after Card and Jackson, 1995). BDZ-Benny deformation zone, PCDZ- Pumphouse Creek deformation zone.

■ MAP AREAS (1992-1996)

Map 1-Morgan Township (Twp.)
 Map 2-Joe Lake, Wisner Twp.
 Map 3-Rockcut Lake, Norman Twp.
 Map 4-Cow Lake, Dowling Twp.
 Map 5-Simmons Lake, Dowling Twp.
 (in pocket)

GLRd=Gordon Lake road area
 FLF=Fecunis Lake fault area,
 also Diabase Lake
 NL= Nelson Lake area
 HPL=Hanmer powerline
 GPL=Garson Lake powerline

* Detailed map areas, peperite localities

A) A&M showing
 B) Gordon Lake Road
 C) Azilda

□ Other Whitewater Group Map Areas

a. Gibbins et al, 1994
 b. Gray et al, 1995
 c. Paakki et al, 1992

• Zn-Cu-Pb occurrences

Figure 1-2: Location of map areas including peperite showings and sulphide occurrences, Onaping Formation, Sudbury Structure

Chapter 2

GEOLOGIC SETTING OF HYDROTHERMAL ALTERATION AND MINERALIZATION WITHIN THE ONAPING FORMATION

2-1. Introduction

The purpose of this chapter is to describe the geological setting of hydrothermally altered rocks and polymetallic massive sulfide deposits in the Whitewater Group, Sudbury Basin (Figures 1-1 and 1-2). This chapter will focus on the stratigraphic and structural architecture of the Onaping Formation with emphasis placed on the geologic features significant to understanding the setting, interpretation and genesis of the alteration and ore deposits. These results may influence interpretations on the emplacement and/or origin of the Onaping Formation and its Zn-Cu-Pb deposits, the Sudbury Igneous Complex (SIC) and the evolution of the Sudbury Structure.

2-2. Nomenclature

A voluminous body of literature exists on the geology of the Sudbury area spanning a century since the discovery of nickel in the late 1800's. The terminology and nomenclature is either unique to the Sudbury Structure or a combination of meteorite impact, igneous or volcanology terms. Part of the problem in describing rock types in the Sudbury Structure is that the names are genetic and not descriptive. The terms and mapping terminology used in this dissertation are listed and defined in Appendix 2-1.

2-3. Regional Geology

The Sudbury Structure (Appendix 2-1) is situated on the east-west boundary between the Archean Superior and Proterozoic Southern Provinces (Figure 1-1). The Archean basement under the northern half of the Structure includes from southeast to northwest, the high-metamorphic grade Levack Gneiss Complex forming an arcuate belt around the northern part of the SIC, the Cartier batholith and Benny greenstone belt (Figure 1-1). The Southern Province basement includes largely sedimentary rocks of the Huronian Supergroup (Card et al., 1984). It is generally accepted that the Sudbury Structure is the result of a meteorite impact; however, the origins of melt (Appendix 2-1), mechanisms of emplacement and timing are controversial (OGS special volume 1, 1984; Chai and Eckstrand, 1994; Grieve et al., 1991; Naldrett et al., 1986; Lightfoot et al., 1997). It is beyond the scope of this thesis to outline the current controversies regarding the complex Sudbury geology .

The Sudbury Structure covers some 15 000 km² in area, with the most prominent feature the 1850 Ma (Krogh et al., 1984) SIC and the inner Whitewater Group which forms the Sudbury Basin (Figure 1-1). Main units of the SIC are: 1) norite, gabbro and granophyre of the Main Mass of the Sudbury Igneous Complex, 2) concentric and radial dykes of quartz diorite or “Offset dykes”, and 3) the Sublayer, a discontinuous zone of inclusion-rich norite at the base of the main mass (Figure 1-1), (Grant and Bite, 1984, Lightfoot et. al., 1997; Corfu and Lightfoot, 1996; Pattison, 1979). The emplacement process and timing of the SIC is controversial, with various schools of thought defining it

1) as an *in situ* differentiated impact melt sheet (Grieve, 1994; Deutsch et al., 1995), 2) a strongly crustal-contaminated, differentiated magmatic body (Naldrett and Hewins, 1984) or 3) a two-magma body with an endogenic, norite base overlain by granophyre; a proposed impact melt (Chai and Eckstrand, 1994).

Timing of the meteorite impact event at Sudbury is interpreted as the age of the SIC magmatic event (Krogh et al., 1984), supported by geochronology results of shocked zircon (Krogh et al., 1996 as compiled in Figure 2-1. The duration of impact events from shock metamorphism to impact-induced hydrothermal alteration in the Sudbury Structure is within the error of U-Pb geochronology, <4 Ma (Ames et al., 1998).

The Whitewater Group within the Sudbury Basin consists of 4 formations (Rousell, 1984; Martin, 1957, Stoness, 1994). The stratigraphically lowest formation within the group is the Onaping, followed by the Vermilion, Onwatin and Chelmsford Formations (Figure 1-1). The fragmental Onaping Formation has traditionally been thought of as 1) a fallback (suevite) breccia and erosion of the crater walls (exogenic theory: Peredery, 1972; Peredery and Morrison, 1984; Grieve et al., 1991; Avermann, 1994) or 2) an explosive volcanic breccia (endogenic theory: Thomson, 1957; Williams, 1957; Stevenson, 1972, 1990; Muir, 1984). Recent studies by Falconbridge Ltd. (1988-1993), Gibbins (1994) and including this dissertation, have produced geological evidence indicating a complex yet mappable depositional history for this formation. The 1.4 km thick, Onaping Formation is conformably overlain by carbonate and turbidite units of the 5-50 m thick Vermilion Formation. It is in turn conformably overlain by 1.1 km of carbonaceous shale of the Onwatin Formation and then greywacke-turbidite units of the

Chelmsford Formation. Details of these units are further described in Ames et al., (1997) and references therein.

The Whitewater Group is transected by a number of intrusive suites. The Onaping Formation is cut by penecontemporaneous intrusions restricted to the Onaping Formation which include aphanitic dykes and the igneous-textured, Basal Intrusion. Aphanitic dykes are commonly flow-banded, amygdaloidal and/or spherulitic with local massive interiors. The base of the Onaping Formation is commonly intruded by the xenolith-rich “Basal Intrusion” (Gibbins, 1994; Table 2-1; North Range Basal Member of Muir and Peredery, 1984). In the Joe Lake area (Map 2), the Basal Intrusion at the exposed base of the Onaping Formation truncates a fluidal-breccia complex and associated aphanitic dykes, suggesting a temporal difference for the two intra-Onaping Formation intrusions. Both of these intrusive types are related to the emplacement of the Onaping Formation, and will be described in further detail in Section 2-4.

The granophyre of the SIC is reported to intrude the base of the Onaping Formation (Muir and Peredery, 1984; Dressler, 1984). However, Grieve and Therriault (pers. comm.) suggest that the impact melt (SIC) squeezed up into its’ breccia cover during crater collapse: similar to that proposed for the Popigai crater (Masaitis, 1996). The youngest intrusive units are northwest-trending mafic dykes that form the regional, 1238 Ma “Sudbury diabase dyke” swarm (Krogh et al., 1987); such dykes were mapped in the Joe Lake area (Map 2).

Structure and Metamorphism

Prior to the 1850 Ma Sudbury Event, the northern footwall rocks were affected by several deformation and metamorphic events during the Archean, and the Proterozoic southern footwall rocks record two major tectono-metamorphic events (Card, 1978; Card and Innes, 1981; Wodicka, 1997; Dressler, 1984; Riller and Schwerdtner, 1996). Coeval with the Sudbury Event are a series of faults, fractures and zones occupied by 1) Onaping Formation melt (Ames and Gibson, 1999; this dissertation), 2) offset dykes (Grant and Bite, 1984), 3) pseudotachylite generally known as Sudbury Breccia (Dressler, 1984; Thompson and Spray, 1994), 4) footwall breccia (Farrow, 1994), 5) Cu-Ni-PGE mineralization (Pye et al., 1984). Shock metamorphic features in the Sudbury Structure include shatter cones (Dietz, 1964; Gibson and Spray, 1997) up to 20 km from the SIC, planar deformation features in zircon from the Levack gneiss and Onaping Formation (Krogh et al., 1984; Krogh et al., 1996), impact diamonds in the Onaping Formation (Masaitis et al., 1997), planar deformation features in quartz, feldspar, and kink bands in biotite 8-10 km from the SIC (Dressler, 1984).

Regional metamorphic grade increases from north to south across the Sudbury Structure from lower greenschist grade in the North Range to amphibolite grade in the South Range (Card et al., 1984; Card, 1978). The SIC and Onaping Formation in the North Range are largely undeformed, affected only by broad open folds, although deformation in the South Range is intense and attributed to the (ca. 1850 Ma) Penokean Orogeny (Cowan and Schwerdtner, 1994; Shanks and Schwerdtner, 1991; Card and Jackson, 1995). Major folding occurs about northeast- and northwest-trending axes (Rousell, 1975; Card, 1978; Cowan and Schwerdtner, 1994). The result has been an

overall northwest-southeast compression of the SIC and Sudbury Basin resulting in the prominent elliptical shape. Recumbent and thrust faulting focused mainly in the southern half of the structure (Figure 2-2). The 5 x 50 km, ductile, South Range shear zone affects the Onaping Formation in the footwall to the Errington and Vermilion Zn-Cu-Pb deposits (Figure 2-2) (Shanks and Schwerdtner, 1991).

High resolution seismic data (Milkereit et al., 1992; Wu et al., 1994) show the strong asymmetric shape of the Sudbury Structure at depth due to northwest directed thrusting. A reconstruction of the subsurface of the Sudbury Structure produces a basin-shaped SIC, 6 km deep, with the Onaping Formation extending to ~4 km depth (Card and Jackson, 1995; Wodicka, 1997). Alternatively, a parabolic shape was reconstructed with a large accumulation of Onaping Formation at depth (Wu et al., 1994).

Mineralization

The Sudbury Structure is the focus for Ni-Cu-PGE, Zn-Cu-Pb and gold mineralization of variable ages (e.g. papers in Pye et al., 1984; Lightfoot and Naldrett, 1994) and is best known as one of the world's largest producers of Ni-Cu-PGE ores (production 125,365,849 tons @ 1.45%Ni, 1.0% Cu and reserves of 158,071,549 tons @ 1.46%Ni and 1.09%Cu; GAC-MAC 1999, First Circular) . Of interest to this dissertation is the presence of Zn-Cu-Pb occurrences and deposits within the Onaping and Vermilion Formations in the Sudbury Basin which are discussed in Chapter 5 (Figure 1-2).

Further details on the regional geology of the Sudbury area are reported in the Ontario Geological Survey Special Volume 1, The Geology and Ore Deposits of the

Sudbury Structure (Pye et al., 1984), the Ontario Geological Survey Special Volume 5, Proceedings of the Sudbury - Norilsk Symposium (Lightfoot and Naldrett, 1994) and references in the text.

2-4. Geology of the Onaping Formation and Associated Intrusions

The remainder of this chapter will focus on the characteristics of the Onaping Formation, associated intrusions and syndepositional structures. Determining the interrelationship between deposition, magmatism and faulting is key to understanding the distribution and character of hydrothermal alteration and mineralization hosted within the Onaping Formation. The descriptions are based on 1:2000 scale mapping and complementary petrography carried out during this study on the Onaping Formation strata, alteration mineral assemblages and base metal occurrences within the Sudbury Basin (Figure 1-2; Appendix 1, Maps 1 to 5). This mapping was integrated with the results of mapping carried out in 1988 to 1993 by Falconbridge Ltd. under the direction of Harold Gibson and Paul Severin, and in particular the studies by Gibbins (1994), Paakki (1992), Stoness (1994) and Gray (1995).

The Onaping Formation is divided into the Garson, Sandcherry and Dowling members (Gibbins, 1994; Ames et al., 1997), (Table 2-1, Figures 2-2, 2-3; Plate 2-1). The most discernible primary features for each member will be described in this chapter although much of the Onaping Formation is hydrothermally altered (Chapters 3-5). The detailed features of each unit are summarized in Tables 2-2 and 2-3 and representative photographs of each unit are shown in Plate 2-1.

2-4a. Garson Member

The basal Garson member includes the “quartzite breccias” of Stevenson (1961), the “Basal Member of the South Range” described by Muir and Peredery (1984), and parts of the South Range “Gray Member” (Dressler, 1984). It has been traced by H. Gibson along the southeastern margin of the Sudbury Structure for approximately 25 km, and is up to 500 m thick in places (Figure 2-2). Definition of the original extent and thickness of the unit is complicated by tight folding and fault offsets. Many of the primary features of this member are obscured by a well-developed penetrative schistosity, a result of the South Range Shear zone and metamorphism (Figure 2-2). It consists of 1 to 100 m thick, poorly sorted beds of clast- to matrix-supported breccia and mega-breccia with blocks of quartzite, up to 30 m in diameter, and subordinate aphyric andesite, gneiss and andesite-coated gneiss (cored bombs), (Plate 2-1a). The blocks are both normally and reversely graded, with some poorly sorted layers. The matrix to the blocks consists of sand to pebble-sized clasts of quartzite, quartz and feldspar, with up to 20% chlorite-rich, angular fragments that resemble devitrified glass shards.

The Garson member formed either as: a) mass flows that originated along the crater walls when the mixing of andesitic melt and water resulted in hydro-magmatic brecciation (Gibson, pers. comm.); or b) as debris flows possibly slumped off a quartzite-dominated (Huronian) peak ring or central peak structure. In the reconstructed Sudbury crater, the South Range is considered to be close to the centre of the original basin (Golightly, 1994).

2-4b Sandcherry Member

The Sandcherry member conformably overlies the Garson member, and can be traced about the circumference of the Sudbury Structure (Figure 2-2). It includes the former Gray Member and parts of the overlying Black Member as defined by Stevenson (1961), Peredery (1972) and Muir and Peredery (1984). It has an apparent thickness between 50 to 1485 m (averages 760 m) over a well constrained 15 km strike length on the North Range (Figure 2-4). On the North Range the general strike of the Sandcherry member is $065\text{-}070^\circ$ although at the eastern and western part of the Sudbury basin the strike changes (Figure 2-2). The paleotopographic relief on the upper surface of the Sandcherry member is up to 750 m, which is similar to the average apparent thickness of the entire member. The dip of the Sandcherry member is unknown. Its true thickness would be close to 500 m if the 40° dipping upper contact of the SIC is conformable with the base of the Sandcherry member. The thickness would be only 360 m if the 28° average dip of the overlying Dowling member is taken as the average dip for the Onaping Formation.

The diachronous nature of carbon in the Onaping Formation has resulted in large areas of carbon-bearing Sandcherry member strata erroneously being assigned to the upper Onaping Formation (Black member). The thickest parts of Sandcherry member strata are exposed on the atypical, type section at highway 144 (Bonney, 1888) and also in Morgan township (Map 1). Unfortunately, numerous field trips, papers and theses described the Black member (i.e. upper part of the Onaping Formation) from outcrops of

the carbon-bearing lower Onaping Formation or Sandcherry member exposed on highway 144.

The Sandcherry member is characterized by the presence of over 60% by volume of glass fragments known as either “fluidal fragments” or “blocky shards” and may or may not contain carbon (Gibbins, 1994). Lapilli-tuff units dominate with subordinate lapillistone, tuff breccia and tuff units. Fluidal fragments are irregular, flow-banded, amoeboid-shaped, rounded to sub-angular clasts of aphyric andesite (Plate 2-1c,d). Blocky shards are angular, lapilli-size, chlorite-altered vitric fragments that commonly have vesicles (Plate 2-1b). Flow-banded aphyric andesitic blocks, aerodynamically-shaped andesitic bombs simple, cored and complex are an integral part of the member (Plate 2-2; Appendix 2-1; Table 2-1). Other fragment types common within this member are lithic fragments such as granitoid, gneiss, amphibolite, gabbro and quartzite, in decreasing order of abundance (Peredery, 1972; Muir and Peredery, 1984). Point counts of hand samples indicated lithic fragments comprise 5% on average (Gibbins, 1994) of the Sandcherry member, however in outcrop the abundance of lithic fragments range from 5 to 15%.

Variations in the ratio of fluidal fragments to blocky shards in the Sandcherry member allow it to be divided into three unit types; equant shard units, fluidal fragment units and transitional units (Table 2-2).

Equant shard units are the most common unit of the Sandcherry member, and are laterally continuous, non-bedded to weakly bedded and characterized by abundant (>50%) pink to dark green, equant, fine lapilli-sized vitric fragments termed shards (Table 2-2;

Figure 2-4; Plate 2-1b). Tuff units dominate with subordinate lapilli-tuff. There is a crude bedding defined by variations in vitric and lithic clast size and percentage, although bedding contacts are difficult to define. Where measured they have inconsistent strikes that range from 010° to 120° , and few measurements indicate shallow ($<30^{\circ}$) dips. Contacts with the fluidal fragment units are dominantly intrusive and rarely gradational (Appendix 2-3).

Accretionary lapilli were reported by Peredery (1972) within this unit. Simple, cored and complex andesitic bombs are common and range up to 2 m (Table 2-2; Plate 2-2). Lithic fragments are dominantly angular to subrounded granitoid, quartzite, white vein quartz, gray to white chert, and pale green aphanitic sedimentary fragments and chlorite-actinolite clots some of which are mafic fragments (Table 2-2; Appendix 2-2, 2-3). Blocks tend to be granitoid whereas finer lithic fragments are dominated by sedimentary clast types. The matrix is fine polycrystalline and contains disseminated <2 mm pink weathering shards.

Fluidal fragment units are distributed throughout the equant shard units as laterally discontinuous bodies that are typically discordant to bedding (Figure 2-4; 2-5; Maps 1 and 2). Their distribution is controlled by syn-depositional faulting (Figures 2-5 and 2-6; Appendix 2-2) and these units are abundant, proximal to the Fecunis Lake and Sandcherry Creek faults. The bodies commonly have an irregular shape and high aspect ratio, with height to width varying between 1300:150 to 1000 m (Figure 2-5). They locally occur at the intersection of faults (Figure 2-6). Fluidal fragment units are observed throughout the

Sandcherry member as vertically stacked or isolated units. Generally these units occur in the lower half of the Sandcherry member (Figure 2-4; Maps 2, 3) although proximal breccias and associated aphanitic dykes locally extend into the base of the overlying Dowling member (Figure 2-5; Map 1).

These breccias are spatially and genetically associated with flow-banded aphanitic dykes and thus the intrusive/extrusive units were collectively called “Fluidal Breccia Complexes” (Gibbins, 1994). The units are characterized by abundant (45-85%), tabular, flow-banded fragments and less than 15% equant shards (Table 2-2). Fluidal breccia complexes may be subdivided into 3 depositional facies (proximal autobrecciated to massive, intermediate and distal), based on variations in the size and percentage of vitric fragments and matrix. The proximal facies of the fluidal breccia complexes consists of closely-packed lapilli to block-size, irregular-shaped, wispy fragments of flow-banded andesite and minor massive andesite mixed with contorted, irregular-shaped andesite bombs that together comprise 80-85 % of the outcrop. Non-brecciated andesite has very contorted flow-banding that is locally concentric and the contacts of these discontinuous bodies are autobrecciated (Plate 2-4). Cuspate, bud-like aphanitic pods project into their own breccia pile. In the Joe Lake and Nelson Lake areas (Map 2, Figure 2-9), fluidal fragments are more vesicular proximal to massive units and contain very amygdaloidal, irregular fluidal bombs (Plate 2-2). Fluidal fragments in massive to autobrecciated facies at Morgan are less vesicular. Proximal fluidal units contain contorted, irregular bombs (Plate 2-2), wispy, torn, delicate flow-banded fragments that represent spatter (Appendix 2-3) and bombs that are chloritic and brown weathering. Some vitric blocks are bleached in

“unaltered” massive to autobrecciated units. The proximal autobreccia is intruded by flow-banded to massive bodies of andesite that form bud-like apophyses, irregular-shaped and sharp walled dykes and sills (Appendix 2-3; 2-4). Dykes may have hyaloclastite-like, quench fragmented and peperitic margins. The dykes are discussed further in section 2-4d.

The intermediate facies locally forms an apron, or margin on the proximal breccias and consists of fewer lapilli-sized flow-banded andesite fragments with a higher proportion of matrix than the proximal facies (Table 2-2; Figure 2-6). Contacts between facies are gradational. The distal facies contains up to 15% lapilli-sized equant shards and contains more matrix material than the proximal autobreccia facies, similar to the intermediate facies of the fluidal fragment units.

Fluidal fragment units contain fewer simple and cored bombs, and more actinolite-chlorite clots/ mafic fragments (Chapter 4; Figure 4-11; Plates 4-4 and 4-5) than the other units comprising the Sandcherry member. Felsic igneous blocks have corroded, irregular contacts in proximal massive to lapillistone fluidal-fragment units. Outcrop descriptions of a fluidal breccia complex in the Joe Lake area (Map 2) are presented in Ames (1997).

Transitional units are spatially related to the fluidal fragment units and are composed of a high proportion (50% to 60%) of lapilli-sized, flow-banded vitric fragments, subordinate (15% to 30%) equant shards, and minor bombs, and vitric and lithic blocks in a fine-grained, tuffaceous matrix (Plate 2-1d; Appendix 2-3). The contact between transitional and equant shard units is gradational and poorly defined whereas contacts with other facies of the fluidal fragment units are discernible over 1 m or are

sharp. The contact with the overlying Dowling member lower unit is sharp. Transitional units contain the greatest percentage of all bomb types in comparison to the rest of the Sandcherry member (Table 2-2).

Detailed mapping in Morgan township and the Joe Lake area (Maps 1 and 2) suggests that these units predate the formation of the fluidal fragment units. The abundance of complex bombs and crosscutting relationships of proximal facies units suggests that the transitional units mark the initiation of eruptions associated with the fluidal breccia complexes and may represent the initiation of melt breaching and fragmentation. This was then followed by the overprinting and emplacement fluidal complexes and generation of the various facies of the fluidal fragment units.

2-4c. Dowling Member

The Dowling member overlies the Sandcherry member, with the contact ranging from conformable, to erosional and irregular (Figure 2-4, 2-6, 2-7). The Dowling member comprises the upper 1000 m of the Onaping Formation, and includes rock units formerly known as the “Black member” and “chlorite shard unit” (Peredery, 1972; Muir and Peredery, 1984) and “Green Member” (Avermann, 1994; 1997); (Table 2-1). The Dowling member is distinguished from the Sandcherry member by the presence of fewer vitric shards (~30%) that are commonly dark green, lenticular, cusped and amygdaloidal and a greater percentage of matrix (~60%), (Gibbins, 1994) and it is generally finer grained (Peredery, 1972), (Plates 2-1, 2-3 and 2-4; Table 2-3). Variations within the

member allow it to be subdivided into four unit types; the contact, lower, middle and upper units (Gibson et al., 1994; Gibbins, 1994), (Tables 2-1; 2-3).

Contact units occur intermittently at the base of the Dowling member, around the circumference of the Sudbury Basin, with thickness' ranging from 35 to 300 m (Figure 2-5, Maps 1 and 2). Whereas earlier descriptions of this unit by Dressler (1987), Gibbins (1994) and Avermann (1997) defined a single unit as a continuous sheet that mantles stratigraphy, mapping during this study has demonstrated that the contact unit in some areas consists of two or more depositional units that occur as discontinuous segments (Figure 2-5; Map 1). This was also observed in the Diabase Fault lake area, near the Fecunis Fault.

Conformable, erosive and fault contacts are present (Appendix 2-2d). Bedding averages $060/39^{\circ}$ in the contact units and is defined by variations in the size and abundance of vitric fragments, block distribution and flattening of chlorite shards (Figure 2-5 inset). Bedding within the contact units is commonly in angular discordance to the surrounding Sandcherry member units along strike, and the discordant contacts are knife sharp and occasionally dyke-filled (Figures 2-7, 2-5). Shards in the contact unit are neither flattened parallel to the sharp contacts with Sandcherry member equant shard units nor is there flow-banding in fluidal fragments that parallels the contact. Therefore, the contact units were not controlled by these topographic features. These observations suggest that these structures are faults and that the contact units were deposited prior to faulting. The

continuous nature of overlying units (Figure 2-5) indicate that its emplacement was temporally related to a short period of syn-depositional faulting .

The contact units can be subdivided into 4 components, with the basal layer being the thinnest (5 to 10 m) and succeeding components up to 130 m thick dominated by tuff and minor lapilli tuff units (Plates 2-1f, 2-3). Progressing upsection these are characterized by 1) a block or lapilli-rich base with subequant blocky shards 2) a change in the morphology of shards from blocky to wispy and lenticular (Plate 2-4) 3) the percentage and size of shards decreases (fining upwards) and 4) the abundance of matrix increases. There is a fining upward of fragment size, with the disappearance of flow-banded clasts and a change in the morphology of the vitric shards from blocky and subequant to wispy and lenticular (Plate 2-4). Breadcrust bombs and blocks of the underlying fluidal fragment units (Sandcherry member) occur in the block-rich basal unit of the contact units (Dowling member) and the top of this basal unit locally contains accretionary lapilli (Plate 2-3). Although accretionary lapilli are common within Sandcherry member, carbon-bearing equant shard units on highway 144 (Peredery, 1972), these have not been previously documented in any Dowling member units. In Morgan Township, the basal block-rich zone of the contact units marks the first appearance of large ~1 m basaltic lithic blocks.

Although most of the contact units are characterized by ~25% lenticular chlorite-altered shards and have minor, <10% lapilli-sized flow banded andesite fragments, they also contain rare angular flow banded blocks that include fragments of contact unit tuff and elongate (30 x 5 cm) wispy, devitrified, irregular flow banded andesite fragments that likely represent spatter (Plate A2-3.2 f). Flow banded andesite blocks and bombs are

amygdaloidal and locally scoriaceous. Welding was not observed in any of the contact units mapped within the study areas, although Gibbins (1994) documented incipiently welded contact unit tuff. Individual sections mapped on the North Range are described in detail in Appendix 2-3d.

The Lower units, Dowling member form 20-30 m thick, heterogeneous, laterally extensive, crudely stratified deposits or channelized block-rich deposits that contain lenticular shards (Figures 2-5, 2-8; Plate 2-1). These occupy topographic irregularities in the underlying Sandcherry member and have a flat upper contact (Figure 2-8). The channel-shaped deposits are small (20 x 150 m and 20 x 40 m) and are reversely-graded at their base, with subrounded lithic and vitric blocks and cored bombs (Figure 2-8; Plate 2-1; Appendix 2-3e), typical of debris flow or mass flow deposits (Cas and Wright, 1987). Lithic blocks include fragments of the underlying Sandcherry member, and the cores of complex bombs may be Dowling member contact unit. In the central Morgan area (Figure 2-5 and 2-8; Map 1), vitric blocks and cored bombs are more abundant than lithic fragments. Three dimensional observations of this debris flow unit revealed sharp, channel-shaped contacts that transect both Dowling member and Sandcherry member units (Figure 2-8). The spatial association with a fluidal vent complex (host sequence), angularity of the blocks, dominance of cored bombs and variably altered vitric blocks suggests that this mass flow deposit is proximal to a fluidal vent complex (Appendix 2-3e).

The laterally extensive lower units are heterogeneous along strike and are normally-, reversely- and non-graded lapillistone to tuff units with a change in shard

morphology from a blocky base to lenticular top (Plate 2-5). They are coarser than the contact units and contain more flow banded lapilli and vitric and lithic blocks (Table 2-3). Internal contacts between the lapilli-rich and tuffaceous units are gradational over 1 m and a sharp contact was observed between two different lower units indicating multiple mass flows. The black carbonaceous matrix hosts 20-30% lapilli-sized chlorite-rich vitric shards, 5-20% partially devitrified bluish white and pale green, flow-banded andesite and minor fine-grained clasts of gray to black chert, quartzite and granitoids and 2% fine, subrounded black quartz (Appendix 2-3e; Table 2-3).

Middle units of the Dowling member are laterally continuous about the circumference of the Sudbury Basin, reaching an aggregate maximum thickness of 780 m. They are block- and bomb-poor tuffaceous units with rare beds of very fine tuff and lapillistone and 15-25% lenticular chlorite shards (Table 2-3; Plate 2-1; Appendix 2-3). The contact with the underlying lower unit is sharp. Long axes of fine tuff pods in the middle units are parallel to well-defined beds in the middle and upper units, Dowling member unit contacts and bedding defined in the contact units (Figure 2-5 inset). Therefore, most of these represent bedding (average $070/28^{\circ}$), although randomly oriented pods, most likely clasts of lapillistone, were observed. It is difficult to define exact thickness' of individual units, however, some units are as thick as 140 m and generally thin with increasing stratigraphic height.

Three stratigraphic sections across the middle units show minor variations at the base of the sequence and define a change in the depositional style mid-way up the section

(Figure 2-9, 2-10; Appendix 2-3f). The lower 300 m contain locally poorly to thinly bedded, coarse- to fine-grained tuff beds 1- 5 m wide (A-A', Figure 2-9). In section C-C' the lowermost unit is 80-160 m wide. It has 1) a reversely graded base progressing upsection from a fine-grained ash-sized base to a block- and lapilli-rich zone containing abundant flow-banded andesite fragments, simple bombs and 2) a thick coarse section normally graded for 50 to 100 m upsection, where it changes into massive homogeneous tuff (Figure 2-8). Upsection the size and abundance of chloritic shards increase, the amount of lapilli-sized vitric and lithic fragments decrease, and, after 50 to 100 m blocks and bombs are absent. Discontinuous beds of scoriaceous fragments are rare.

Above 300 m there is a marked increase in the presence of lens-shaped ash-sized and lapillistone blocks. The upper, middle units have similar concentrations of fine chloritic shards but in detail have more coarse 0.5 to 2 cm chloritic shards than the lower middle units. These tuff units are texturally inhomogeneous with irregular (5 to 40 cm) pods of densely packed coarse, 2 cm chlorite shards. Ash-rich blocks contain abundant 1 to 2 mm lenticular chlorite-rich vitric shards and varying amounts to 20% of fine-grained lithic lapilli fragments. The lapillistone blocks contain up to 20% fine chlorite-rich shards to 2 mm in size, up to 40% coarse-grained blocky chlorite-rich shards to 4 cm in size and lapilli of blocky flow-banded andesite and lithics. These reworked block-rich layers may be up to 12 m in thickness and have strike lengths of up to 80 m, suggesting channelized deposition.

The Upper units of the Dowling member are laterally continuous about the circumference of the Sudbury Basin, and range in thickness from 140 to 220 m (Figure 2-3), (Gibbins, 1994). The unit is poorly exposed due to overburden at the top of the Onaping Formation on the North Range and is strongly deformed on the South Range. Contacts with the underlying Middle units are gradational over several meters, with the first appearance of upper units defined by outcrops with > 70% fine tuff (< 2 mm) fragments (Appendix 2-3). The upper units are generally thinly-bedded, normal to non-graded beds of reworked tuff that dip shallowly (21°) (Plate 2-1) (Figure 2-5, inset and Table 2-3). Beds range in thickness up to 50 cm, with coarse-grained sandstone bases and finer-grained, well-sorted ash-sized, sandstone tops. The abundance of the chloritic shards that are ubiquitous to the Dowling member decrease with increased stratigraphic height. They maintain a delicate morphology, with truncated bubble-wall margins with no evidence of abrasion and rounding (Figure 2-11). Detailed upper unit descriptions are in Appendix 2-2, summarized in Table 2-3 and field photographs are shown in Appendix 2-3.

The upper units likely represent reworked and redeposited, subaqueously deposited mass flow deposits transported with laminar flow suggested by the preservation of fine delicate shards in the bedded units and the angularity of lithic fragments. The upper units mark the first appearance of significant reworking and redeposition in the Onaping Formation producing thin, normally to non-graded bedded units (Paakki, 1992; Gibbins, 1994; Gray, 1995).

2-4d. Intrusive Units Associated with the Onaping Formation

There are numerous dykes and sills of andesite/quartz diorite composition that intrude and are restricted to the Onaping Formation (Figure 2-3). These have been mapped previously as a combination of glassy bodies, melt bodies and Basal Member (Peredery, 1972; Muir and Peredery, 1984). Their distribution and character have important implications with respect to the development of the Onaping-hosted alteration system and place critical constraints on the timing and genesis of the Onaping Formation.

The intrusive types are divided primarily by textures (aphanitic versus igneous-textured) as there is very little difference in composition (Chapter 3). Their timing of emplacement relative to each other is sometimes ambiguous, however the Basal intrusion which is igneous-textured locally crosscuts fluidal breccia complexes and their associated aphanitic dykes (Map 2).

Aphanitic Dykes (Plate 2-6)

A series of vitric andesitic dykes described as dykes by Muir and Peredery, (1984) and "dike-like apophyses of melt bodies" by Peredery, (1972) cut mainly the Sandcherry member of the Onaping Formation up to and including the Contact units of the Dowling member. Some of the dykes continue up into the Middle and Upper units, particularly in the stratigraphic footwall to the Errington and Vermilion massive sulfide deposits. Lower in the section they are spatially associated with Fluidal Breccia complexes and are morphologically and texturally similar to the flow banded fluidal fragments that comprise the fluidal fragment units. In general, dykes are flow banded at the base of the Onaping Formation and are more spherulitic and amygdaloidal toward the top (Appendix 2-3).

Dykes range in width up to 15 m, but are more commonly less than 50 cm wide. The dykes tend to be planar, with sharp or autobrecciated margins and apophyses that parallel bedding in the host strata or are bulbous. The dykes are commonly xenolith-rich at the microscopic scale, flow-banded, amygdaloidal and some have massive cores. Appendix 2-4 contains sketches of the dyke morphology, tables of dyke petrography, orientations and dyke contact relationships.

Dykes intrusive into the upper parts of the Dowling member may form peperite complexes up to 200 m wide and 1000 m in length (Plate 2-6, Appendix 2-5). Peperite is defined as a rock generated by mixing of coherent magma with unconsolidated wet sediment (McPhie et al., 1993). In the Onaping Formation on the North Range peperite is localized (<50 cm) at the margins of aphanitic dykes intruded into the contact units, Dowling member. However, the extent and abundance of peperite are greater in middle and upper units in the southwestern part of the South Range, particularly below the Vermilion Zn-Cu-Pb deposit (Figures 1-2; 2-12). The results of the detailed mapping of these blocky and lensoidal peperite occurrences are documented in Appendix 2-5.

Basal Intrusions

The “Basal Intrusion” of Gibbins (1994) includes intrusive units previously described as the “Basal Member” and “melt bodies” by Peredery (1972) and Muir and Peredery (1984) (Table 2-1). The larger bodies of Basal Intrusion are localized along the contact between the granophyre of the SIC and the Onaping Formation as broadly semi-conformable and sheet-like bodies (Gibbins, 1994). However, in detail, this lower zone of

basal intrusion is irregular and intrusive into Sandcherry member strata (Map 2, 3). The lower zone of basal intrusion ranges up to 300 thick and is discontinuous along the SIC/Onaping Formation contact (Muir and Peredery, 1984; Gibbins, 1994) (Fig 2-4). Smaller, semi-circular occurrences (“pipe-like” bodies, Gibbins, 1994) are more abundant within the Sandcherry member and, in particular, group near the contact between the Sandcherry and overlying Dowling member, although they cut the entire Onaping Formation (Maps 1, 2, 3; Figure 2-3).

The contact between the granophyre and basal intrusion is apparently sharp (Peredery, 1972) or gradational (Gibbins, 1994; Brockmeyer, 1990). Contacts between the basal intrusion and Sandcherry member strata vary from sharp adjacent to the equant shard units to gradational and diffuse or sharp with the Fluidal Fragment units. The lower zone of basal intrusion consists of fine-grained, intersertal-textured quartz diorite that can contain up to 85% xenoliths by volume. Xenoliths are dominantly felsic basement rocks consisting of granite, pegmatite and gneiss and metasedimentary rocks (Peredery, 1972; Muir and Peredery, 1984) that range in size from 4 mm up to 40 m. The basal intrusion has local zones that are block-rich, separated by xenolith-poor massive to flow-banded intrusion (Map 3). The larger xenoliths are locally aligned and brecciated *in situ*. Smaller xenoliths include granitoids that commonly have corroded, rounded to subrounded margins and irregular quartz-feldspar xenoliths with corroded margins, indicative of partially assimilated xenoliths (Peredery, 1972; Muir and Peredery, 1984). The host intrusion is fine-grained, sugary textured and consists dominantly of 20-35%, 0.1 to 1 mm albite laths and 15-25%, < 2 mm pyroxene/amphibole lathes in a quartzofeldspathic

matrix. It may contain amygdales, with some vugs up to 60 cm long and 15 cm wide. Vugs are filled with chlorite, epidote and quartz euhedra or coarse Kfeldspar and quartz. Amygdales contain amphibole, quartz, pyrite, pyrrhotite or chalcopyrite. Angular and subrounded chlorite/actinolite blebs and fragments are common (0-5%) and may have a bleached rim. Accessory minerals are titanite, pyrrhotite, chalcopyrite and trace chlorite, carbonate, pyrite, epidote, ilmenite, clinozoisite, marcasite, biotite and sericite.

Smaller bodies of basal intrusion commonly have xenolith-rich cores and vitric, flow-banded, amygdaloidal margins $\pm$ spherulites. The flow banded margins may form < 1 m spherulitic, amygdaloidal lobe-like apophyses into Sandcherry member strata. There is commonly a close spatial relationship between the pipes of Basal Intrusion and earlier-formed Fluidal Fragment units (Map 1, Figure 2-5, 2-6).

The basal intrusion may represent the melted basal part of the Onaping Formation due to heat from the underlying complex. This melt was locally intruded along syndepositional faults in the Sandcherry member strata forming small intrusive bodies.

Structural Control on Intrusion Emplacement

Aphanitic dykes form two major orientations across the North Range, 310/70° and 015/65° (Figure 2-13). A third trend of 065° represent apophyses off the main dykes that subparallel bedding in the host strata. The coeval dykes are not concentric or radial relative to the SIC/Onaping Formation contact and represent faults or fractures syndepositional with the Onaping Formation. The structural analyses and detailed field relationships of the aphanitic dykes are presented in Appendix 2-4.

The orientation of basal intrusions over a 25 km strike length reveals northwesterly trending linear features but no northeasterly trending zones as observed in the structural analyses of the aphanitic dykes (Figure 2-14). Individual pods commonly have northwesterly strike and subvertical dip. The distribution of small pods of basal intrusion in Morgan Township is controlled by northwest -trending syndepositional faults (Map 1; Figures 2-6, 2-14). These syndepositional faults correspond to oblique contacts between Sandcherry member and Dowling member strata, may be intruded by flow banded aphanitic dykes, are proximal to channel-shaped debris flows of the lower units and are aligned with a localized carbonate-absent area within the regional semi-conformable calcite alteration zone (Map 1B, Chapter 4).

2-5. Discussion

Irrespective of the controversy over the origin of the Onaping Formation and associated intrusions, the mapping completed over the last 10 years (Falconbridge Ltd., Gibbins, 1994; this dissertation) has demonstrated that the strata were not emplaced chaotically as the result of a single catastrophic event (Peredery, 1972; Grieve et al., 1991; Deutsch et al., 1994). Distinctly separate depositional events for the fragmental units are subtly linked to contemporaneous “magmatic” events, both of which show a strong structural control. This has several implications with respect to the development of alteration zones that affect broad areas of the Onaping Formation, and more proximal alteration systems directly associated with base metal occurrences and deposits.

The field maps appear unusually complex due to variations in outcrop relief (up to 140 m), shallow to steep dips of the units and syn-depositional faulting. It was perhaps these factors that led earlier workers to define the Onaping Formation as chaotic. In fact, the 1400 m thick Onaping Formation has a very well developed stratigraphy with nine major unit types and two intra-Onaping intrusions all distinguished by textural features.

2-5b. Fragmentation, emplacement and deposition

2-5a. Setting

The Onaping Formation was likely deposited in a shallow subaqueous environment with local subaerial “islands”. Subaerial eruption columns dominated when magma breached the earth’s surface. Evidence for a subaqueous environment of deposition includes a) the hyaloclastite-like morphologies of vitric lapilli-sized fragments along the margins of aphanitic dykes in the fluidal breccia complexes, Sandcherry member b) extensive peperite units associated with aphanitic dykes in the Dowling member and c) gradual reworking and redeposition of the upper middle units and the upper units, Dowling member. Overwhelming evidence of water in the Onaping Formation is the presence of extensive hydrothermal alteration which is described and discussed in succeeding chapters. Features suggestive of subaerial deposition are largely contained in the contact units of the Dowling member and include incipiently welded zones, accretionary lapilli and bread-crust bombs (Cas and Wright, 1991). This suggests that these units were hot when they were deposited. Reworking in middle unit time and the absence of fine tuff tops to the pyroclastic-like deposits suggests a marine environment although sedimentary features indicative of wave base are lacking (Cas and Wright, 1991).

The gradation of the upper units into the shales of the Onwatin Formation, the shallowing of dips in the Onaping Formation (Figure 2-5) and paleomagnetic data (Morris, 1984) suggest a deepening of the Sudbury basin with time. Peperite formation in the middle and upper units is theoretically restricted to <1.7 km (Kokelaar, 1982; Appendix 2-5).

2-5b. Fragmentation, emplacement and deposition

The dominant processes responsible for the production of vitric shards in volcanic deposits have been classified and serve as a base from which to develop and incorporate field observations. Characteristically blocky, equant shards are attributed to hydrovolcanic processes and passive mechanisms whereas lenticular, bubble-wall shards are due to magmatic processes and explosive mechanisms in volcanic deposits (Heiken, 1972; Heiken and Wohletz, 1991; Wohletz, 1986; Sheridan and Wohletz, 1983; Sparks, 1978; Cioni et al., 1992). Hence, the change from blocky, equant shards in the Sandcherry member to lenticular shard morphologies in the Dowling member were suggested to be the change from passive to a more explosive hydrovolcanic fragmentation upon emplacement of melt into a subaqueous environment (Gibbins, 1994).

Meteorite impact crater fill deposits are composed of suevite, a rock composed of vitric, rock and shock metamorphosed fragments (Melosh, 1989). Surprisingly little is known about natural impact breccia deposits since extraterrestrial crater observations are from photographs only and most of the terrestrial impact craters have been deeply eroded (Vredefort, Rochechouart, Mistassin, Charlevoix, Strangways, Gosses Bluff, Lappajarvi, Lake Mien), covered by post-impact sediments (Lunar, Meteor, Ries, Chicxulub) or are

essentially inaccessible (Popigai). Suevite deposits in the 15 km, Ries crater are well studied and indicate that the glass fragments in the crater-fill and out of crater deposits are minor, (5-15%) and consist of bombs and subrounded to irregular spherules (von Engelhardt, 1967; von Engelhardt et al., 1995), in contrast to the Sandcherry member glasses. Blocky, fluidal fragments are present at the large subaerially impacted Popigai crater, Russia and lenticular bubble-wall vitric fragments are present in the subaqueously impacted, Chicxulub crater, Mexico (Figure 2-15). The suevite rocks immediately above the melt sheet at Khara Khai, Rhassoka river along the western part of the Popigai crater (Masaitis, 1994) contain 60-75 % dominantly equant vitric fragments with subordinate fluidal vitric fragments (Figure 2-15). These “suevites” are very similar to the equant shard units in the lower part of the Onaping Formation.

In terrestrial impact structures, the vitric fragments in suevite are interpreted to be produced in the conical ejectal plume due to quenching and cooling of melt, possibly in the presence of water vapour if the target area contained ground and/or seawater (Kieffer and Simonds, 1980). This results in the blocky shapes that are also typical of hydrovolcanic, passive fragmentation similar to that described by Wohletz (1983).

Sandcherry member

The Sandcherry member has been variably interpreted as a fallback breccia or meteorite ground surge deposit, similar to the Ries suevite (Peredery, 1972; Avermann, 1994; Grieve et al., 1991; Deutsch et al., 1994), ash flow deposits (Muir, 1984), welded ignimbrite deposits (Stevenson, 1972; 1990) or hydroclastic breccias (Gibbins, 1994).

Gibbins (1994) discusses problems associated with the earlier interpretations and devised a new model for the emplacement of the Sandcherry member. In this model, the fluidal fragment units were interpreted as the products of explosive eruptions characterized by submarine and subaerial fountaining and spattering from vents, with associated intrusion of melt into the breccias forming intrusive hydroclastic breccias and peperites. "Intrusive hydroclastic breccia" terminology should be used for fluidal fragment units. Utilization of peperite (Gibbins, 1994) for these is a misnomer. There is no evidence of mixing with wet sediment but they intrude their own autoclastic (blocky textures therefore quenching) pile. Fluidal-fragment complexes represent intrusive hydroclastic deposits that record the quenching and fragmentation of large volumes of melt into wet fragmental rocks at shallow levels and intermittent breaching to produce redeposited hydroclastic breccias. The equant shard units (Shard-rich units of Gibbins, 1994) were interpreted as subaqueous "pyroclastic" falls of hyaloclastic flows venting from the Fluidal fragment vents similar to hyaloclastic flows on seamount summits (Batiza et al., 1984). Gibbins (1994) suggested that the units comprising the Sandcherry member represent different vent facies of the same eruptive process and that no fallback breccia is present. It is surmised that the fallback breccia may be partially represented by the lower Basal Intrusion but likely consumed by the SIC (Gibbins, 1994). The overwhelming evidence for the Sudbury Structure being an impact crater and the absence of Onaping Formation sourced xenoliths at the top of the SIC raises questions regarding the amount of assimilation of the Onaping Formation by the SIC and the timing of the granophyre relative to the base of the Onaping Formation.

An alternate hypothesis is that the equant-shard units represent a “fallback” and the fluidal breccia complexes were emplaced incrementally, as fissure controlled intrusive/extrusive complexes along northwest and northeasterly trending structures that cut the earlier “fallback” units. Pulses of melt could be injected from below due to movements in the melt sheet and earthquake activity during transient crater modification. Although in the fallback scenario previous workers (Peredery, 1972; Deutsch et al., 1994) envisioned ground surge deposits similar to the Ries suevite, there is no evidence for this type of deposition in the Sandcherry member (Gibbins, 1994). The equant-shard units are laterally extensive, non-bedded, block-rich deposits with ~60% equant shards. Vitric blocks, bombs and accretionary lapilli are more abundant near the top of the unit (e.g. carbon-bearing equant shard units with abundant accretionary lapilli, Highway 144).

In both of these scenarios the fluidal breccia complexes are interpreted to be vent complexes. Evidence for this includes the presence of multiple injections of melt or dykes intruding their own pile, autoclastic textures, dominance of large 1-2 m, flow banded vitric blocks, spatter-like textures and the linear fault control on these units (*i.e.* Morgan Township, Joe lake, Nelson lake, Crystal lake). Proximal facies fluidal units contain contorted, locally highly amygdaloidal bombs and vitric fragments, locally silicified bombs, spatter-like fragments and partially assimilated felsic lithic fragments. The majority of these were emplaced after the equant-shard and contact units as they contain fragments of these units and generally have sharp intrusive contacts. However some were likely emplaced during deposition of the equant-shard units as suggested by the presence of fluidal lapilli tuff fragments with a lithic fragment in equant shard units and rare

gradational contacts. Fluidal-fragment units locally push through the lower units of the overlying Dowling member, “jacking up” the succeeding units (Figure 2-8) indicating that melt injection was prolonged.

The apparently chaotic map distribution of such units is a consequence of partial syndepositional fault control, co-genetic dyke injection, and shallowly-dipping strata coupled with high topographic relief. The Sandcherry member formed an irregular topography that was deposited synchronously with faulting, probably during impact crater modification.

Dowling member

The Dowling member appears to have had a much different emplacement history than the Sandcherry member. The Dowling member is interpreted to have been emplaced as a combination of mass flows and debris flows, deposited on the irregular Sandcherry member topography, and volumetrically large (>3600 m) pyroclastic-like deposits followed by a period of resedimentation. Deposition of the contact and lower units of the Dowling member was concurrent with emplacement of some fluidal fragment units as fire fountaining and spatter deposited some contorted, irregular, elongate vitric fragments in the basal units of the Dowling member.

In contrast to the historical interpretation of the upper part of the Onaping Formation being material washed in from the crater walls by tsunami-like waves (Peredery, 1972; Grieve, 1994), Gibbins (1994) interpreted the Dowling as a sequence of “pyroclastic” falls, flows and subsequent mass flows. The contact units which mark the

change in deposition and fragmentation in the Onaping Formation have been interpreted as 1) the fireball layer due to final collapse of an impact ejecta cloud from high atmospheric levels (Avermann and Brockmeyer, 1992) or 2) a gradual change in the fragmentation and ejection process from the same “eruptions” as the equant shard units (Gibbins, 1994). Another scenario could be 3) “pyroclastic-like” eruptions initiated due to crater collapse and subsequent faulting outside of the transient crater.

The discontinuous distribution of the contact units negates hypothesis (1). If the contact unit (Dowling member) was deposited from a collapsed ejecta cloud, it should mantle stratigraphy. The internal morphology and composition of the contact units is compatible with fragmentation due to changes in relative explosivity (Wohletz, 1983) and emplacement as mass flow deposits synchronous with and likely triggered by a major period of tectonic instability. In Morgan Township (Map 1) the contact units are displaced along syndepositional faults that control the emplacement of some fluidal breccia complexes after deposition of the contact units. Tectonic instability is also indicated by the emplacement of channelized debris flows and mass flows of the lower units that locally directly overlie the Sandcherry member. The middle units, however, have the internal morphology, large volume and laterally extensive, characteristics representative of non-welded “ash-flow” -like deposits. Blocks and bombs are rare at the base of the sequence and signify the termination of fluidal breccia complex emplacement. Rare aphanitic dykelets are found at the immediate base of the middle units. Deposition of the middle units essentially “capped” the vents that formed the fluidal fragment units. Reworking of these “ash-flow like” deposits is evident 300 m above the base of the middle units with

major reworking evident in the thinly bedded carbonaceous upper units at the top of the Onaping Formation.

The change in the processes from which the Sandcherry and Dowling members originated, and the apparent, erosional hiatus between the two has important implications as to how the Sudbury Structure evolved. This will be discussed in more detail after introduction of the geochemistry in Chapter 3.

2-5c. Syndepositional faulting

The third component of the geological setting is faulting which places constraints on the emplacement and timing of units in the Onaping Formation. Detailed field evidence and structural analyses described in the text and Appendix 2-4 clearly show that a coeval set of subvertical faults played a significant role in localizing some units of the Onaping Formation. The northwest and northeast set of faults were active during injection of aphanitic dykes but the northwest set dominated a short time later during emplacement of small stocks of basal intrusion (Figures 2-13, 2-14). These fault sets when rotated back to the horizontal are oriented NW; 315/70 and N; 000/60 (Appendix 2-4)

The orientation and timing of this possible conjugate set of faults has implications with respect to the stress regime under which the Sudbury Structure was developed. The northwesterly trending set of faults synchronous with the Onaping Formation also parallels the trend of regional faults in the Sudbury area which that were active over a long period of time. Regional faults include: the Onaping Faults (Sandcherry Creek and Fecunis Lake faults) and the Matachewan dyke swarm (ca. 2462-2600), (Fahrig and West, 1987;

Rousell et al., 1997). Faulting (NW and N or NNE) synchronous with the Onaping Formation may have been a response to the local stress field very shortly after impact, being gradually dominated by the regional stress field (NW) with time.

Major periods of syn-Onaping faulting are indicated by 1) the transition from Sandcherry to Dowling member deposition, 2) deposition of fluidal breccia complexes which was stopped at “middle unit” time and 3) peperite formation along northeasterly trending linear structures in the South Range. The recognition of peperite is significant as it reveals that the timing of intrusions is late-syn depositional with the unconsolidated, wet host strata near the top of the Onaping Formation and indicates an extended period of dyke injection in the crater-fill sequence (Appendix 2-5). Dykes with peperitic margins have also been noted in drillcore in the Vermilion Formation (Stoness, pers. comm.). The Sudbury Structure underwent a period of lithostatic extension and subsequent melt injection, possibly even melted lower Onaping Formation (basal intrusion) likely during Onwatin time. The evolution of the chemical composition of glass and dykes throughout the Onaping Formation can be tracked (Chapter 3).

The recognition of syn-Onaping fault sets is important in understanding first, the mechanisms responsible for the complex depositional processes for the Onaping fragmental units, and secondly, the distribution and variety of alteration mineral assemblages that affect the crater-fill sequence below Zn-Cu-Pb deposits. This permeable, vitric, water-rich sequence of fragmental rocks and associated syn-depositional faults is an ideal environment for the development of an extensive hydrothermal circulation system.

Figure 2-1: Time-space chart with the geochronological ages of plutonic, structural, metamorphic and impact events within the Sudbury area. Data sources are, Krogh et al., 1984; Ostermann et al., 1996; Wodicka, 1997; Corfu and Lightfoot, 1998; Ames et al., 1998.

Figure 2-2: General geology map of the Onaping Formation, Sudbury Structure (Data sources; Falconbridge Ltd. unpublished maps, Gray, 1995; Gibblins, 1994; Pye et al., 1984; Ames et al., 1998; Shanks and Schwerdtner, 1991). VD = Vermilion deposit; ED = Errington deposit.

Figure 2-3: Simplified stratigraphic section for the Onaping Formation, Sudbury Structure.

FIGURE CAPTION

Figure 2-4: A) Simplified geology map of the stratigraphic subdivisions within the Onaping Formation, North Range, Sudbury Structure. Note the dominance of fluidal-fragment units around the Fecunis Lake and Sandcherry Creek faults. Map extends from Highway 144 to the Nickel Offset road. Mapping from this study (Maps 1 and 4, pocket); Falconbridge Ltd. staff in Gibbins, 1994. Note the undefined units (Gibbins, 1994) are silicified Sandcherry member units.

B) Distribution of carbon within the Onaping Formation (shaded area is carbon-bearing rocks). The carbon front is diachronous across the Sandcherry member (SM)- Dowling member (DM) stratigraphic contact. Note the isolated patches of carbon in the lower Onaping Formation, particularly the large area of carbon-bearing Sandcherry member strata along Highway 144.

Figure 2-5: Simplified geology of the Onaping Formation, Morgan township. Inset, equal area projection of poles to bedding.

Figure 2-6: Detailed map showing the structural control on the emplacement of fluidal fragment units, Sandcherry member, and the small pods of 'basal intrusion'. The contact unit distribution has been affected by north-northwesterly trending faults. Note 1) the orthogonal subvertical contacts interpreted as syndepositional faults that control the deposition of fluidal fragment breccias, 2) the linear distribution of small 'basal intrusion' bodies that subparallel the NW structure and 3) the northwesterly trending contact between the Sandcherry member and Dowling member. See Map 1 pocket for geologic context of figure area.

DOWLING MEMBER

Middle units (~600 m)

Basal unit of middle units (>140 m).

Fine ash base (cm-A) overlain by 5 m of block-rich eutaxitic ash to fine tuff (B) grading into a 3 m zone of lapilli-rich tuff (C) and overlain by a thick sequence of homogeneous massive tuff (D).

Vitric fragments reversely graded at base with normal grading up sequence. Lithic fragments are normally graded.

A: Fine ash, block-poor in sharp yet undulose contact with block-rich (10%, 7% subrounded 20cm vitric, 3% angular lithic) lower units. Bedding 085/65.

B: Block-rich (15%) welded ash. Ratio of vitric to lithic blocks, 2:1. 7% 1.5 cm lithic fragments (white and black chert, granitoids). Elongate anhedral contorted 1.5m x 20 cm flow banded andesite fragments (spatter). Fine 1 cm stringers of flow-banded andesite subparallel to unit contacts (3%) spatter. 15 cm rounded andesitic bomb with large chlorite-filled gas cavities along outer contacts.

C: Lapilli-tuff. 20% lapilli in a matrix of fine tuff-ash. ~6% armoured lapilli with cm-scale andesite rims. Minor discontinuous pods of fine ash at top of 3 m wide zone.

D: Overlain by massive, poorly sorted tuff.

Lower units (20-30 m)

Channelized deposits: reversely graded subrounded vitric and lithic blocks.

Basal zone 0.75 to 1 m wide contains 35% blocks. Lithic blocks, 15%, subrounded to angular, heterolithologic and 2%, 1-10 cm lithic fragments.

Vitric blocks averaging 10 x 6 cm are sub-angular to angular and dominate the block population at 20%. The matrix is composed of ash-sized particles. The upper zone contains 18%, subrounded to angular vitric blocks that average 25 x 15cm (max. 75 cm) and 12% lithic subrounded blocks averaging 20 x 20 cm, max. 80 x 50 cm in a fine ash matrix with a flattening dipping 54°S.

Sheet-like deposits: normal grading of lithic and vitric fragments. Lapilli-stone to tuff units and block-rich to block-poor units. Shard morphology changes from blocky to lenticular.

SANDCHERRY MEMBER

Fluidal breccia complex

Figure 2-8: Detailed stratigraphic section through the lower and middle units, Dowling member.

Figure 2-9: Middle units, Dowling member. Location of detailed stratigraphic sections (A-A') in Figure 2-10. Inset A: equal area projection of poles to bedding measurements. Inset B: Rose diagram of bedding measurements within the middle units, Morgan Township. Inset C: Rose diagram of bedding measurements within the middle units across the North Range, see Figure 1-1 for map areas.

Figure 2-10: Measured sections through the middle units, Dowling member showing detailed stratigraphy and characteristics. Changes in component size and percentage with increasing stratigraphic height. See Figure 2-9 for location of sections.

Figure 2-11: Thin section sketch of the upper units, Dowling member. Chloritic shards are vesicular with shard boundaries cutting vesicles. Note the delicate morphology of shards retained in these reworked units. Sample AV-318, Morgan Township.

Figure 2-12: Distribution of, A&M and Gordon Lake road, peeperite showings and anomalous zones of dykes. The Onwatin Formation- to Onwatin Formation contact broadly follows the southern edge of Vermilion Lake. The A&M and Gordon Lake road peeperite showings were mapped at 1:200 and are described in Appendix 2-5. SRSZ=South Range shear zone (Shanks and Schwerdtner, 1991).

Figure 2-13: Structural analyses and distribution of andesitic dykes, North Range, Onaping Formation. Inset A: Rose diagram of aphanitic dykes. Inset B: Equal area stereographic projection of poles to measured dykes.

(mapping from this study; Gibbins, 1994; Falconbridge Ltd.)

Figure 2-15: A) Photograph of suevite from the Popigai crater, Khara Kaia, Rhassoka River. Note the blocky, vesiculated nature of the equant shards or vitric fragment. B) Blocky vesiculated shard, 2 mm from suevite, Chixculub crater. Thin section Y-6 N14 courtesy of A. Hildebrand.

Table 2-1: History of Nomenclature of the Onaping Formation.

	This study (Ames et al., 1997; Ames et al., 1998)	Gibson et al., (1994) 1400m	Stoffler et al. (1994)	Avermann (1992) 1800m	Brockmeyer (1990)	Muir and Peredery (1984) 1600m	Peredery, (1984, 1972)
O	Dowling Member	Dowling Member	Black Member	Upper	Upper	Black Member	Black Member
N	Upper Units	Upper Units	Upper Units	Black Member	Black Member		
A	Middle Units-lower/upper	Middle Units	Lower Units	Lower Black Member			
P	Lower Units	Lower Units					
I	Contact Units	Contact Unit	Green Member	Green Member	Green Member	chlorite-shard horizon	Gray Member chloritized shard-like fragment horizon
N			Gray Member	Gray Member	Gray Member	Gray Member	
G							
F	Sandcherry Member	Sandcherry Member					
	Equant Shard Units	Shard-rich Units					
	Fluidal-fragment Units	Fluidal-fragment Units					
R	Garson Member						
M	Quartzite breccia Units						
A	Basal Intrusion ¹	Basal Intrusion	Basal Member	Basal Member	Basal Member	Melt bodies South Range Basal Member North Range Basal Member	Melt bodies South Range Basal Member North Range Basal Member
T		Pipe-like Bodies					
I							
O							
N		Sheet-like Bodies					

	Stevenson (1961, 1963, 1990)	Thomson, Williams (1957)	Collins, (1937)	Burrows and Rickaby (1929), Collins in B&R (1929)	Coleman (1905)	Bell (1893)	Bomey (1888)
O	Black tuff Member	Bedded tuffaceous sediments	Black tuff ash rock	Onaping Volcanic Fragmentals	Onaping Tuff	Pyroclastic sediments	Volcanic ash (High Falls area) (devitrified features)
N							
A							
P		coarse tuff breccia		(tuff, breccia, lava)	pyroclastic sediments		
I							
N							
G	Gray tuff Member	lapilli tuff glowing avalanche deposits	tuff				
F				flow breccia			
O	flinty green rhyolite (welded, shard-rich rhyolite ignimbrite)				vitrophyre tuff		
R							
M							
A		andesite with rhyo. breccia					
T		Rhyolite breccia					
I	Quartzite breccia		angular tuff agglomerate				
O	Pepper and salt micropegmatite				Trout Lake conglomerate	quartzite conglomerate	
N	(includes some melt bodies)						

Table 2-2: Lithological characteristics of units in the Sandcherry member.

Unit	Vitric fragments and matrix			Bomb distribution		Actinolite/ chlorite clots		Lithic fragments		Proportion of lithic: vitric blocks
	modal estimate	size	description	% of outcrops simple/cored	complex	size (m)	% outcrops	modal est.	modal est.	size
Equant shard	50-60%	0.2-1.5 cm	equant	42	16	0.1 to 2	16	2	2-30%	2 mm- 6 cm
	10%	2-6 cm	flow banded; tabular						(10%)	
	5-10%	20-30 cm	flow banded; massive						2-15%	>6 cm
	15-30%	up to 2 m	angular						<30%	
		< 2 mm	matrix							
Fluidal fragment										
Proximal facies (lapillistone)	80-85%	2 mm - 6 cm	flow banded; amoeboid	25	0	0.2 to 0.5	16	<10	-	V>L blocks
			contorted fragments							
	5-30%	6 cm- 2 m (30-50 cm)	massive, flow banded							
			contorted, angular							
	~10%	<2mm	subrounded							
			matrix							
Intermediate facies	20-55%	2 mm-1.5 cm	flow banded; tabular	23	0	1	38	5-10	-	
	10-15%	2-4 cm	flow banded							
	25-40%	<2 mm	matrix							
Distal facies	45%	2 mm - 6 cm	flow banded; tabular	16	0	0.1	42	<5	<2-30%	> 6 cm
	0-15%	< 1 cm	equant							
	< 5%	> 6 cm	massive, flow banded							
	15-30%	< 2 mm	matrix							L=V
Transitional	50-60%	~< 2 cm	flow banded	55	30	0.1 to 1.0	25	1-3	2-30% (L and V)	> 6 cm
	15-30%	0.2 to 1.5 cm	equant							
	10-20%	< 2 mm	matrix							L>V

Table 2-3: Lithological characteristics of units in the Dowling member.

Unit	Lithology modal estimate	Vitric Blocks and Bombs	Lithic fragments	Blocks
Contact units (40° dip) tuff, lapilli tuff thin units				
Basal unit-Map 1 (5-10 m)	40-55%, 2-4 mm equant to lenticular shards 15%, 1 cm, flow banded andesite 20% bluish greenish gray matrix rare accretionary lapilli	17% angular, rounded, composite	8% chert, quartz, granitoid quartzite basalt ~ 1 m	L<V
Basal unit-Map2		10%, avg. 20 x 10 cm subangular * 20 x 15 cm equant shard unit max. 70 x 30 cm breadcrust bomb	1%, max. 80 x 30 cm sub-angular, -rounded	L=V
contact unit (10-15 m to 100 m <10%	25%, 2 mm, lenticular chlorite shards up to 25%, < 6.4cm flow banded andesite 20-30%, 0.5 cm equant shards, mark the base of new units. up to 30% bluish green matrix may contain Corg, pyrrhotite, pyrite, chalcopyrite, calcite, sphalerite.	<2 decrease in size and %	5-10%, < 1 cm	L>V
Lower units				
(20-30 m) <15 m units	heterogeneous, tuff, lapilli-tuff to lapillistone 20-30% blocky to lenticular chlorite shards 5-20% flow banded andesite, bluish white and pale green up to 50% carbonaceous matrix ubiquitous block-poor lapillistone to block-rich tuff upsection or, block-poor tuff base and block-rich tuff top channel shaped deposits in text 2-4, Figure 2-8	up to 30% subrounded, avg. 30x 15 cm max. 50x40 cm, min. 10x3 cm 2-3%, cored bombs	15% subangular, avg. 25 x 15 cm max. 2 x 3 m min. 10 x 3 cm	V>L
Middle units (28° dip)				
~150 m units lower (0-300m)	tuff, minor lapillituff, rare lapillistone thick units see figure 2-10 for more detail 25-35%, <2 mm to 2 cm lenticular chlorite shards 2-10 %, < 6 cm flow banded andesite 50-60% black carbonaceous matrix	bombs at base rare above 100 m ~3-5% very fine tuff blocks < 1% lapillistone blocks (10-50 cm)	few lithic blocks, rare above 100 m < 7% 2mm - 2 cm lithics gray chert, quartzite carbonaceous fragments quartz grains sub rounded at base locally <15%	very few
Upper > 300m	25-35%, < 2 mm to 2 cm lenticular chlorite shards more coarse 0.5 to 2 cm chlorite shards than lower units <1-2% flow banded andesite lapilli 50-60 % black carbonaceous matrix	vitric blocks are absent fine tuff and lapillistone blocks increase upwards (20 x 100 cm on average) near top lenses reach 10-12 m thick and extend 20-80 m	<5% 2mm-6 cm lithic carbonaceous fragments quartz grains, chert,	
Upper units				
thinly bedded thins upwards (21° dip)	< 15%, ~ 2 mm chlorite shards >70% black carbonaceous matrix composed dominantly of fine lithic fragments carbonate, pyrrhotite and chalcopyrite	Absent	60-70%, < 2 mm lithics 30-40%, 1 mm angular quartz 5-10% 2-4 mm angularquartz 20% polycrystalline quartz fragments 5-15% chlorite-titanite-ep shards <2% Kfeldspar, <2% albite trace felsic rock fragments 1-5% subrounded carbonaceous frags	Absent

.PLATE CAPTIONS

Plate 2-1: Stratigraphy of the 1400 m Onaping Formation, Sudbury Structure.

- a) Block-rich Garson member. Blocks are Mississagi quartzite. Garson powerline, photo 24-27.
- b) Polished slab of equant-shard unit, Sandcherry member, Onaping Formation. Blocky shards are albitized. Capreol area, station 363, sample AV-491.
- c) Polished slab of fluidal-fragment unit, Sandcherry member. Morgan township, station 131, sample AV-187.
- d) Polished slab of transitional unit, Sandcherry member. Morgan township, station 114, sample AV-175.
- e) Channelized block-rich deposit, lower units, Dowling member. Morgan township, station 258, photo 24-36.
- f) Close-up of contact unit tuff, Dowling member. Note dark recessive weathering chloritic shards. Morgan township, station 277, photo 30-12.
- g) Close-up of middle unit tuff, Dowling member. Morgan township, station 186, photo 15-3.
- h) Shallowly dipping (024° S) beds of upper units, Dowling member. Photo 32-2, looking west, Morgan township, station 314.

PLATE CAPTIONS

Plate 2-2. Blocks and bombs, Sandcherry member.

- a) Mafic block in equant shard unit partially altered to actinolite marked with an arrow. Morgan township, station 101, photo 6-28.
- b) Cored bomb with core of Sandcherry member. Morgan township, station 087, photo 5-12.
- c) Bleached tadpole-shaped bomb in equant-shard unit, Sandcherry member. Morgan township, station 102, photo 6-31.
- d) Complex cored bomb in fluidal-fragment unit, Sandcherry member. Morgan township, station 017, photo 1-21.
- e) Block of fluidal-fragment unit containing lithic fragment within equant-shard unit, Sandcherry member. Indicative of mass wasting of fluidal units. Morgan township, station 070, photo 3-33.
- f) Contorted flow-banding in irregular bomb within fluidal-fragment lapilli-tuff, Sandcherry member. Morgan township, station 072, photo 3-36.
- g) Block-rich equant shard unit, Sandcherry member. Morgan township, photo 5-17.
- h) Broken lithic fragment in equant-shard unit, Sandcherry member. Morgan township, station 069, photo 3-23.

PLATE CAPTIONS

Plate 2-3: Characteristics of the contact units, Dowling member.

- a) Shallowly dipping, block-rich unit (bottom) in contact with block-poor unit (top) of the contact units. Note the large basaltic lithic block adjacent to the hammer. Morgan township, station 200, photo 15-7.
- b). Fragment of underlying fluidal-fragment lapilli-tuff in the block-rich base of the contact units. Morgan township, station 85, photo 32-9.
- c) Mafic/ultramafic fragment in the block-rich basal unit, contact units. Morgan township, station 200, photo 15-9.
- d) Cracks on the surface of a “breadcrust bomb”, block-rich base of the contact units. Joe lake, station 445, photo 28-21.
- e) Polished slab of accretionary lapilli in contact tuff at the top of the basal unit. Morgan township, sample AV-191, station 134.
- f) Close-up of representative contact unit. Note the recessive weathering, lenticular, chloritic shards. Morgan township, station 088/089, photo 23.

PLATE CAPTIONS

Plate 2-4. Petrographic sketch and thin section photographs from base (2-4a) to top (2-4d) through the Contact units, Dowling member.

- a) Block-rich base of the Contact units, Morgan township. Angular, blocky shards composed of alteration minerals. Sample AV-105.
- b) Top of block-rich zone at base of the Contact units, Morgan township. Angular, vesicular blocky shards ~ 55% contain quartzose lithic fragments. Sample AV-109.
- c) Mid to upper Contact unit tuff with fewer shards than the basal zones and more lenticular shard morphology. Sample AV-113.
- d) Top of the Contact unit tuff with 20% discernible lenticular, wispy shards in a fine aphanitic matrix. Note the change in shard morphology from base (2-4a) to top (2-4d) and the decrease in percentage of shards. Sample AV-242.

PLATE CAPTIONS

Plate 2-5: Shard morphology in the lower units, Dowling member.

Plate 2-5a, b. Channelized lower unit deposit, Morgan township, station 63.

- a) Blocky shard and vitric fragments at the base. Thin section AV-75.
- b) Note decreased size and percentage of lenticular shards at the top of the lower unit deposit. Thin section AV-76.

Plate 2-5c, d. Blanket-shaped lower unit deposit. Morgan township, station 257.

- c) Lapillistone basal zone with blocky vesiculated vitric fragments. Fragment of small simple cored bomb at arrow.
- d) Lapilli-tuff to tuffaceous top to graded unit, displaying a more lenticular shard shape and a decrease in size and abundance of shards.

PLATE CAPTIONS

Plate 2-6: Dyke morphology and contact relationships.

- a) Autobrecciated contact of massive flow-banded dyke with equant-shard unit. Nelson Lake, station 600, photo 36-2.
- b) Aphanitic flow banded dyke crosscuts SMFL breccia, in upper part of Sandcherry member, Nelson Lake. Orientation 016/32 [D8]; Sample SA 36400 (Falconbridge Ltd.), Photo 36-4.
- c) Characteristic texture of lensoidal peperite, A&M showing. Sediment component is light gray and silicified, to dark brown. The “magma component” is strongly devitrified with white to gray spherulites (arrow).
- d) Characteristic texture of blocky peperite, Gordon Lake road. Sediment component is silicified and white whereas the dark angular “magma” component is strongly sericitized and greenish weathering on outcrop.
- e) Polished slab of basal intrusion illustrating fine igneous textured matrix. Joe Lake area, station 413, AV-513.
- f) Polished slab of basal intrusion near contact with the granophyre, Morgan Township. Note the partially corroded felsic xenolith and the felsic clots in the matrix. Station 155, sample AV-207,

Chapter 3

GEOCHEMISTRY OF LEAST ALTERED ONAPING FORMATION

3-1. Introduction

Published studies on the geochemistry of the Onaping Formation utilized whole rock geochemical analyses and/or major element microprobe analyses to distinguish the glass compositions in what was considered to be essentially a chaotic fragmental unit with chemically heterogeneous glass (Peredery, 1972, Brockmeyer, 1990; Muir and Peredery, 1984). Gibbins (1994) used a large geochemical database collected for a mineral exploration program by Falconbridge Ltd, with whole rock and limited trace element data to define the average composition of units within the Onaping Formation. Average compositions were determined regardless of alteration or mineralization and therefore represent average compositions of altered units in the Onaping Formation.

Because of extensive alteration it is difficult to define a true protolith composition. The new stratigraphic sections combined with alteration mapping provided the basis for well constrained sampling of the Onaping Formation for whole rock, trace element and rare earth element analyses in order to distinguish the least altered geochemical characteristics of each unit (Appendix 3-1, Table 3-1).

3-2. Method of sampling and analysis

The main purpose for analyzing the Onaping Formation units in this study is to determine the composition of least altered units in order to determine the chemical gains

of the Onaping Formation relative to the other units in the Sudbury Structure. Muir and Peredery (1984) suggested that the Onaping Formation was chemically zoned with a silicic calc-alkaline base and more mafic tholeiitic top based on element variations with stratigraphic height. Gibbins (1994) convincingly indicated through the use of ratios with less mobile elements (TiO_2) as the denominator that most of the variations are apparent and a function of alteration. He suggested that the melt was essentially chemically homogeneous, andesitic, with variations in Zr, SiO_2 , $\text{K}_2\text{O}/\text{TiO}_2$ due to limited fractionation or the addition of lithic detritus.

Distinguishing the “least altered” material is quite difficult as the entire formation has interacted with hydrothermal fluid (see Chapter 4). Altered vitric fragments in the Onaping Formation are monomineralic (e.g. chlorite, calcite) or are composed of monomineralic bands (e.g. feldspar-lining and chlorite or actinolite core to shards). “Least altered” glass is composed of a number of minerals that are randomly oriented such as plagioclase, amphibole, chlorite, quartz, and titanite. Samples for chemical analyses with bleaching, veinlets and lithic fragments were avoided and those collected were crushed and hand-picked to avoid any lithic component. Samples collected to determine the least altered compositions include the massive, xenocryst-absent cores to aphanitic dykes, vitric blocks and bombs, and massive, igneous-textured parts of the Basal Intrusion matrix. Massive parts of feeder aphanitic dykes to fluidal-fragment units are representative of the least altered composition of fluidal-fragment units of the Sandcherry member. To test for chemical variation with stratigraphic height the massive portions of aphanitic dykes were sampled within both Sandcherry and Dowling members. Recrystallized glass blocks and

bombs were analyzed in a section through the Sandcherry member to test for any differentiation with stratigraphic height.

3-3. Results

All chemical analyses were completed by the analytical chemistry section at the Geological Survey of Canada. Major element analyses were determined by XRF, except FeO, H₂O^T, CO₂ C and S by chemical methods. Trace elements were analyzed utilizing ICP-emission spectroscopy, and ICP-mass spectroscopy. Zr was determined by XRF except at concentrations below 100 ppm where ICP-MS was used. Fluorine, chlorine and S were determined using a Dionex ion chromatography analyzer. For details on the methods and determination limits refer to the website at <http://132.156.95.172>.

Analyses for major elements and 40 trace elements are listed for 113 “least altered” samples in Appendix 3-1. Table A3-1 provides average, minimum, maximum and standard deviation data for the least altered, units in the Onaping Formation, vitric blocks and bombs, aphanitic dykes and basal intrusion with a summary in Table 3-1. Standard deviation calculations were not performed for sample populations less than 10.

3-4. Classification

In order to chemically classify the rocks of the Onaping Formation common volcanic diagrams were used. Classification systems for rocks use major elements but these are the most susceptible to mobility during alteration. Using a combination of whole rock elements and less mobile trace and rare elements the chemical characteristics of the

rock elements and less mobile trace and rare elements the chemical characteristics of the least altered Onaping Formation can be distinguished. The average compositions of individual units on a Jensen (1976) diagram (Figure 3-1a) show the Sandcherry member strata in the calc-alkaline basalt field and the Dowling member strata within the tholeiitic high magnesia basalt field similar to that shown by Muir and Peredery (1984) (i.e., Gray and Black Members). It is apparent from the major element data particularly SiO_2 that the Onaping Formation is not basaltic (Table 3-1).

An interesting trend is that the points all lie close to a line (93% Al_2O_3 on the $\text{Al}_2\text{O}_3/\text{MgO}$ join to 53% $\text{FeO}+\text{TiO}_2$ on the $\text{FeO} + \text{TiO}_2/\text{MgO}$ join). If these samples are in fact still altered, the protolith could have been 1) an andesite that was progressively depleted in Al_2O_3 due to addition of FeO^* and/or MgO , possibly by chlorite alteration or 2) a basalt that was apparently enriched in Al_2O_3 through alteration by depletion of other elements. $\text{FeO}^*/\text{TiO}_2$ increases with stratigraphic height (Table 3-1) whereas the ratios of Al_2O_3 or MgO versus TiO_2 (Gibbins, 1994) and the Fe/Mg ratio in chlorite, remain constant throughout the stratigraphy (Chapter 4). The S content increases, therefore, increased Fe-sulphides in the Dowling Member likely affect the standard chemical classification systems. Removing enough iron to account for the Cu, Zn and S values eliminates the effect of sulphides (Figure 3-1). Following this correction, $\text{FeO}^*/\text{TiO}_2$ still increases (Figure 3-2) and the data points are shifted down on the Jensen diagram into the calc-alkaline field (Figure 3-1a). On other major element discriminant diagrams the seven major units of the Onaping Formation, vitric blocks and bombs, aphanitic dykes and basal intrusions all plot in the calc-alkaline, subalkaline fields (Figure 3-1b, c).

The Onaping Formation rocks straddle the andesite/dacite boundary with Sandcherry member strata being felsic and Dowling member strata being more mafic, in terms of SiO_2 content (Figure 3-1d). The effect of volatiles is significant for the middle and upper units as they include > 5 wt. % combined water, carbon dioxide, sulphur and carbon but are negligible for other units at < 2 wt% total volatiles (Table 3-1a). The volatile-free compositions shift all of the units into the dacite field. In terms of the relatively immobile trace elements, Zr and TiO_2 , the Onaping Formation units have consistent ratios irrespective of SiO_2 (Figure 3-1e). To limit the effects of alteration relatively immobile trace elements are also used to help classify the Onaping Formation (Figure 3-1f). The data forms a tight cluster on the andesite/dacite boundary except for the reworked upper units. Based on these comparisons, it is likely that the protolith for the Onaping Formation was an andesite with calc-alkaline affinity.

3-4a. Least altered composition

What is readily apparent is that the “least altered” units are altered. In order to determine the least of the less altered samples, field and petrographic observations were coupled with the geochemistry to further cull the suite of samples. The Upper units are excluded due to reworking and increased quartz detritus.

Sandcherry and Dowling members not only differ in their style of fragmentation and percentage of glass fragments but also show differences in their major element volatile-free chemical composition particularly Na_2O and FeO^* (Figure 3-2). Na_2O changes with stratigraphic height are not consistent and likely reflect hydrothermal

alteration. The Sandcherry member units and Dowling member contact units have increased Na_2O whereas the aphanitic dykes, lower units, blocks and bombs form a cluster between the middle units which have decreased Na_2O . If this was a fundamental difference between the Sandcherry and Dowling member protolith compositions (Gibbins, 1994), the changes should be consistent. Field observations show that the Sandcherry member units and contact units are weakly to intensely albitized (Chapter 4). Although the “least altered” samples were selected the effects of this regionally extensive alteration zone is still evident. In terms of FeO^* the Dowling member and Sandcherry member strata form two groups with the aphanitic dykes and vitric blocks between them (Figure 3-2a). These represent either a difference in the protolith or the addition or depletion of FeO^* to a rock type compositionally similar to the vitric dykes and blocks during alteration. Sodium and iron do not change antipathetically. Relative to the aphanitic dykes and vitric blocks the Sandcherry member units show an increase in sodium whereas the contact units show an increase in sodium and iron, the lower units an increase in FeO^* only and the middle units a slight depletion in Na_2O and an increase in FeO^* similar to the lower units (Figure 3-2c).

In terms of trace elements La/Sm increases in the Dowling member (Table 3-1), Th/Zr remains consistent throughout and La/Nb is higher in the Dowling member and Sandcherry member fluidal units relative to the Sandcherry member equant shard units (Table 3-1). The similar, elevated REE, chondrite normalized patterns of Sandcherry member, Dowling member and aphanitic dykes all form a tight group which is consistent with a comagmatic origin (Figure 3-3a). A scatter diagram for the major units in the Onaping Formation normalized to primitive mantle shows the tight cluster of all samples at

Th and Nb and REE whereas the low field strength elements (LFSE: Cs, Rb, Ba, and K), and Sr are scattered (Figure 3-3b). This also suggests that the entire Onaping Formation including the least altered samples have been metasomatised.

Previous studies on the North Range (Gibbins et al., 1997) suggested that the Onaping Formation was emplaced by continuous introduction of a melt of uniform composition and that aphanitic dykes sampled in the Sandcherry member represent the protolith composition but may be contaminated by quartz-filled amygdales (Gibbins, 1994). To test this hypothesis, samples were collected from the North and South range and from various stratigraphic levels. Careful selection of samples of massive or flow-banded quartz/amygdale-free aphanitic dykes give representative compositions of a fluidal-fragment unit feeder dyke intruded at the Sandcherry/Dowling member contact (AV-21, 22A, 22B Fig. 2- 6), a massive dyke intrusive into and “jacking-up” the lower units (AV-336, Fig. 2-7) and a massive dyke cutting the upper units (AV-140, Gordon Lake road). The dyke highest in the stratigraphy shows slightly elevated HREE but the composition of the dykes remains consistent throughout the entire Onaping Formation (Figure 3-4). Vitric block (AV-53) and bomb (AV-91) within the equant shard units are similar in composition to the vitric dykes (Figure 3-4). The representative samples of Onaping Formation were collected from both North Range and South Range with no variation in composition due to spatial distribution (i.e., North Range vs. South Range). The average composition of these 7 samples are deemed most representative of the least altered or protolith composition of the Onaping Formation (Table 3-1).

3-5. Discussion

3-5a. Geochemical comparison of the Onaping Formation and Sudbury Igneous Complex

A study of the geochemical relationship of the melt composition of the Onaping Formation with other Sudbury event magmas/melts is now feasible. The hypothesis of a heterogeneous melt composition (Peredery, 1984; Dressler, 1996) was a misconception based on limited geochemical data and non-recognition of hydrothermal alteration zones.

The ratios of incompatible trace elements (Sm, La) in the 117 less altered samples as well as the least altered composition of the Onaping Formation lie in the ranges defined by the compositions of rock types in the Sudbury Igneous Complex (Lightfoot et al., 1997). Data from the Onaping Formation overlap those of the main mass felsic norite, mafic norite and the quartz diorite of the Parkin offset but differ significantly from the granophyre and quartz gabbro (Figure 3-5). The average primitive-mantle normalized trend (Figure 3-3b) shows that all units in the Onaping Formation are enriched in large ion lithophile elements, light rare earth elements and have pronounced negative Nb and Ti anomalies similar to that established for the SIC (Naldrett et al., 1986; Chai and Eckstrand, 1994; Lightfoot et al., 1997).

Composition of the Onaping Formation melt with respect to the compositional gap:

The two main rock types of the SIC show marked compositional differences in terms of whole rock and some trace element geochemistry with a compositional gap from

58-68 wt. % SiO_2 (Chai and Eckstrand, 1994) but show similar trace element ratios (Lightfoot et al., 1997). The Onaping Formation fills the compositional gap with SiO_2 values between 58.1-69.7 wt.%, and most samples range between ~60-64 wt. % SiO_2 (Table 3-1) (Figure 3-6) . Chemical changes due to alteration are more pronounced for CaO , Na_2O , K_2O , MnO , Sr and Ba and thus a limited set of chemical components is used for comparison. The Onaping Formation is compositionally 1) intermediate between the norite and granophyre in its Y content and closer to the felsic norite for MgO , 2) similar to the felsic norite in TiO_2 and Zr , 3) similar to the granophyre in Co and equal or less in Al_2O_3 and 4) similar to both the felsic norite and granophyre in Sc , V and La/Sm . In general the Onaping Formation has more similarities in both major and trace elements to the felsic norite than to the granophyre, as previously suggested by Deutsch et al., (1995) and Dressler et al., (1996).

Variations with stratigraphic height:

Fifty of the less altered samples were collected from a transect across the entire Onaping Formation in Morgan Township, and trace element ratios according to stratigraphic height are shown for comparison with the units of the SIC (Figure 3-7). Eu/Sm values in the Onaping Formation is intermediate between that for the norite and granophyre, La/Sm values are more similar to the felsic norite ratio and Th/Y decreases with height, although all values lie within the fields of the felsic norite and granophyre. The Onaping Formation shows many compositional similarities to the SIC.

Felsic norite-normalization of the Onaping Formation rocks:

The apparent compositional similarity between the Onaping Formation and the SIC can be tested by normalizing the average less altered and least altered unit compositions of the Onaping Formation with the compositional average of the North Range felsic norite (Lightfoot et al., 1997). The overall rare earth elemental abundances are similar to that of the felsic norite (Figure 3-8) whereas those in the granophyre show elevated abundances (1.7-2.2 times felsic norite: Lightfoot et al., 1997). There is a slight HFSE enrichment and negative Sr, Eu and P anomalies relative to the felsic norite, with the latter reflecting the abundance of feldspar and apatite. The similarities between the LREE and HREE content of the Onaping Formation glass and felsic norite strongly suggest that they have similar compositions which supports a comagmatic derivation that is consistent with established spatial and temporal relationships.

3-5b. Geochemical comparison of the Onaping Formation and Offset dykes

Lightfoot et al. (1997) illustrated that the compositional similarities between offset dykes and the main mass of the SIC in terms of trace element ratios and note that the composition of the offset dykes, “quartz diorite” is also intermediate between the felsic norite and granophyre. They suggested, that the main mass and offset quartz diorite dykes crystallized from the same magma type and that the offset dykes provide the best estimate of the original magma from which the SIC crystallized.

The average compositions of less altered Onaping units, blocks, bombs, feeder dykes and basal intrusion are compared to the composition of the offset dykes in Figure 3-

9. The offset dykes show compositional differences with geographic location, in both the North and South range, but the Onaping Formation composition is consistent irrespective of location in the Sudbury Structure. Less altered Onaping Formation units generally have higher SiO_2 contents but have similar incompatible element ratios to the North Range offsets (excluding Sr). The Fluidal-fragment units have similarities with the Parkin and Foy offsets with the highest La/Yb and Gd/Yb values for the Sudbury Structure “magmas”, reflecting the slope of the light to heavy REE. The least altered composition of the Onaping Formation (Figure 3-9) shows a strong correlation with the fields of the North Range and Manchester offset dykes, except in Sr when both the Onaping Formation and Manchester offset dykes overlap the field of the South Range offset dykes. The least altered Onaping Formation has low TiO_2 and Sr, elevated La/Yb, La/Sm, Gd/Yb and is chemically most similar to the Manchester offset dyke, a concentric dyke that intruded Huronian sedimentary rocks on the southeastern part of the structure. To illustrate the compositional similarities, the least altered Onaping Formation was normalized to average Manchester offset data (Figure 3-10). The strong correlation of incompatible trace elements between the Onaping Formation, offset dykes and felsic norite supports the interpretation that they were derived from the same source.

The geochemical traits of North Range versus South Range offset dykes are attributed to assimilation of respective host rocks (Archean granitoid and gneissic rocks or Proterozoic sediments) during dyke emplacement (Lightfoot et al., 1997). The homogenous geochemical melt signature of the Onaping Formation, irrespective of geographic location, is consistent with a large quantity of crustally-derived melt of

andesite composition below, intruding and forming units of the crater-fill sequence. The direct relationship of this melt with the layered SIC and its offset dykes is problematic and beyond the scope of this dissertation. However, these new data have a profound influence on current models (section 3-5d).

3-5c. Relationship between the Basal Intrusion (former Basal member), SIC and Onaping Formation

The Basal Intrusion (Basal Member of Peredery, 1972) is a clast-rich melt rock comprising mainly ~80% Huronian xenoliths or blocks. This “Basal Member” was considered to be a member of the Onaping Formation until recently (Deutsch et al., 1995; Brockmeyer, 1990) when it was suggested to be the upper clast-rich part of the granophyre based on major and trace element analyses. The analyses used to formulate this hypothesis are very limited; restricted to 12 whole rock and the trace elements Co and Ni (Brockmeyer, 1990). The elements SiO_2 , $\text{Na}_2\text{O}+\text{K}_2\text{O}$, $\text{MgO}+\text{FeO}$ used on a ternary diagram to make this hypothesis (Deutsch et al., 1990) are strongly mobile elements in any hydrothermal system.

In fact, the matrix of the Basal Intrusion (former Basal member) is compositionally similar to the Onaping melt but has a higher SiO_2 content (Table 3-1, Figs. 3-5 to 7), is granodioritic and has overall incompatible element abundances similar to the felsic norite (Figure 3-11). The incompatible element abundances of the basal intrusion are not elevated as in the granophyre. The higher SiO_2 content reflects the field observations of partially assimilated, corroded Huronian quartzite xenoliths. Clearly the Basal intrusion

(Basal Member) is not a clast-rich granophyric phase of the SIC. The apparent intrusive relationship (Muir and Peredery, 1984) between the granophyre and Basal intrusion is an important factor when modeling the Sudbury Structure and its various “melts”.

The igneous-textured Basal intrusion is discordant to the Sandcherry member strata at its exposed base and occupies northwest trending fracture zones also responsible for emplacement of the fluidal breccia complexes. The compositional similarities, spatial distribution and relative timing of emplacement suggests that the Basal intrusion represents a clast-rich melt “pool” at the base of the Onaping Formation that intruded the base of the fragmental pile in the later stages of crater formation. Aphanitic dykes initially emplaced along coeval northeast and northwest fractures, were chilled quickly while the clast-laden melt of the Basal intrusion cooled slower and was locally injected along northwest fractures. The basal intrusion is intimately related to the aphanitic dykes (Peredery, 1972; Gibbins, 1994).

3-5d. Implications for Genetic Models

It is beyond the scope of this thesis to invoke a model of emplacement and formation for the melts of SIC, offset, and Onaping Formation rocks but the following important points from this new data must be taken into account for future modeling of the Sudbury Structure.

- 1) The Onaping melt has chemical affinities more with the norite and quartz diorite offset dykes than with the granophyre of the SIC.
- 2) The least altered Onaping composition and the quartz diorite of the offset dykes

both fill the apparent compositional gap between the norite and granophyre.

The least altered Onaping composition represents a Sudbury melt composition.

Three basic models have been hypothesized for the origin of the SIC: 1) two-magma model (Chai and Eckstrand, 1994), 2) single differentiated melt sheet (Faggart et al., 1985; Grieve et al., 1991; 1994), 3) mantle contaminated crustal melt (Naldrett, 1986).

Two-magma model:

In Chai and Eckstrand's (1994) two magma model the granophyre represents the melted upper crust produced during impact whereas the norite is a mantle magma contaminated by lower crust. Assuming the Onaping melt to be impact-derived, using this model the magma composition should be similar to the granophyre as suggested by Deutsch et al., (1995), although not stated by Chai and Eckstrand (1994). This study, compared with published data of the SIC (Lightfoot et al., 1997) shows that the Onaping melt has trace element and some major element characteristics (MgO) more like that of the mafic component and that the source of the norite and Onaping glass is similar.

Single differentiated melt sheet:

The geochemical data presented in this dissertation addresses the interpretation of the composition of the parent magma. A well known problem, for the hypothesis of differentiation of a single melt sheet origin for the SIC by Grieve et al., (1991), is that there is too much granophyre for the amount of norite which comprises ~ 33% of the volume of the complex. Lightfoot et al. (1997) suggest that if the Onaping Formation was

derived from a granophyric magma then perhaps the volume of the felsic norite would be much less than 33%, producing a parent composition more like that of an andesite. Based on the data presented in this dissertation, this is not a valid assumption.

The volume of glass in each unit within the Onaping Formation was calculated from the field and petrographic observations (Table 3-2). A conservative calculation of the amount of melt in the Onaping Formation produces one-third of the observed volume which is slightly less than the melt volume represented by the norite. Therefore, the Sudbury melt system contained similar amounts by volume of granophyre and norite-equivalent compositions.

The timing of events based on field relationships (Dressler and Sharpton, 1997) such as the intrusive nature of the granophyre into the base of the Onaping Formation raises questions concerning the emplacement and differentiation processes of the SIC. Another point is that Onaping Formation rocks have not been found as partially assimilated fragments or xenoliths at the top of the SIC in the granophyre as would be expected for an *in situ* differentiated melt sheet.

Crustal-contaminated mantle-derived magma:

The model of Naldrett et al., (1986) is that of a strongly crustally-contaminated mantle magma. This is supported by Lightfoot et al. (1997) to explain the mafic and ultramafic xenoliths and Cu-Ni-PGE ores at the base of the SIC. The data in this dissertation is compatible with the idea that the original melt below the Onaping Formation was andesitic with a strong crustal component (i.e. the basal intrusion and

source of aphanitic dykes), similar to the SIC (e.g. Naldrett et al., 1986) and offset dykes (Lightfoot et al., 1997), and that this melt was tapped periodically during deposition of the entire Onaping Formation. This thesis data do not address the possible contribution from mantle-derived picritic magma to a possible melt sheet but does not rule this out.

Rousell et al. (1997) invoke a model of emplacement of the SIC incorporating features from the above three models. The composition of the SIC is based on the assumption that a mantle-derived magma was contaminated by a largely anatectic (induced by impact) crustal melt and was emplaced in successive batches from felsic to mafic (i.e., granophyre, norite, sublayer). They suggest that the sublayer and Ni-Cu ores were emplaced late, although all were emplaced within the error of geochronology (Figure 2-1) and did not form through *in situ* differentiation of the SIC. The Onaping Formation-norite-offset relationship is not clear in terms of this model. In this scenario (Rousell et al., 1997) the Onaping Formation melt represents the second batch of magma (equivalent to norite and offset dyke melt). The aphanitic dykes in the Onaping Formation should cut the previously emplaced intrusion represented by the granophyre. Evidence for this does not exist.

Relative timing based on field relationships:

The quartz diorite was emplaced early before the main mass was differentiated based on rare felsic norite xenoliths within the quartz diorite dykes (Lightfoot et al., 1997a). Aphanitic dykes in the Onaping Formation were feeders to parts of the Sandcherry member and yet compositionally similar dykes also intrude the reworked upper

units. There is no evidence of differentiation in the dyke melt from the base to the top of the Onaping Formation. These aphanitic dykes do not cut the granophyre of the SIC. Muir and Peredery, (1984) suggest that the SIC/Onaping Formation contact is intrusive. It is likely that the Onaping Formation was emplaced early prior to differentiation or emplacement of the SIC in its present position.

3-5e. Protolith composition

The protolith composition of the Onaping Formation rocks is a single crustally-contaminated melt of andesitic composition. Identification of the compositional similarities of the least altered Onaping Formation melt to the felsic norite and offset dykes is significant. Offset dykes although contaminated by assimilation of local crust are linked with the event that formed the main mass of the SIC. Using an impact context as a working scenario, the vitric glass composition defined here for the Onaping Formation may have represented an “original” melt composition at one point in time. The possible contributions from other sources (i.e. mantle) and the dynamics of subsequent events are extremely complicated and the focus of ongoing research.

Critical for the remainder of this dissertation is that the precursor composition of the least altered Onaping Formation rocks has been defined and serves as the protolith for superimposed hydrothermal alteration.

Figure 3-1: Common volcanic classification diagrams defining the chemical affinities of the Onaping Formation. Red symbols=raw data, Black symbols=recalculated data volatile and sulphur-free. A) Jensen (1976) diagrams, B) AFM diagram (Irvine and Baragar, 1971), C) Na₂O +K₂O vs. SiO₂ bivariate diagram Irvine and Baragar, 1971), D) K₂O vs. SiO₂ bivariate diagram (fields from LeMaitre et al., 1989), E) SiO₂ vs. Zr/TiO₂ (fields from Winchester and Floyd, 1977), F) Zr/TiO₂ vs. Nb/Y bivariate diagram (fields after Winchester and Floyd, 1977).

Figure 3-2: Variation in FeO* and Na₂O for the average less altered compositions for Onaping Formation units and representative least altered composition (recalculated sulphur & volatile-free).

Figure 3-3: a) Chondrite normalized rare earth element pattern for average less altered compositions for Onaping Formation units b) Primitive normalized scatter diagram of average less altered units in the Onaping Formation. (normalizing values, Sun and McDonough, 1989).

Figure 3-4: A) Chondrite normalized rare earth element diagram and B) primitive normalized scatter diagram for vitric aphanitic dykes, block and bomb representative of the least altered composition for the Onaping Formation (normalizing values after Sun and McDonough, 1989).

Figure 3-5: Variation in La and Sm for units of the Onaping Formation compared to rock types of the SIC. Fields for offset and SIC from Lightfoot et al., 1997.

Figure 3-6: Selected major and trace element bivariate diagrams showing less and least altered compositions of major Onaping Formation units compared to units within the SIC (fields from Chai and Eckstrand, 1994; Lightfoot et al., 1997). FN, MN=felsic norite, mafic norite; TG=transition zone quartz gabbro, G=granophyre.

Figure 3-6 (cont'd)

Figure 3-7: Variation in selected trace element ratios in a composite transect from the base of the SIC to the top of the Onaping Formation (fields from Lightfoot et al., 1997). Onaping Formation transect in Morgan Township.

Figure 3-8: Felsic norite-normalized incompatible trace element patterns for a) average less altered units, Onaping Formation b) individual least altered aphanitic dykes, vitric block and bomb and c) average least altered composition representative of the Onaping Formation. All data are normalized to the average composition of the felsic norite of the SIC (data from Lightfoot et al., 1997).

Figure 3-9: Geochemical comparison of selected major and trace element bivariate plots of major units of the Onaping Formations with offset dykes of the SIC (fields from Lightfoot et al., 1997).

Figure 3-10: Incompatible trace element pattern for the least altered Onaping Formation composition normalized to the average composition of the Manchester quartz diorite offset dyke (normalizing data from Lightfoot et al., 1997).

Figure 3-11: Chondrite (A) and felsic-norite (B) normalized incompatible trace element patterns for average compositions of Basal intrusion. (normalizing values from Sun and McDonough, 1989; Lightfoot et al., 1997).

Table 3-1: Summary of average "less altered" unit compositions, Onaping Formation

	SMEQ	SMFL	SMCU	DMCT	DMLU	DMMU	DMUU	B&B SM	A-dyke	BI-"S"	BI-"N"	Least Altered
	n=12	n=10	n=4	n=21	n=7	n=23	n=8	n=6	n=12	n=5	n=5	n=7
SIO ₂	64.97	64.03	65.75	62.36	61.83	60.98	62.80	62.87	62.66	64.62	64.54	61.56
TIO ₂	0.51	0.54	0.49	0.56	0.51	0.49	0.45	0.57	0.61	0.57	0.57	0.61
AL ₂ O ₃	12.15	12.75	12.03	12.21	11.81	10.87	9.64	13.48	13.58	13.56	13.20	13.59
FE ₂ O ₃ T	6.67	6.94	6.68	8.46	8.89	9.78	11.94	7.27	7.46	5.86	6.32	8.40
FE ₂ O ₃	1.03	1.00	0.95	1.44	1.99	2.23	2.03	1.30	1.36	1.18	0.88	1.46
FEO	5.07	5.34	5.15	6.32	6.21	6.17	6.24	5.37	5.49	4.20	4.90	6.24
MNO	0.12	0.13	0.14	0.19	0.30	0.39	0.53	0.13	0.19	0.09	0.15	0.17
MGO	4.55	3.87	3.91	4.70	4.59	4.38	4.69	3.94	3.94	3.61	3.70	4.28
CAO	3.61	3.68	3.67	3.82	4.15	4.41	3.05	2.57	2.26	3.72	2.38	2.63
NA ₂ O	4.76	4.60	4.65	4.40	3.56	2.23	1.15	3.80	3.69	3.78	3.88	4.19
K ₂ O	1.16	2.02	1.70	1.43	2.08	1.68	1.64	3.53	3.23	2.34	3.48	2.66
H ₂ OT	1.78	1.65	1.38	2.03	2.03	2.78	2.90	2.08	2.38	2.06	1.90	2.31
CO ₂	0.08	0.19	0.06	0.17	0.22	1.71	1.06	0.10	0.39	0.07	0.07	0.09
C	0.15	0.10	0.30	0.14	0.41	0.47	0.40	0.10	0.11	0.10	0.10	0.10
P ₂ O ₅	0.13	0.14	0.11	0.15	0.14	0.14	0.16	0.14	0.15	0.13	0.14	0.15
S	0.12	0.22	0.19	0.19	0.36	0.61	0.71	0.14	0.10	0.03	0.08	0.13
S	1148.00	2150.70	1900.00	1885.71	3585.71	6069.57	7062.50	1416.67	1033.33	338.20	800.00	1342.86
Ba	377.50	654.00	435.00	429.05	695.71	657.39	875.00	1330.00	1511.67	602.00	1660.00	1095.71
Be	1.79	2.10	1.45	1.41	1.36	1.51	1.48	1.13	1.19	5.02	1.42	1.23
Co	14.58	20.30	15.50	18.90	16.43	17.78	16.50	20.17	20.58	14.60	16.40	22.71
Cr	93.42	103.70	78.25	96.33	79.71	78.96	70.88	103.00	108.00	107.40	104.80	107.14
Cu	55.08	154.00	23.50	61.57	32.57	66.22	64.50	69.00	120.08	13.00	34.80	185.29
Ni	51.17	70.20	54.25	62.76	63.57	68.87	63.38	59.67	61.58	55.00	58.20	61.86
Pb	3.92	12.90	3.00	3.71	4.94	22.04	39.09	4.30	22.58	5.80	8.30	3.83
Rb	39.38	65.80	55.30	43.65	60.57	40.43	34.50	135.83	86.33	68.40	116.00	95.86
Sc	11.67	12.80	11.25	12.38	11.86	11.00	9.79	13.83	14.25	13.80	13.60	14.43
Sr	156.42	180.10	168.50	91.95	122.29	118.52	77.00	215.00	157.17	292.00	164.00	151.29
V	108.83	104.90	102.50	121.14	118.57	115.22	121.25	108.33	108.75	87.40	101.60	115.71
Y	17.33	17.50	16.25	18.52	17.43	17.83	17.50	17.83	18.92	18.00	17.40	18.57
Tb	1.58	1.45	1.48	1.70	1.59	1.56	1.55	1.72	1.84	1.64	1.70	1.80
Zn	23.50	28.40	27.25	57.52	96.43	196.30	125.50	26.17	106.42	15.20	39.20	49.71
Zr	140.00	144.00	125.00	137.14	132.86	131.74	138.75	145.00	148.33	152.00	146.00	147.14
Ag	0.10	0.10	0.09	0.10	0.08	0.15	0.18	0.37	0.21	0.08	0.09	0.27
Ce	50.00	59.40	44.25	62.43	58.14	56.22	49.00	64.17	65.67	57.20	57.80	65.43
Cs	0.18	0.35	0.20	0.24	0.32	0.41	0.51	0.54	0.45	0.26	0.40	0.39
Dy	2.98	3.04	2.88	3.21	2.97	2.97	2.85	3.32	3.52	3.04	3.16	3.46
Er	1.63	1.57	1.53	1.75	1.66	1.58	1.63	1.82	1.88	1.62	1.76	1.90
Eu	0.81	0.96	0.94	1.05	0.97	0.98	0.81	0.96	0.95	0.92	0.67	1.03
Ga	15.33	15.80	14.25	15.43	15.14	14.91	12.25	14.83	15.67	16.20	14.60	15.29
Gd	3.69	3.83	3.78	4.00	3.80	3.65	3.18	3.98	4.08	3.70	4.00	4.10
Hf	3.66	3.60	3.15	3.59	3.37	3.33	3.60	4.05	4.08	3.88	3.76	4.19
Ho	0.59	0.60	0.57	0.64	0.61	0.59	0.92	0.64	0.68	0.60	0.63	0.67
In	0.03	0.04	0.03	0.03	-0.03	0.01	0.03	-0.01	0.02	-0.02	0.03	
La	25.33	30.20	21.78	32.10	29.86	28.83	23.13	31.33	33.83	27.60	28.20	32.43
Lu	0.25	0.25	0.23	0.26	0.25	0.24	0.25	0.27	0.28	0.26	0.27	0.27
Mo	9.68	17.38	3.78	4.48	5.61	5.91	3.63	0.41	1.10	2.80	1.54	0.51
Nb	9.23	8.44	8.33	9.21	9.36	9.79	10.96	7.90	8.51	8.00	8.04	8.14
Nd	23.50	25.90	20.75	25.86	24.29	23.48	20.50	28.17	29.42	24.40	25.60	31.43
Pr	6.18	6.95	5.38	7.01	6.46	6.38	5.55	7.50	7.56	6.34	6.70	7.61
Sm	4.42	4.58	4.28	4.64	4.33	4.22	3.84	4.97	4.90	4.36	4.54	5.14
Ta	0.63	0.52	0.63	0.62	0.58	0.64	0.68	0.52	0.52	0.76	0.52	0.53
Tb	0.52	0.54	0.51	0.57	0.53	0.53	0.47	0.57	0.60	0.55	0.57	0.59
Th	7.76	7.52	7.10	7.67	7.46	7.06	6.71	8.38	8.13	7.96	7.96	8.17
Ti	0.18	0.33	0.27	0.24	0.38	0.28	0.33	0.77	0.57	0.37	0.67	0.57
Tm	0.26	0.25	0.25	0.27	0.25	0.25	0.25	0.27	0.29	0.27	0.27	0.28
U	4.05	2.81	2.80	3.58	3.40	3.56	3.90	2.57	2.43	2.44	2.32	2.41
F	551.42	511.80	364.25	389.19	516.57	511.17	348.63	1.00	181.42	553.60	379.60	1.00
CL	265.25	352.70	285.25	177.05	193.14	201.35	105.63	1.00	94.92	283.40	173.20	1.00
Bi	0.51	0.56	0.40	0.41	0.44	0.60	0.49	0.10	0.23	0.90	0.34	

SM=Sandcherry member, DM=Dowling member, B&B=Blocks and bombs, Adykes=aphanitic dykes
BI=Basal intrusion, S-sheet-like, N-necks. EQ=equant shard units, FL=fluidal fragment units, CU=conductive equant shard units,
CT=contact units, LU=lower units, MU=middle units, UU, upper units.

Table 3-2: Amount of glass in a section across the Onaping Formation. Brackets denote amount used.

	Modal estimate (% glass	True thickness	m of glass
<hr/>			
Garson member	10-20 (10)	0-500 (100)	10
Sandcherry	60	360	216
Dowling			
Contact	40-55	35-300	38.5
Lower	20-30	20-30	7.5
Middle	35	600-780	242
Upper	<15	140-220	27
Basal intrusion	25-75 (30)	0-300 (150)	45
Aphanitic dykes	80-100	negligible	-
		Total	586 m

Chapter 4

REGIONAL SEMICONFORMABLE AND LOCAL HYDROTHERMAL ALTERATION

4-1. Introduction

Historically, hydrothermal alteration was used unknowingly to define the stratigraphy of the Onaping Formation (Gray, Green and Black member, Peredery, 1972; Avermann, 1992). Initial recognition that the carbon contact is diachronous (Muir, 1984; Gibbins, 1994) called into question the exact nature of alteration affecting the crater-fill sequence. Circulation of hydrothermal fluids in modern and paleoseafloor settings has long been recognized as a critical process in the formulation of VMS deposits. The vertical stacking of regional-scale silicification, albitization, chloritization and carbonatization in the Onaping Formation is unusual for typical VMS settings as only one or two of these alteration types are usually present in any one district. The setting of alteration in the Sudbury Structure, generally recognized as a meteorite impact crater, is unique since most terrestrial impact craters bear the signature of only minor, volumetrically insignificant alteration predominantly lining vugs and open spaces (Allen et al., 1982; McCarville and Crossey, 1996; Masaytis and Naumov, 1995; Sturkell et al., 1998).

Recently, hydrothermal alteration has also been recognized in the basement rocks below the SIC in large zones associated with brecciated footwall rocks “Sudbury Breccia” and proximal to Cu-PGE mineralization (Watkinson, 1990; Farrow and Watkinson, 1992; Farrow, 1994; Watkinson, 1994; Molnar et al., 1997) however the relationship between

the two apparent hydrothermal systems has not yet been studied. The hydrothermal alteration in the crater-fill deposit, will be referred to as the “Upper hydrothermal system” and hydrothermal alteration below the SIC is referred to as the “Lower hydrothermal system” of the Sudbury Structure. This dissertation focuses on defining the characteristics of the Upper hydrothermal system of the Sudbury Structure.

The purpose of this chapter is to document a) the controls on alteration including stratigraphy and structure b) the spatial distribution, mineralogy, mineral- and bulk rock-chemical characteristics, timing and origin of alteration types to show that the alteration paragenetic sequence was diagenetic alteration, albitization, chloritization, carbonatization and likely silicification at ~ 1848 Ma. The relationship between regional-scale alteration, intra-Onaping base metal occurrences and the overlying Zn-Cu-Pb deposits is documented in succeeding chapters. This dissertation is the first comprehensive study to document and link regional-scale, local and deposit-scale hydrothermal alteration in the Onaping Formation, define their interrelationships and illustrate their significance to ore-forming processes.

Each alteration type's morphology, distribution, mineral assemblages, mineral chemistry and whole rock mass balance with a discussion of the implications for each alteration type are documented in this Chapter and Appendices 4-1 to 4-3. The regional alteration types are described stratigraphically from the base of the Onaping Formation to the top. A comprehensive discussion and working model of the entire hydrothermal system and paragenetic sequence in the Sudbury Basin, including the ore deposits and

alteration isotope constraints are formulated in the final Summary and Conclusion Chapter, 7.

4-2. Regional hydrothermal alteration.

A major hydrothermal circulation system in the Sudbury Structure altered the crater-fill deposits around the entire circumference of the exposed structure (Figure 4-1). The effects of early stage, low temperature diagenetic alteration and devitrification are widespread in the Onaping Formation and have been overprinted by hydrothermal alteration zones named after the principal alteration mineral. Evidence for a regional, subseafloor hydrothermal system in the Onaping Formation includes vertically stacked, basin-wide, semiconformable alteration zones in which the rocks have undergone, from base to top, silicification, albitization, chloritization, carbonatization and, in the uppermost zone, complex feldspathization, the distribution of which is not well constrained (Figure 4-1, Ames et al., 1998; Ames and Gibson, 1995). Most of these concordant zones also have a volumetrically minor, yet significant, discordant fracture-controlled manifestation. The fracture-controlled alteration occurs as pervasive replacement of the host rocks in alteration halos immediately adjacent to fractures that commonly do not have a central vein (i.e., silicification, albitization, chloritization).

Mass balance methodology and protolith compositions

To examine the chemical aspects of each alteration zone, the mass gain and loss of components during metasomatism were calculated. Element mobility was then related to

the observed mineralogy. The principles of mass balance were established by Akella (1966) and Gresens (1967). Grant (1986) developed the isocon (equal concentration) plot based on concepts introduced by Gresens (1967) which enables only one altered sample (altered concentrations for each element) to be plotted against an unaltered parent sample or average composition. Isocon diagrams are difficult and cumbersome to compare multiple altered samples as each altered sample is typically shown on a single isocon plot. To overcome this Huston (1993) developed an arbitrary scaling factor for each element. The scaling factors (1-31) are selected by sequencing elements with large mass gains before those with small to large mass losses (Appendix 4-1), with immobile elements dispersed throughout.

The chemical changes produced by alteration were determined using Huston's (1993) modification of Grant's (1986) graphical isocon method. The equations for determining the scaling factor, the net mass change relative to the least altered parent rock, the relative density change of altered rocks, volume changes, relative and absolute mass changes are well explained by Huston (1993). Elemental mass gains and losses during metasomatism can be calculated by comparing less altered and altered rocks but the selection of the unaltered protolith is critical. The least altered Onaping Formation, as determined in Chapter 2, represents an average of 7 vitric samples.

The interpreted 'comagmatic' nature of the Onaping Formation with the felsic norite documented in Chapter 2 enables a comparison of the chemical mass gains and losses of the least altered Onaping Formation with the felsic norite (Table 4-1). The least altered Onaping Formation has undergone considerable alkali exchange with gains in Ba,

Na, K and a major loss of Ca relative to a felsic norite precursor (Appendix 4-1, Figure A4-1.1). Other losses include ferric iron, CO₂, Cr, Ni, Sr and Zn. Uncertainty in the original, unaltered precursor of the Onaping Formation being similar to the composition of the felsic norite or the quartz diorite and/or subsequent changes in the felsic norite due to alteration renders any succeeding mass balance calculations interpretive. Therefore initially all mass balance calculations of altered rocks in the Onaping Formation (242 analyses) were performed using the average least altered composition shown in Table 3-1. As mass changes during the hydrothermal evolution of the system were incremental with succeeding alteration zones overprinting an earlier phase of alteration, a second mass balance calculation was performed utilizing precursor average alteration types or samples specifically collected in the field as pairs for mass balance computations.

Detailed descriptions of localities, methodology and results of mass balance calculations for each alteration type are outlined in Appendix 4-1. Mineral chemistry of the alteration minerals are listed in Appendix 4-2.

4-2a. Diagenetic alteration and devitrification

Relict textures of “gel”- and fibrous-palagonite, zeolites, spherulites and clay minerals are distributed widely throughout the Onaping Formation. The entire formation has been affected by variable degrees of early diagenetic alteration, palagonitization, devitrification and overprinting hydrothermal alteration which were subsequently recrystallized during subgreenschist facies metamorphism. Textural preservation is best within a 150-300 m wide transition zone between the lower semiconformable zone of

albitization and the zone of calcite alteration (Map 1B). Relict perlitic cracks decorated with Fe-Ti oxides are commonly observed in the Dowling member lower, middle and upper units and less commonly in the Sandcherry member. Sector crystallization is evident in shards now replaced with albite. Fine laminar textures decorated with fine Fe-Ti oxides are common at the shard rims and along internal fractures (Plate 4-1). These textures retained in albite in the Sandcherry member and chlorite in the Dowling member, are likely the replacement of an early phase of palagonitic alteration and represent alteration minerals pseudomorphous after gel-palagonite. Relict fibro-palagonitic textures are less common.

Devitrification textures are abundant particularly in the Dowling member units, aphanitic dykes, and lobes in the peperitic zones. Spherulites are present in various degrees of preservation from fibro-radial coarsely recrystallized albite-Kfeldspar-quartz, to micropoikiloblastic quartz overgrowths and fine polycrystalline aggregates of quartz (Plate 4-1).

The degree and relative rates of devitrification and diagenetic alteration are dependent on the relative rates of cooling, the thickness of units, permeability, the presence of trapped gas and pore fluid compositions.

4-2b. Silicification

Silicification occurs as 1) a pervasive to patchy semiconformable zone at the base of the exposed Onaping Formation within the Sandcherry member and Basal intrusion, 2) silicified blocks, bombs and proximal fluidal fragment units, 3) isolated patches at the top

of the Sandcherry member, 4) disconformable, fracture-controlled alteration and 5) a local alteration type associated with peperite and base metals. The peperite-associated and base metal deposit-proximal silicification will be discussed in sections 4-3 and 4-4 respectively.

Semiconformable alteration zones:

Morphology, contact relationships, controls on distribution: Semiconformable, discontinuous silicified zones up to 1300 m long by 280 m thick have been traced for more than 30 km at the exposed base of the Onaping Formation in the North Range (Figure 4-2). This extensive silicification zone is exposed 1-1.5 km below the stratigraphic level of the Errington and Vermilion massive sulphide deposits. Silicification affects both equant shard units and fluidal fragment units of the Sandcherry member. The Basal intrusion contains windows or fragments of silicified fluidal fragment units in sharp contact and is locally silicified itself. Contacts between silicified and less altered Sandcherry member rocks are knife sharp. Silicified fragments were observed in overlying units south of Diabase Fault Lake (Gibbins, 1994) and in relatively unaltered equant shard units 200 m above the semiconformable basal zone in Morgan Township (Plate 4-2).

The widest zones of silicification occur where the granophyre is in direct contact with the Sandcherry member at highway 144 and Morgan Township but less altered Onaping Formation is also in contact with the SIC where the Basal intrusion is absent. The spatial distribution of silicified zones is not controlled by the emplacement of the Basal intrusion, fluidal breccia complexes nor does it form an annular rim around the SIC.

Mineralogy and mineral chemistry: Silicification is generally pervasive, affecting matrix and less commonly shards. Macroscopically, relict, recessive weathering, blocky shard-like outlines decorate buff weathering, orange and yellowish stained outcrop (Plate 4-2). Local, 30 cm diameter, intensely bleached patches are scattered throughout the regional alteration zone. The basal zone consists of albite, quartz, actinolite, chlorite, titanite, epidote and minor Kfeldspar, calcite, pyroxene and muscovite with traces of apatite, chalcopyrite, pyrrhotite, covellite, sphalerite, and magnetite (Table 4-2) .

Relict shards are composed of quartz-albite-actinolite-chlorite-minor titanite, trace Kfeldspar, calcite and clinopyroxene. Shards have coarse albite-rich rims with chlorite-amphibole-clinopyroxene $\pm$ albite in the core. Quartz occurs dominantly in the matrix, where it has preferentially replaced flow bands but it also occurs, in minor to trace amounts, in shard cores. Alteration fronts show quartz ($<$ albite) alteration overprinting an albite dominant alteration type (Plate 4-3). Albite is a principal mineral and contains much finer, and volumetrically less, anhedral Kfeldspar (Plate 4-3). This earlier phase of Kfeldspar alteration is overprinted by albite, quartz and epidote. Extremely fine radiating albite with undulose extinction replaces shards, matrix and fills amygdales and locally reveals a polygonal fracture pattern (Plate 4-3). The composition of chlorite in this silicified zone indicates that it is a moderate-Fe pycnochlorite (Figure 4-3). This chlorite is more Mg-rich than the regional chlorite (high-Fe pycnochlorite). Chlorite-calcite domains locally contain minor pyroxene and/or amphibole. It is likely that pyroxene was hydrated to amphibole which upon addition of CO_2 partially altered to chlorite and calcite.

Epidote is not apparent in hand specimen and is a minor constituent of the silicified zone. Where observed epidote is intimately associated with pyrrhotite, chalcopyrite $\pm$ clinopyroxene (Figure 4-4) and is Fe-poor and Al-rich (Figure 4-5). The atomic Fe^{3+} content of epidote increases with distance from the granophyre contact within the silicification zone. At ~ 10 m from the granophyre the mean atomic Fe^{3+} content is 0.58 and at ~ 200 m, Fe^{3+} increases to 0.72. Epidote in the basal silicification zone, closest to the SIC and therefore deepest in the section, is the most Fe-poor epidote of the entire Onaping Formation.

Disconformable alteration zones:

Morphology, contact relationships, controls on distribution: Discordant fracture-controlled silicification, manifested as pervasive zones of quartz-albite alteration, is present higher in the stratigraphic section within Sandcherry member equant shard units and Dowling member contact and middle units (Map 1B) (Plate 4-2d-f). Areas of fracture-controlled silicification are proximal to flow-banded, spherulitic or massive dykes and pods.

In the footwall to the Limerick Cu showing (Map 1B) is a 3 x 3 m zone of patchy silicification at the boundary between the contact and middle units (Plate 4-2d). Silicified patches, 70 x 45 cm and smaller, generally strike 035° and in this locality are crossed by a network of quartz veinlets (dominant $064/19$). Less than 150 m to the west are 50 cm silicified patches in the contact units. Another area of silicification is situated approximately 650 m above the base of the middle units in Morgan Township within a

calcite-absent zone in the regional semiconformable zone of carbonatization (calcite) (Map 1B). It occurs as 036° trending, linear, silicified zones that merge into 20-40 cm irregular, prominent weathering patches of intense silicification. The area affected is 1 m² with 40% silicified patches. Relict lithic fragments are prominent on the outcrop.

On the Hanmer powerline, fracture-controlled silicification zones cross the contact between the Sandcherry member and Dowling member (Plate 4-2e,f). They are 3-4 cm wide, locally 20 cm, planar zones that are continuous for 2 m and discontinuous for 5 m and do not contain a central fracture. Irregular apophyses protrude from the main 'fracture'. The main 'fractures' are oriented north or east-southeast (100°). They are typified by pinkish-white shards in a whitish silicified matrix and are more spectacular in the Sandcherry than Dowling member due to the abundance of coarse blocky shards (Plate 4-2f).

Mineralogy and mineral chemistry: The discordant alteration is similar to the semiconformable alteration zone mineralogically (Table 4-1), although the sulphide mineralogy is dominated by pyrite, instead of pyrrhotite, and epidote is absent. Chlorite is absent or present in trace amounts and texturally the chlorite distribution differs from that in the host albitized zones at the Hanmer powerline. In silicified rocks, chlorite and felsic minerals are evenly distributed throughout the relict shards whereas in the adjacent albitized rocks there is a distinct zonation with felsic rims and mafic cores.

Geochemistry of semiconformable and disconformable silicification:

The average SiO_2 content of silicified rocks progressively increases with stratigraphic height. The average SiO_2 contents are: 67.5 wt. % for the basal silicification, 70.9 wt. % for silicified fluidal breccia, Sandcherry member; 75.5 wt. % for patchy silicification in the contact units and 81.1 for fracture-controlled silicification in the middle units, Dowling member. Mass changes calculated for the basal silicification zone relative to the least altered vitric precursor showed significant gains in Si, Ca, Mo and S and losses in K, Ba, Rb and Mn; Cu, Pb and Zn are erratic (Appendix 4-1, Figure A4-1.2a). Typically relative mass gains in Si are minor, ranging from 20-25%, with associated minor to major Ca gains. Petrographic observations of silicification overprinting earlier albitization validates the use of the average weak feldspar alteration as a “precursor” composition (Figure A4-1.2b). The difference in utilizing an altered precursor is that the earlier effects of albitization are isolated from chemical changes during the silicification process. Gains of Si, Fe, Cu, Zn, Pb, S and a loss of Na are evident for the basal zone of silicification (Table 4-3; Figure A4-1.2b). These chemical changes are compatible with petrographic and field observations of increased chalcopyrite, pyrrhotite and sphalerite in patches and vesicle fillings; epidote and clinopyroxene are volumetrically insignificant and actinolite is a minor constituent. Geochemically, Ca shows little change with respect to the altered precursor but showed major addition relative to the least altered Onaping Formation composition. Using the same precursor, the major chemical changes between silicified Sandcherry member (+Si, Ca, Cu, Zn, S) versus the basal intrusion (+Si, Na and - Cu, Zn, S) is in the Ca/Na ratio of mass changes and the respective gain and loss of metals (Figure A4-1.2 a and c).

Mass changes calculated for various discordant zones of silicification (Appendix 4-1a) showed that fracture controlled silicification was accompanied by increases in Si, K and Pb and decreases in Na, Ca, Fe, Mn, Mg, Cu, Zn and S (Figure A4-1.3) whereas patchy silicification has increases in Si and Pb and decreases in K, Ca, Sr, Ba, Fe and Co. The differences between the fracture-controlled silicification (higher in the middle units) and the patchy silicification (at the base of the middle units) is the gain or loss of Na, K and Ba (Table 4-4). Silicified fluidal breccia complexes at Joe Lake and the Hanmer powerline are characterized by gains in Si and Na and losses in Mn, Cu, Zn and S (Table 4-4; Figure A4-1.3c).

Implications and timing:

Silicification is found at many stratigraphic levels in the footwall to massive sulphides in the Onaping Formation although the regionally extensive semiconformable zone is exposed 1-2 km below the Errington-Vermilion deposit horizon. There is no direct spatial link between the regionally extensive semiconformable silicification zone, the SIC or the basal intrusion, nor is it restricted to a particular unit. Although the basal silicification is broadly annular, in detail the SIC is discordant and cuts the basal silicification zone. This supports observations of Peredery and Muir (1984) that the SIC (granophyre) is intrusive into the Onaping Formation and supports the emplacement of the granophyric phase of the SIC shortly after the Sudbury Structure was formed (Peredery and Morrison, 1984; Cowan et al., in press; Dressler, 1987).

Textural and structural evidence indicate that silicification overprints an earlier albite ($\ll$ Kfeldspar) dominant, alkali metasomatic alteration. However, fragments of a previously metasomatized, lithified equant shard unit in a stratigraphically higher, relatively unaltered equant shard unit suggests at least a partial syndepositional timing for the silicification. Windows or fragments of strongly silicified Sandcherry member in weakly silicified basal intrusion also suggests that silicification was multistaged or long lived. At least one stage predated the basal intrusion and one was post-basal intrusion. Emplacement of the basal intrusion and silicification of the lower part of the Onaping Formation were broadly coincident. Similarly, some fluidal breccia complexes are silicified (Joe Lake) and others not (Morgan Township) although both occupy the same stratigraphic position.

Changes in silicification with stratigraphic position are not only manifested in the style (semiconformable-deep/ discordant-shallow) but in the mineralogy (ep-cpx-po-sph-cpy/py) and geochemistry of the alteration. Regional semiconformable silicification zones show metal enrichment accompanied by minor Si addition whereas local discordant zones of silicification are characterized by metal losses, and major Si-K-Ba enrichment (Tables 4-3 and 4-4; Appendix 4-1).

Silicification is only one phase of the hydrothermal system within the Sudbury Basin, yet its extent signifies interaction of a large volume of fluid with the vitric rocks of the Onaping Formation. Semiconformable silicification post-dates albitization and was accompanied by systematic additions of Si, Fe, Cu, Zn and S (Table 4-3). Quartz and sulphides in vesicles and in the matrix implies that the hydrothermal fluid became saturated

with respect to Si, Fe, S and metals. Silicification of the basal intrusion and fluidal breccia complexes, however, was accompanied by Na addition and Fe, Mg, K, Cu, Zn, S depletion.

Regional zones of silicification in VMS camps are commonly metal depleted and reported to be the result of either low temperature alteration at or near the paleoseafloor (Skirrow and Franklin, 1994; Gibson et al., 1983) or high temperature alteration in a deep subsurface reaction zone (Skirrow and Franklin, 1994). Silicification in the Onaping Formation occurs as the replacement of andesitic groundmass. A variety of PT conditions may cause the precipitation of SiO_2 from Si-saturated fluids in hydrothermal systems (Skirrow and Franklin, 1994). However, the presence of abundant hydrothermally altered andesitic glass in a permeable fragmental pile (Table 3-2) suggests that fluid was equilibrated with andesitic glass and this is the logical source for Si-saturated fluids (Seyfried and Bischoff, 1977). Earlier albitization was also accompanied by depletion of Fe, Cu, Zn and S which are enriched in the basal zone of silicification.

Si-saturated fluids likely precipitated quartz in response to increasing temperature as the fluid moved deeper in the pile into the temperature range of retrograde solubility ($T=340\text{-}450^\circ\text{C}$, $P<900$ bars; Fournier, 1983). Metal deposition is commonly controlled by decreased temperature or increased pH (Barnes, 1979). The chalcopyrite-sphalerite-pyrrhotite assemblage could have been deposited largely in voids and patches associated with calcite during cooling, although boiling and/or a magmatic contribution cannot be ruled out. The late paragenetic relationship between silicification and albitization in the Onaping Formation coupled with the chalcopyrite-pyrrhotite-sphalerite-Fe-poor epidote-

actinolite association is suggestive of a relatively high temperature, low fO_2 , moderate fS_2 alteration overprinting an earlier, lower temperature alkali metasomatic event.

4-2c. Albitization

Two types of albitic alteration has affected the Sandcherry member strata (Ames and Gibson, 1995). Whereas type 1 is a syndepositional, pervasive alteration and is broadly semiconformable in morphology, type 2 is fracture-controlled and discordant (Plates 4-4-7).

Type 1: Semiconformable albitization:

Morphology, contact relationships, distribution and controls:

Albitization defines a semiconformable zone 280-425 m thick, situated 1 km below the Onwatin/Onaping contact. In Morgan Township, it is twice as thick as the underlying zone of semiconformable silicification (Map 1B). Albitization is best developed within the Sandcherry member but it also occurs within the contact and lower units and rarely the middle units of the Dowling member (Maps 1B, 2B). Coarser shards (0.5-1 cm) within the contact units are preferentially altered particularly those within the basal block-rich zone where most shards are sugary textured with 80% feldspar/quartz and 20% chlorite. Intense to moderate zones of albitization are discordant to strata in detail (Maps 1B and 2B) but lie within a broad, semiconformable weak zone of albitization.

Weak albitization is characterized by the development of randomly distributed actinolite, plagioclase, quartz and titanite within shards. Weakly albitized Sandcherry

member rocks weather grayish green, have green shards and may contain <5% shards with pinkish beige weathering rims (Plate 4-4). Moderately albitized shards have distinctive, coarse 2-5 mm, pinkish beige weathering rims and green amphibole and/or chlorite-rich cores. There is minor replacement of shards by albite-Kfeldspar-quartz. Outcrops weather pinkish beige in areas of intense albitization (Plate 4-4). This pervasive intense alteration is characterized by partial to total replacement of the glass shards by albite-Kfeldspar-quartz and minor chlorite/actinolite, and partial to total replacement of lithic fragments and matrix by an albite-Kfeldspar-quartz assemblage (Plate 4-4). In contrast, the weak and moderate albitized rocks have chlorite-amphibole-rich matrices.

The intensity of albite alteration increases towards aphanitic fluidal dykes and discordant fluidal breccia complexes, although not all have associated albitic alteration aureoles (Maps 1 to 5). Albitized aureoles consist of irregular pinkish beige zones that become mottled and patchy with decreasing intensity. The spatial association of flow-banded aphanitic sills, dykes, and breccia complexes with alteration is particularly well developed near Nelson, Garson and Joe Lakes (Map 2B; Plates 4-4 to 4-6). Intense replacement of autobrecciated, hyaloclastite-like shards and dyke fragments by albitic assemblages within 1-m-wide envelopes around isolated dyke apophyses, attests to the syndepositional timing of this alteration (Plate 4-5). Above sills, intense alteration is aerially extensive and the density of sills and dykes correlates with the albite alteration intensity and distribution (Maps 1B and 2B).

Within the contact units (Dowling member) the distribution of albitization is also controlled by the emplacement of aphanitic dykes. At the western contact unit exposure in

Morgan Township, a series of 040° trending, coarsely spherulitic (4 mm-65%) and amygdaloidal dykes (15%) transect the Dowling member contact unit. In this locality, the increase in the intensity of albite alteration is manifested by a change from chloritic shards in low intensity alteration away from dykes, to strongly bleached albitic patches and pervasive albitization within a 30 cm wide zone adjacent to dykes. The feldspar alteration is also evident into the base of the middle units where Kfeldspar is a dominant mineral along with albite in the fine shards with lesser chlorite.

The spatial relationship between amphibole and albite is strong. Pinkish weathering albitized shards are commonly set in a matrix of amphibole at dyke terminations and margins (Plate 4-5c). Extensional veins with intensely bleached albitized halos are filled with amphibole and occur at a dyke termination at Nelson Lake (Plate 4-5b). Amphibole rims shards and lithic fragments in intensely albitized zones, cores altered shards in all of the zones, partially to totally fills amygdales and vugs, pseudomorphs mafic fragments and occurs as fracture fillings and rims on fracture-controlled albitization (Plates 4-4 to 6). Bleached albitized rims are common on actinolite-rich amygdales in the basal intrusion and Sandcherry member, on mafic fragments and anhedral mafic clots or vugs and on amphibole-filled stringers and veins. Intensely albitized zones, which are proximal to aphanitic dykes in the Nelson Lake area, have altered shards and metasomatic halos with multiple monomineralic bands consisting of alternating albite- and actinolite-rich zones. Six alternating albite- and actinolite-rich bands attest to multiple fluid pulses (Plate 4-5d). Albitized halos are absent on fine amphibole veinlets in the core of a fluidal breccia complex, Morgan Township.

Mineral assemblages and chemistry: The regional, semiconformable albite zone is mineralogically simple, consisting of variable proportions of albite-quartz-Kfeldspar-actinolite-chlorite-prehnite-titanite depending on the intensity of alteration (Table 4-5).

Coarse-grained, 0.1 mm, albite and Kfeldspar typically outlines or totally replaces shards. The feldspar crystals are oriented perpendicular to shard margins with sector crystallization along fractures. Shards at the autobrecciated margins of flow banded dykes show a transition from rim to core of polycrystalline felsic aggregates, followed by monomineralic coarse, inwardly growing feldspar and a core of actinolite and feldspar. In zones of weak albitization, larger albite and untwinned Kfeldspar crystals replaced the shard margins and are dusty, brown and may be rimmed by clear, colourless, finer-grained albite or Kfeldspar. There is no systematic pattern to the distribution of albite or Kfeldspar in the outer rim or in flow-banded shards where they coexist (Plate 4-7 b, c) suggesting their coeval development within the broad semiconformable zone.

In general, Kfeldspar is coarser grained (~1 mm) in the cores of moderately altered shards and occurs as fine (20-100 μm), anhedral grains in the matrix and areas of more intense albitic alteration (Plate 4-7f). Fine anhedral Kfeldspar grains may represent relict larger Kfeldspar crystals overgrown by a later albitic alteration phase or their coeval development and/or both.

Plagioclase compositions are dominated by end-member albite with minor to trace end-member Kfeldspar in individual samples (Figure 4-6). There is no difference in composition between the cores and rims of albite and Kfeldspar. In zones of weak

albitization the albite has a composition of $An_{(0-3.4)}$ and Kfeldspar has $An_{(0-6.1)}$, $Ab_{(0.8-1.6)}$, (Table A4-2.6). Barian Kfeldspar is irregularly distributed and contains Cn (celsian) (<2.14). One alkali feldspar was analyzed with $Ab_7 Or_{88}An_4Cn_1$ in the weak zone. In zones of strong albitization, the albite is essentially stoichiometric ($An_{<0.7}$) and Kfeldspar has $An_{<7}$ and a low barian component $Cn_{<0.8}$. Albite contains less than 0.1 wt. % CaO and has a low K_2O content. Kfeldspar occurring as relict anhedral grains contains small amounts of Na_2O (average 0.24 wt %) and trace BaO (0.33 wt %).

Light coloured “bleached” halos surrounding amphibole-bearing amygdales and mafic fragments are composed dominantly of albite although one halo consists of fine granular epidote (Figure 4-7). In the dyke-proximal albitization at Joe Lake (Map 2B) the bleached rims are quartz-free and composed of albite with minor Kfeldspar (Plate 4-4D). Relict shards in the bleached halo have monomineralic rims of albite with amphibole-albite and trace quartz-apatite in the core.

Amphibole compositions were determined from Sandcherry and Dowling member shards and matrix, basal intrusion, vugs, matrix, veins and mafic fragments (Table A4-2.1; Appendix 4-2). Amphiboles in the Onaping Formation are all essentially actinolitic with minor actinolitic hornblende and tremolite (Figure 4-8). The $Mg/Mg+Fe^{2+}$ ratios, (Mg#) range from 0.6 to 1.0 and average ~ 0.8 . Individual amphibole crystals are relatively homogeneous with minor zonation evident in some mafic fragments in the intensely albitized proximal fluidal fragment units at Joe Lake with Mg-rich rims and Fe-rich cores (AV-524).

Amphibole in shards within intensely albitized zones of fluidal fragment units near the base of the regional albite alteration zone in Morgan Township (AV-196) are compositionally actinolitic-hornblende. Amphibole in intensely albitized contact units (AV-256, 286) are essentially low-Mg actinolite with minor overlap into the ferro-actinolite and actinolitic hornblende fields (Figure 4-8). These relatively Fe-rich amphiboles in the altered contact units are associated with Fe-rich chlorite ($Mg\#=0.4-0.28$), chalcopyrite and pyrrhotite. Actinolite associated with chlorite in the middle units are less Fe-rich and are associated with more Mg-chlorite ($Mg\#=0.39$).

Amphiboles in the Joe Lake area are more magnesian than those in the Morgan area and are actinolite-tremolite. The cores of weakly albitized shards in the Sandcherry member tuff contain moderate-Mg actinolite (AV-512) whereas matrix compositions in vent proximal, altered fluidal fragment units have more Mg-rich compositions, which span the actinolite to tremolite boundary (AV-567). Tremolitic amphiboles are spatially associated with intense alteration adjacent to aphanitic dykes. Amphibole-filled amygdales with albitized halos in the basal intrusion at Joe Lake are composed of high-Mg actinolite (AV-517) whereas less altered, skeletal matrix amphibole in another locality in the Joe Lake is a more Fe-rich actinolite to actinolitic hornblende (AV-501). There is a trend of increasing Si with respect to Al and Mg in the calcic amphiboles within increasing alteration. The Mg content of chlorite also increases in the same samples (Figure 4-8).

In the Nelson Lake area, amphibolitization is intense and is associated with dyke proximal albitization (Plate 4-5b, c, d). Amphibole in the matrix, amygdales and veinlets in the aphanitic dyke are moderate-Mg actinolite (AV-698) whereas amygdales in distal

altered fluidal units are actinolitic hornblende. The intense matrix amphibole at dyke terminations (Plate 4-5c) is a more Mg-rich actinolite than that in the dyke. Compositional changes in amphibole with increased alteration follow a negative slope on the Mg/Mg+Fe versus Si compositional diagram (Figure 4-8). These assemblages are chlorite-absent.

Mafic fragments in intensely albitized zones commonly have albitized halos (Figure 4-7). Most of the amphiboles in the mafic lithic fragments are actinolite and actinolitic-hornblende with fewer compositions spanning the tremolitic hornblende and ferro-actinolite fields (Figure 4-8c). These compositions are essentially similar to amphiboles within the host rocks. At Joe Lake, a mafic fragment shows compositional differences from core to rim (increased Mg) with the composition of the rim more similar to the host matrix amphibole (AV-567, Figure 4-8a, c) again emphasizing the trend of increasing Mg with alteration.

Titanite within dyke-proximal, syn-depositional alteration occurs in the matrix, shards and along flow-bands. It is predominantly poikiloblastic with inclusions of albite and quartz. Titanite compositions have low F content (< .89 wt. %) although titanite in the more weakly altered samples have higher F content than those in the intensely albitized rocks (Table A4-2.12).

Prehnite is a trace to minor component in areas of weak alteration where it occurs as open space fillings commonly associated with quartz and pyrrhotite and as shard replacements. Mineral assemblages consist of chlorite-feldspar-titanite-prehnite-pyrrhotite±epidote±calcite. Prehnite forms fine grained, 0.2 mm, radiating, platy crystals in the core of shards associated with sector birefringent chlorite and is associated with

pyrrhotite in vesicles, lithic fragments and inter-shard spaces. Prehnite compositions were analyzed from the main fluidal breccia complex in Morgan Township (Map 1A) and from the Dowling member contact unit at Soul Lake, west of the Morgan study area (Table A4-2.5). Prehnite is replaced by epidote (AV-194, Appendix 4-2) and calcite is locally pseudomorphous after epidote/prehnite. Pumpellyite identified in a weakly altered fluidal breccia complex (Morgan Township) replaced a blocky shard.

Type 2: Disconformable albitization

Morphology, contact relationships, distribution and controls: Fracture-controlled albitization typically does not contain vein-fillings, although rare, <2 cm, actinolite cores have been observed. The linear zones of pinkish-white pervasively albitized rocks may also be rimmed by actinolite and/or have no central fracture-filling (Plate 4-6). Fracture-controlled albitization cuts the Basal intrusion and Sandcherry member strata and is common in the Joe Lake area. The dominant fracture orientation is north (Figure 4-9).

Fracture-controlled albitization within equant shard units near Joe Lake (Field stop 4-11 in Ames et al., 1997) produces pinkish-weathering halos with relict quartzose lithic fragments, and on polished surfaces the relict blocky shard shapes are cream-coloured (Plate 4-6b). The alteration halos are 20 cm wide and locally reach 1 m. Multiple alteration selvages are evident (Plate 4-6a, 5d). The margins of fracture-controlled albitization with the host rock are irregular, diffuse and commonly have a fine mm rim of actinolite. Away from the main “fracture” are intensely altered apophyses and isolated 1-3 cm ovoid patches of intensely altered tuff locally with actinolitic cores (Plate 4-6a and b). Actinolite

fills open spaces such as the contacts between lithic fragments and the wall rock, amygdales and rare 40 cm diameter ovoid pods containing radial amphibole. A 3 mm-wide actinolite veinlet can be surrounded by a 1.5 cm albitized halo.

Within the basal intrusion, at Joe Lake, “fractures” or planar zones of albitized rock are devoid of actinolite or any fracture filling and comprise 20 cm wide zones with prominent pinkish white weathering alteration (Plate 4-6c). These zones of albitization extend along strike for over 15 m and feather out into the adjacent Sandcherry member equant shard units (Map 2B). The dominant orientation is 075° with fracture apophyses at 000 , 095 and 325° (Figure 4-9b). Dip is 70 - 84° to the southeast and northwest.

North of Capreol seven actinolite veins with bleached albite-quartz-rich margins cut Sandcherry member strata immediately adjacent to a dyke/sill complex of flow-banded aphanitic dykes (Plate 4-6d to f, Map 3). The northeast (043°) trending, subvertical zone consists of south stepping en-echelon veins and is 3 m in diameter. Fibrous actinolite filling the vein is 1-2 cm wide and is enveloped by randomly asymmetric alteration halos (10-18 cm wide) that taper out at the ends. The basal intrusion in this area also contains subvertical veins with actinolite growth perpendicular to the vein walls, but the veins are northwesterly trending. A 1-3-cm wide zone of albitized wallrock also envelops these veins.

The vein-fillings comprise cores of actinolite and a 4 mm rim of fine polycrystalline radiating albite with sector birefringence. The vein contacts with the wallrock are rimmed with minor coarse, 4 mm, titanite euhedra. Various intensities of alteration are present in the alteration haloes. In a 1 cm zone adjacent to the vein there is less than 5% mafic

minerals. Actinolite occurs as fine needles and titanite in the albitized wall rock is fine, anhedral and altered to leucoxene. The grain size of felsic minerals, dominantly albite and quartz is variable between samples. Radiating bowtie to semi-spherical plagioclase contains abundant fine titanite and magnetite, and locally magnetite (2 mm) is intergrown with coarse titanite; pyrite is rare. The less altered zones adjacent to the veins contain up to 40% amphibole and skeletal titanite. Three metres from the actinolite veins are quartz-amphibole-pyrrhotite-chalcopyrite stringers.

Mineral assemblages and chemistry: Fracture-controlled alteration is mineralogically simple with abundant albite (70-80%), minor Kfeldspar, titanite, quartz and trace ilmenite and minute grains of zircon. Trace amounts of hematite, sphalerite, magnetite and ilmenite are present and molybdenite is associated with fracture controlled alteration locally. Fracture-controlled albitization is cut by microscopic fractures filled with calcite. Spongy amygdales contain albite-Kfeldspar-quartz. Image analysis of the very fine polycrystalline matrix indicates that the albite to Kfeldspar ratio varies between 87-94:6-13 (Plate 4-7). The 100 μm , grain size, and anhedral form of the Kfeldspar is similar to the matrix grains in the dyke-proximal intense albitization.

Titanite is a common accessory mineral throughout the Onaping Formation but it is coarser grained in the discordant zones of albitization. Titanite within the albitized halos form 200-1000 μm , euhedral to subhedral grains with domains of relict ilmenite (Ames et al., 1998). In contrast, titanite within less intensely albitized rocks is finer-grained and anhedral to skeletal. Vein proximal titanite associated with quartz and amphibole is

generally Ba-bearing (<3600 ppm) whereas the skeletal fine titanite is Ba-poor (<1000 ppm) (Appendix 4-2).

Vein amphibole at the Capreol locality (Map 3B) are moderate to high-Mg actinolite (AV-488, 486) which is similar in composition to the alteration amphibole at Nelson Lake, in equant shard units on the east side of Rockcut Lake near Capreol and amphibole in the matrix and amygdales of the altered basal intrusion at Joe Lake (Figure 4-8D).

Geochemistry of albitization

Regional semiconformable alteration:

Regional albitization in the Sandcherry member is characterized by gains in Na, Ca and minor Si and losses in Cu, Zn, S, K, Ba, Rb, Fe, Co and Mn (Table 4-3; Appendix 4-1, Figure A4-1.4a). The subdivision of this albitic alteration into weak, moderate and strong based on field observations (Table 4-5) is confirmed by increased losses (Fe, Co, Mn, K, Ba, Rb) and gains (Na), (Table 4-3). Analyses of individual samples of intensely altered fluidal fragment show similar mass changes (Appendix 4-1).

The Sandcherry member fluidal units in Morgan Township show the least chemical change with respect to the vitric protolith, which supports the field observations and interpretation that vitric dykes intrude their own autobrecciated fragmental pile. Albitized fluidal breccias from the South Range on the Garson powerline are slightly different in that K is gained and Ba is lost (Appendix 4-2; Figure A4-1.4c). The major difference between weak albitization in the Sandcherry versus Dowling members is in Mg, which is conserved

in the Sandcherry member but added in the Dowling member (Table 4-2). The effects of chloritization on the Dowling member units are assessed in section 4-2d.

Discordant alteration:

Mass changes using the average composition of the most intense, fracture-controlled albitization show similar relative mass gains and losses regardless of the host rock, locality, or presence or absence of veins, except for Pb, Mo and Sr (Figure A4-1.5a, Table 4-4). The abundance of albite, quartz and minor calcite in the discordant alteration zones is reflected in significant gains in Na, Si and CO₂. Since calcite is late, only Na and Si additions characterize discordant albitization. Losses are evident for most other elements and oxides including, Cu, Zn, Ni, S, Fe, V, Co, Cr, Y, Mn, Mg, K, Ba, Rb, Ca, Sr, and H₂O_t. Discordant albitization is depleted in Cu and Zn although one fracture in Joe Lake contains visible molybdenite which biases the average. Pb shows relative gains in the Capreol veins although galena was not observed (Figure A4-2.5b). In general, the strongest alteration in terms of relative mass changes is in the Joe Lake Basal intrusion. Mass changes in Joe Lake equant shard units and the Capreol area are smaller.

Albitized fractures clearly cut an earlier phase of regional albitization in the Sandcherry member strata. Mass calculations were determined for sample pairs, representative of altered and less altered rocks, with the less altered composition used as the 'protolith'. Fracture-controlled alteration was compared to the less altered wallrock sampled from the same outcrop. An average composition derived from three vein samples (Joe Lake; Ames et al., 1998) was compared to the wallrock adjacent to the veins (AV-

532A) which is strongly albitized relative to the vitric “least altered Onaping Formation” and the slope of the isocon was determined using an average of the ratios of Al, Y, Zr and Nb. What is readily apparent is that Ti is mobile in the discordant zones (Figure A4-1.6a). Ti, P and Mo show major gains relative to the adjacent altered wallrock whereas Fe, Cr, Mn, Mg, Ca and H₂O are significantly depleted (Figure A4-1.6b).

Implications

Distribution: The distribution of semiconformable albitization in the Onaping Formation is strongly controlled by the emplacement of aphanitic dykes and fluidal breccia complexes. The restriction of major dyking and fluidal breccias to Sandcherry member and, less commonly, lower Dowling member rocks explains why the regional alteration pattern is broadly coincident with the Sandcherry member. In the regional alteration, albitization affects the vitric shards most commonly; less than 2 % of the alteration zone is so intense that it affects the matrix and lithic fragments and <<1% is vein controlled. Major factors controlling hydrothermal fluid pathways are permeability and faults. Discordant fluidal complexes partially define syndepositional faults that formed at a high angle to the paleosurface. The porous, vitric fragmental rocks and subvertical fracture system defined by the dyke set in the lower part of the Onaping Formation are interpreted to have acted as excellent fluid conduits for both lateral and vertical fluid flow.

The fragmental Sandcherry member strata with >60% altered vitric shards (Gibbins, 1994) represents a porous and permeable, highly reactive medium whereas dykes form discordant dense impermeable units. Regional, lower intensity albitization may

represent diffuse fluid flow whereas the intensely altered discordant zones reflect more focused and higher temperature hydrothermal fluid flow along syndepositional faults. The absence of strong albitization around some of the dykes and fluidal breccia complexes is likely a consequence of the relative lithification (i.e., permeability) of the host rocks and the timing and availability of water. Fluidal breccia complexes were emplaced at various stratigraphic levels in the Sandcherry member with the intensely altered Joe Lake complex injected into weak to moderately altered, partially lithified equant shard units. The Sandcherry member strata was predominantly a wet porous, fragmental sequence prior to deposition of the Dowling member. In the early stages of Onaping Formation deposition it is likely that subaerial and shallow submarine to “soaked-only” micro-environments were present within the crater.

The Nelson-Capreol segment of the North Range is particularly albitized. Features indicative of a major zone of weakness at Joe Lake include: 1) the discordant fluidal breccia complex and intense alteration; 2) a large protuberance of basal intrusion up into the Sandcherry member and 3) extension to the Foy offset into the basement.

The timing of albitization has major implications for the interpretation of the mechanisms for emplacement of the Onaping Formation and the influx of water into the crater. Intense syndepositional albitization shows that the dykes were injected into a wet medium. Various phases of albitization overprint one another with albitization ongoing during relatively late (Sandcherry member time) dyke emplacement. The lower Onaping Formation was therefore water saturated during deposition of the fluidal fragment units of the Sandcherry member. This means that water was introduced into the crater

considerably earlier than published interpretations regarding the entry of water into the crater causing the emplacement of the Dowling member ("Black"), (Peredery, 1972; Grieve et al., 1991; Avermann, 1994). Albitization likely continued, once the entire Onaping Formation was deposited, deeper in the pile.

The aphanitic dykes acted as local heat sources for hydrothermal activity, but on a larger scale heat was likely supplied by the Sudbury Igneous Complex, the basal intrusion and the basement heated by the impact event. A high geothermal gradient was therefore established at circa 1850 Ma. The paleotopography of the crater floor and walls and the sequence of intrusive events for the emplacement of the SIC and offset dykes influenced the heat and fluid flow, which is reflected in the hydrothermal alteration of the crater-fill sequence.

Conditions of albitization: Conditions of albitization are constrained using mineral chemistry and assemblages by comparison with, well documented case studies in modern and young hydrothermal systems, as well as experimental and theoretical studies.

Alteration mineral assemblages record the interaction of hydrothermal fluids at various stages in the evolution of the hydrothermal system. They may be a product of 1) prograde alteration during heating of the system; 2) retrograde alteration during cooling of the pile; 3) multiple hydrothermal events separated by a significant time period and 4) higher-temperature regional metamorphic events. Changes in assemblages such as prehnite-pumpellyite, albite-Kfeldspar-chlorite- actinolite-epidote to albite-actinolite could suggest an increase in metamorphic grade. The mode of occurrence of prehnite in cavities and its association with pyrrhotite and the distribution of amphibole in discordant zones

associated with dyke injection is incompatible with a regional metamorphic origin for the prehnite and actinolite. There are no crosscutting field relationships between albite and actinolite to suggest multiple hydrothermal events. Therefore regional albitization is an alkali metasomatic event characterized by coeval development of an albite-actinolite-Kfeldspar alteration assemblage.

Case studies of geothermal, ophiolitic and modern mid-oceanic ridge systems note that changes in mineral assemblages from smectite-chlorite to chlorite to actinolite-only, correspond to increasing temperature (Schiffman and Fridleifsson, 1988; Gillis, 1995). The first appearance of chlorite-smectite corresponds to temperatures of 150-180°C, 230-275°C for chlorite and 250-300°C for actinolite-only (Schiffman and Fridleifsson, 1988; Gillis, 1995). The albite-chlorite $\pm$ actinolite to albite-actinolite mineralogical change is mappable with albite-chlorite assemblages widespread within the weak to moderate facies of the regional semiconformable zone of albitization, whereas albite-actinolite is spatially restricted to dyke emplacement. In a general sense, the weak to strong alteration is manifested by prehnite-chlorite to chlorite-actinolite-albite to actinolite-albite assemblages (Figure 4-10).

Temperatures of formation of prehnite-pumpellyite is 200-250°C although prehnite can persist in high temperature conditions up to 315°C (Harper, 1995). The mode of occurrence and presence in weakly albitized fluidal fragment units suggests that the prehnite formed during cooling of the breccias under low temperature conditions. The phase relationships between prehnite-pumpellyite-epidote are dependent on the $a\text{Ca}^{+2}/a\text{H}^{+}$ and $a\text{Fe}^{+3}/a\text{H}^{+}$ of the hydrothermal fluid (Harper, 1995). Prehnite-pyrrhotite in the weakly

albitized fluidal breccia complexes likely formed from Ca-rich fluids with a low fO_2 and was overprinted by a fluid with higher fO_2 to form epidote and a later- CO_2 -rich fluid to form calcite. Epidote replaces prehnite at higher temperature, aFe and/or fO_2 and is likely related to the overprinting silicification at the base of the zone of albitization.

Actinolite occurs as both halos and open-space fillings on intensely albitized rocks and albite forms halos on amphibole fragments and vugs implying a close genetic relationship between albite and actinolite. Hydrothermal alteration and hydration of glass typically involves a increase in volume. Interaction between seawater and andesite would involve exchange of alkalis (Na, K) and Ca is released to the fluid phase. In the Onaping Formation some of the Ca removed from the glass is retained in alteration minerals, in open spaces between glass shards, gas cavities, amygdales and fractures. The formation of actinolite is not only temperature-dependent but also may be controlled by fluid compositions, aCa^{++} and fO_2 (Mevel, 1987; Ito and Anderson, 1983). The spatial association of the albite-actinolite (only) assemblage with dyke injection implies that increasing temperature was the most important controlling factor.

Textural and morphological changes in albite and Kfeldspar with increasing alteration from coexisting coarse intergrown albite/Kfeldspar to albite with Kfeldspar inclusions and finally albite-only reflects increasing aNa^+/aK^+ or increasing temperature (Henley et al., 1984). At constant aNa^+/aK^+ ratios in the fluid, the observed mineralogical changes can be explained by a fluid in equilibrium with Na-feldspar and Kfeldspar undergoing an increase in temperature (Giggenbach, 1984). Increasing temperatures result in dissolution of the K-Al silicates as reflected in their increased solubility at high

temperatures (Giggenbach, 1984). Kfeldspar in the lower part of the Onaping Formation is poorly ordered intermediate microcline and the albite is almost pure and ordered (Schandl et al., 1986). In, an albeit limited data set of 15 samples from a composite section of the “Gray tuff”, the degree of ordering in the feldspars is independent of location (i.e., North Range vs. South Range) and depth and temperature estimates of less than 300°C were made (Schandl et al., 1986).

Calcic amphiboles in the Onaping Formation show compositional variability from tremolite-actinolite to actinolitic hornblende and rare magnesio-hornblende. Amphibole chemistry is affected by changes in temperature, pressure, fO_2 , fluid composition and water/rock ratio (McCollom and Schock, 1998; Spear, 1982). Mineral assemblage distribution in conjunction with textural observations provide limitations on the range of physical conditions. The progression from actinolitic hornblende to actinolite to tremolite can be explained by either increasing water-rock (W/R) ratio at a constant temperature and/or a decrease in temperature (McCollom and Shock, 1998). The trend in amphibole compositions to more Mg-rich varieties with increasing alteration and proximity to aphanitic dykes is mimicked also in the chlorite compositions (Figure 4-8.). The Mg-rich amphiboles occupy amygdales, veinlets, shards and less commonly replace the matrix which is compatible with increasing W/R ratio with increasing alteration intensity (Figure 4-8). At constant P and increasing T, the Si contents decrease and Aliv, Ti and Site A (Na+K) increase in amphiboles, whereas at constant P and T the Mg/Fe ratios increase with increasing fO_2 (Spear, 1981). The Si/Al variations are constrained by the mineral calculations but Si shows a strong negative correlation with Ti and a negative correlation

with Site A $(\text{Na}+\text{K}) > 0.07$ which is consistent with increasing T (Figure 4-11). The trends shown by amphibole compositions are compatible with increase in W/R ratio and increase in $f\text{O}_2$. A decrease in temperature contradicts the field evidence of Mg-rich amphiboles adjacent to dykes which would presumably be hotter.

The mineral chemistry, alteration assemblages and field relationships are compatible with discordant relatively high temperature ($>250^\circ\text{C}$), actinolite-albite alteration zones interrupting the lower temperature ($\sim 200\text{--}250^\circ\text{C}$) regional chl-albite-Kfeldspar $\pm$ prehnite $\pm$ actinolite alteration.

Fluid compositions: Abundant calcic and sodic alteration mineral assemblages combined with mass exchange data indicates that the fluids responsible for albitization were Ca-Na-Si-rich, K-bearing fluids. The regional fluids were at equilibrium with coexisting albite-microcline but were elevated to increased temperatures due to dyke injection causing precipitation of calcic minerals such as actinolite. The assemblage microcline-albite-chlorite restricts the temperature of formation between $150\text{--}300^\circ\text{C}$ and slightly alkaline pH conditions (Henley and Ellis, 1983; Henley et al., 1984). The presence of hydrothermal microcline in the absence of muscovite restricts the pH (>5.6) and can be indicative of relatively alkaline fluid compositions at constant $a\text{K}^+$ (Henley et al., 1983; Heald et al., 1987). The microcline stability field can be retained either by low $a\text{K}^+$ and high pH or high $a\text{K}^+$ and low pH (Henley et al., 1984) and at a temperature of 250°C Kfeldspar is stable from a pH of 3.3 to 7 (Reyes, 1990). These fluids were capable of leaching Fe, Mn, Ba, K as well as Cu, Zn and S.

Sodium-calcium exchange is well documented for mafic rocks interacting with seawater (Mottl and Holland, 1978; Seyfried and Janecky, 1985; Seyfried et al., 1988; Seyfried and Bischoff, 1977, 1979). The dominant site for alteration assemblages in the regional zone of albitization in the Onaping Formation is the former vitric shards. Alteration of mafic glass to smectite by seawater typically involves the addition of Na and K, Ti is relatively immobile and significant amounts of Ca are lost (Mottl and Holland, 1978; Seyfried and Bischoff, 1979). Alteration of glass in the Onaping Formation is one logical source of Ca for the Sudbury Structure hydrothermal fluids.

The CaO content of the least altered protolith composition for the Onaping Formation is low (2.63 wt.%) and generally less than the average least altered compositions of Sandcherry member units (3.8 wt.%), Dowling member units (4.1-4.4 wt.%), mafic norite (4.54 wt.%), and felsic norite (6.38 wt.%), although it is higher than that in the granophyre (1.8 wt.%) (Table 3-1; Lightfoot et al., 1997). The discordant intrusive units such as the basal intrusion and aphanitic dykes have low values of CaO (Table 3-1). The interpretation of the protolith composition drastically affects whether Ca was actually added to the system or just remobilized within the vitric fragmental pile (Table 4-3). If one assumes the original CaO content of the Onaping Formation to be that of 1) a typical andesite (6-8 %: Wilson, 1989), 2) the average continental crust (4.2 wt %: Taylor and McLennan, 1995) or 3) Lightfoot et al. (1997) average SIC composition (3.67 wt.%) the protolith CaO content used in mass balance calculations is low and significant CaO removal has affected the protolith. The average CaO content of the weak, moderate and strong albitization zones (3.14, 4.55 and 3.78 wt. % respectively),

are less than any of the possible protolith compositions indicating Ca mobility although, the variability is large between 1.21 and 7.58 wt. %. The Onaping glass was a source of CaO however the feldspars in the granophyre and the top of the norite of the SIC are considered less calcic and more sodic than their original composition (Naldrett et al., 1970; Schandl et al., 1986). The abundance of epidosite pods and epidote-pyrite-Kfeldspar-quartz veins in the top of the granophyre observed at Joe Lake suggests that the Sudbury Igneous Complex underwent Ca-Na exchange due to interaction with the hydrothermal fluids altering the Onaping Formation from the Upper hydrothermal system. The origin of the epidote in the SIC whether hydrothermal, metamorphic and/or magmatic has not yet been studied.

It is difficult to ascertain with any certainty the quantity of fluid or Ca-flux required from an external source, such as alteration of the granophyre, for the crater-fill hydrothermal system or whether there is a mass balance of CaO between various alteration zones due to alteration of glass in the Onaping Formation itself. Calculations involving the volume of glass altered versus the relative mass gains of CaO in the zone of albitization are highly speculative and dependent on the precursor composition of the SIC and Onaping Formation. A discussion of element mobility in the zone of albitization relative to the entire system in the Onaping Formation follows (Chapter 7).

In this section emphasis is placed on the mineral assemblages and their distribution to evaluate the fluid chemistry responsible for the hydrothermal alteration. Albite-Kfeldspar pseudomorphous after palagonite and chlorite and/or actinolite in shard cores indicates that the reactions forming these minerals most likely influenced the composition

of the convecting fluid. The abundance of sodic minerals and addition of Na to the rocks could suggest that in part the fluid was of Early Proterozoic seawater origin. The absence of Mg-addition and dominance of albite in the alteration zone suggests that the fluid was already Mg-depleted with high Na/Mg ratios. Therefore the albitization zone could represent a moderately deep portion of a subsurface convective system in which Mg-hydrolysis reactions and Na-Ca exchange had occurred in another part of the system producing an evolved seawater rich in Na-Ca-Si.

4-2d. Chloritization:

Chloritization of shards is evident throughout the entire Onaping Formation, although the proportion of chlorite changes. Variation in the amount of chlorite is dependent on the regional alteration type and its intensity as well as the abundance of vitric shards. The percentage of glass shards in the contact units is higher than that of the other Dowling member units and it is only locally, weakly albitized (e.g., near their base). Thus, the contact units (former Green member or chlorite shard horizon of Muir and Peredery, 1984; Avermann, 1992; 1997, Table 2-1) appear “more chloritized”.

The chlorite alteration zone regionally mimics the distribution of the contact units. Regionally the Contact Unit outcrops as discontinuous units up to 10 km long and 5-150 m wide, averaging 30 m for over a strike length of 50 km (Figure 4-2). Since, chloritization is essentially a ubiquitous feature of the contact unit, chlorite alteration occurs as a regional semiconformable zone in the Onaping Formation. The distribution of the contact units in Morgan Township is largely structurally controlled; however,

erosional contacts with the underlying Sandcherry member strata (observations Morgan Township, Joe Lake and Simmons area Maps 1, 2, and 5) indicate that these units and therefore chlorite alteration overlies the regional zone of albitization. The abundance of chlorite as a replacement of shards and vesicle fillings, increases in the albitized Sandcherry member towards the contact with the Dowling member. The abrupt lateral termination of the chloritized contact units against albitized Sandcherry member units in Morgan Township indicates that faulting post-dates chloritization of the contact units (Map 1).

Chlorite is also prominent in the middle and upper units as an alteration mineral affecting larger, 1-2 mm, shards in the overlying semiconformable calcite zone. In this zone the altered shards are typically composed of chlorite-calcite and have been included in a separate alteration zone. Chlorite occurs in minor amounts in shard cores in the semiconformable silicification, moderate and weak albitization and transitional zones, and in trace amounts in the intense zones of albitization or silicification.

Alteration assemblages and mineral chemistry:

A prominent feature of the contact units is 20-45% dark green chloritic shards in a bluish to greenish gray matrix (Gibbins, 1994; Green Member, Avermann, 1994), (Plate 2-3). Petrographic studies of ~25 thin sections of the contact units from numerous North Range localities (Map 1, 2, 5 and the Hanmer powerline) reveal that chlorite is not the most common alteration mineral in the contact units glass shards. Feldspar is most abundant within 54% of the sections studied, actinolite in 23%, chlorite in 19% and

subequal amounts of actinolite and chlorite in the remainder. Albitized shards are composed of albite-orthoclase, minor actinolite and/or chlorite and trace amounts of titanite-prehnite or pumpellyite(?). In any one section shard mineralogy is variably dominated by chlorite, actinolite or feldspar.

Actinolite is a common replacement of smaller shards, filling larger shard cores and open spaces including vesicles. Actinolite-chlorite-rich shards are within a ferromagnesian poor matrix producing a striking contrast in colours (Plate 2-3). The quartzo-feldspathic matrix contains fine lithic crystals of quartz set in a mesostasis of very fine spherulites. Amphibole compositions are dominantly actinolite with minor overlap into the ferro-actinolite and actinolitic hornblende fields (Figure 4-8). Amphibole in the contact units is more iron-rich than that in the underlying zone of albitization. The calcic minerals prehnite and/or titanite are associated with actinolite.

Chlorite occurs as fine radiating masses with sector birefringence and in weakly altered samples consists of an amorphous mass commonly occupying the core of shards. Chlorite is less commonly intergrown with actinolite. Samples were selected from a transect across the Onaping Formation to test for variability in chlorite composition between rock types and alteration zones (Figure 4-3). Chlorite compositions within the contact units are variable with Fe/Fe+Mg+Mn ratios ranging from 0.4 to 0.6, $n=28$ (Appendix 4-2, AV-286, 256, 284). Average Fe/Fe+Mg+Mn ratios from three sections across the contact units increase with stratigraphic height from 0.49 to 0.56 to 0.58. Chlorite in the core of intensely albitized shards adjacent to spherulitic aphanitic dykes (amorphous pods) associated with albite-Kfeldspar have lower Fe/Fe+Mg+Mn ratios

(averaging 0.49), than chlorite in assemblages of albite-actinolite-chlorite-chalcopyrite-pyrrhotite (at 0.56) and trace chlorite in albite-actinolite assemblages (at 0.58).

Coarse euhedral to subhedral feldspar that commonly replaces shard margins is likely related to the overprinting phase of albitization that affects the lower part of the contact units. Feldspar compositions average $[Ab_{97.84} Or_{1.48} An_{0.57} Cn_{0.11}, Ab_{1.58} Or_{97.73} An_{0.14} Cn_{0.55}]$ for coexisting albite-orthoclase and $[Ab_{98.34} Or_{0.55} An_{1.07} Cn_{0.04}]$ for albite only assemblages. Shards that lack the distinct zonation have spherulites and radiating feldspar that are randomly distributed within poorly crystalline mats of chlorite. These feldspars are a product of devitrification in the weakly chloritized contact units.

Prehnite (?) and titanite are associated with actinolite in the core of shards or partially replaces chloritic shard margins. Prehnite (?) rims voids as coarse bowtie and radiating aggregates. Titanite is coarse, forming 0.1 mm euhedra to subhedra. Trace to minor amounts of calcite in the contact units is late. Calcite partially to totally replaces amphibole, prehnite and titanite.

Pyrrhotite-chalcopyrite-sphalerite are accessory minerals filling voids and partially replacing shards. Pyrrhotite is commonly associated with carbonate although it also occurs in carbonate absent rocks. Sulphides form a lining with calcite in the core. Prehnite forms radiating growths on pyrrhotite-chalcopyrite and may be partially replaced by chlorite. Pyrrhotite and calcite are poikiloblastic containing minor actinolite. The paragenetic void filling sequence is 1) actinolite 2) pyrrhotite-chalcopyrite-sphalerite-quartz 3) prehnite and 4) calcite.

Geochemistry of chloritization:

Chloritization is accompanied by addition of Ca, Mg, Mn and S and depletion of K and Ba (Table 4-3; Appendix 4-1).

Implications:

The contact unit has been interpreted as a strongly chloritized breccia (Avermann, 1997), a least altered composition of the Onaping Formation (Gibbins, 1994) and the collapsed fireball horizon (Avermann, 1997; Deutsch et al., 1995). The chloritic shards have been interpreted as collapsed chlorite-filled cavities or void spaces between fragments (Brockmeyer, 1990; Deutsch et al., 1995) although the presence of vesicles in the shards, relict devitrification and palagonitic textures and vesicles truncated along glass boundaries (Gibbins, 1994) clearly indicate that the chloritized domains in the contact unit were glass shards. The contact units are enriched in Ca and only minor Mg (Table 4-3). Ca gain is not particularly compatible with chlorization of a mafic to intermediate vitric rock. The relatively minor gain of Mg shows that the contact units are only “weakly chloritized”. In local areas where the contact unit is absent chlorite fills amygdales in the uppermost Sandcherry member. Weak chloritization affects a volume of rock at least 105 km³ composed of 20-45% andesitic glass (50 x 60-80 x .03 km) or a conservative estimate of a 35 km³ block of andesitic glass.

The relative timing of Mg and/or Ca addition is important for interpretation of the hydrothermal system. Chloritization is overprinted and/or coeval with albitization at the base of the alteration zone and is overprinted by more calcic alteration resulting in

actinolite, pyrrhotite-chalcopyrite-sphalerite, prehnite and finally calcite. The structural control on the distribution of the weakly chloritized contact units in Morgan Township suggests that chlorite-amphibole alteration predates or is synchronous with block faulting and pre-dates dyke injection (Map 1). The contact units were preferentially altered as a consequence of their hot, subaerial to shallow water emplacement during a major period of faulting and introduction to water. These faults were also local conduits for fluids responsible for albitization of the contact units as albite alteration extends <1m into the contact units from the trace of the faults. The relative timing of events is 1A) early chloritization, 1B) block faulting, 2) dyke emplacement 3) actinolite 4) pyrrhotite-chalcopyrite-sphalerite 5) prehnite 6) calcite.

4-2e. Transition zone between albite-Kfeldspar-quartz and calcite-chlorite alteration zones.

Morphology, contact relationships, distribution

The transitional zone between the lower albite-microcline and upper chlorite-calcite alteration zones ranges from 0-500 m wide although it is typically a 150 m wide discontinuous zone (Map 1B). The transition zone alteration affects the carbonaceous Dowling member lower units and the base of the middle units. In Morgan Township, (Map 1) the chloritized contact units and weakly altered carbonaceous lower units are rarely in contact but, in the Joe Lake area (Map 2) the gradational contact is marked by a change in chloritized shards in a quartzo-feldspathic matrix to bluish shards in a black carbonaceous

matrix (Plate 4-8). This gradational contact between the contact unit and lower unit is more common (Gibbins, 1994) and in terms of alteration marks the change from weak chloritization to transition-type alteration.

The lower units consist of 20-30% lenticular chloritic shards with or without a fine bluish rim, and 10-25% characteristic bluish, lapilli-sized altered glass fragments (Plate 4-8). These altered glass shards lack the pinkish beige colour typical of the underlying albitized rocks, the chlorite-actinolite shards of the weak zone of chloritization and the calcite-chlorite assemblage of the overlying alteration zone.

Mineral assemblages:

The petrographic difficulties in identifying epidote from prehnite and albite from Kfeldspar in these fine-grained rocks have resulted in the use of a slash (/) to indicate this uncertainty unless they have been identified by alternate methods such as SEM or microprobe analyses. The zone is mineralogically heterogeneous along strike in Morgan Township (Map 1). In the lower units proximal to the central fluidal breccia complex that intrudes the lower units, shards have distinctive albitic rims and to the east, chlorite-prehnite/epidote altered shards are present near Sandcherry Creek. Immediately above the vent complex shards have 10-30 μm albite rims on recrystallized albite-actinolite-prehnite/epidote altered shards. The outer clear, oxide-free rim is typically composed of albite grains oriented normal to the shard margin and along fractures forming bulbous-fibrous forms impinging on the chloritic core (Plate 4-8). The effects of the fluidal breccia

complex are quite local as rocks 50 m along strike have chlorite and quartzo-feldspathic radiating to spherulitic textures randomly distributed in the shards (i.e., no zonation).

Glass shards are texturally complex, variably devitrified and compositionally variable. They consist of chlorite-albite/Kfeldspar-titanite-quartz $\pm$ prehnite/epidote-actinolite-pyrrhotite-sphalerite-chalcopyrite-pyrite. The bluish shards are a complex mixture dominated by (70-80%) feldspar/quartz in radiating, globular, spherulitic, sector crystallized and poorly defined masses with disseminated chlorite (5-15%), titanite (<5%) and variable amounts of radiating, reniform masses of prehnite (5-15%). Feldspar is anhedral to euhedral and in thin section varies from colourless to brown. The composition of the matrix is difficult to determine owing to the presence of fine black carbonaceous matter. However, the matrix at the base of the middle units contains abundant amphibole, likely actinolite.

Textures pseudomorphous after gel-palagonite are evident in replacement feldspar and locally in chlorite along shard margins. These consist of micron-scale layered textures outlined by thin Fe-Ti oxides or leiseegang rings. The shard cores are commonly composed of spherical chlorite with sector birefringence, titanite $\pm$ fibro-radial spherulites of feldspar with trace radiating prehnite-epidote. The contacts between feldspathic and chloritic domains are commonly diffuse, irregular and Fe-Ti oxide-rich. Perlitic crack outlines, decorated with titanite and Fe-Ti oxides, attest to the former glassy nature of the shards. Titanite is ubiquitous both within shards and in the matrix of the lower units.

Prehnite/epidote lines amygdales, forms coarse radiating crystals at the edge of glass shards, partially to totally replaces shards that contain relict amygdales, forms 0.3 to

0.4 mm classic bowtie masses finely disseminated within chloritic shards or bowtie coarse crystals in the core of devitrified albite-chlorite shards. Prehnite is typically a minor component but locally comprises 10% of the rock. Pyrrhotite-sphalerite-chalcopryrite are most common in the core of shards and within amygdales.

Geochemistry of the transition zone:

Mass balance calculations with the vitric precursor composition indicate a major gain in Ca, Mn, Zn, Pb C and S and loss of Cu, Ba and Rb (Table 4-3; Appendix 4-1). The transition zone marks a change from the loss of Zn in underlying strata to the addition of Zn in overlying rocks (Table 4-3). The corresponding mineral assemblage in the transition zone rocks includes 1) carbon in the matrix, 2) calcic minerals prehnite/epidote/actinolite and 3) disseminated sulphides, predominantly sphalerite.

Implications:

The mineralogical and chemical data suggest that hydrothermal alteration is fairly weak in the transition zone, a marked contrast to the underlying zone of albitization and the zone of weak chloritization. The heterogeneous and complex devitrification textures in the shards, the lack of distinctive mineralogical zonation and the minimal mass change suggest minimal alteration.

The Dowling member lower units mark a period of tectonic instability with debris flows channelized within paleotopographic features. Prehnite-epidote and sphalerite-pyrrhotite with minor chalcopryrite deposited in open spaces, and the presence of sulphide

fragments also suggest this was a period of metal deposition and reworking. This zone may represent a short hiatus in deposition of the Onaping Formation in which relatively low temperature metal and sulfur rich hydrothermal fluids deposited sulphides in a tectonically unstable environment (Figure 4-10). Differences in alteration between the contact units and lower units, both deposited in a tectonically active regime are the consequence of the temperatures of emplacement for the units. The hot incipiently welded contact units are more altered than the cold debris flows of the lower units.

4-2g. The transition zone alteration abuts against the chloritized contact units suggesting that a simple layer-cake stratigraphic and alteration sequence is not present.

4-2f. Calcitization

Formal Volumetrically, most calcite alteration occurs in a regional semiconformable zone in the upper 60-70% of the Onaping Formation. Only trace amounts of calcite are present in the lower part of the Onaping Formation (Map 1B) and adjacent to the granophyre. In the basal silicification zone, 2 mm calcite lathes coexist in the mafic-rich portions with chlorite, amphibole, epidote, titanite and sulphide. Trace calcite in fluidal fragment units occurs in the cores of intensely albitized shards and coexists with coarse 2 mm titanite euhedra. Calcite also occurs in late veinlets crosscutting fracture-controlled albitization.

Ampl Calcite alteration is locally absent around base metal showings and local silicified zones producing discordant calcite-free zones within the regional semiconformable alteration (Maps 1, 4, 5, and Appendix 5-1). Fe-Mg-Mn carbonate is present at the base metal showings where they occur in veins and restricted alteration halos.

Semiconformable zones:

Morphology, contact relationships, distribution: A semiconformable zone of calcite alteration is regionally pervasive in the upper 800-1000 m of the Onaping Formation around the circumference of the Sudbury Basin (Gibbins et al., 1992; Ames et al., 1998; Figure 4-1). In detail, the upper and lower contacts of the calcite zone are slightly discordant to stratigraphy and the lower calcite contact crosses the carbon contact (Map 1). Calcite alteration is less extensive than carbon and the lower ~150 m of the black carbonaceous rocks are generally calcite-free although locally calcite alteration affects carbon-free rocks. Regional calcite alteration directly overlies the weakly altered transition zone and underlies Ca-Fe-Mg carbonate alteration at the very top of the Onaping Formation and in the Vermilion Formation.

Calcite alteration affects most middle and upper units of the Dowling member and is less common and patchy in the lower part of the Dowling member, in the lower units and contact units. Microprobe analyses of over 100 carbonates throughout this regional alteration zone identifies only calcite which is readily distinguished in the field (Figure 4-12). Calcite is ubiquitous in shards and less commonly, in the matrix, as rims on lithic fragments, and as fragments with pyrrhotite, chalcopyrite, pyrite and sphalerite. Amygdales in discordant pods of basal intrusion in the middle units often contain calcite-quartz-chalcopyrite-pyrrhotite and pyrite.

Mineral assemblages and chemistry: The semiconformable calcite zone in the Onaping Formation is characterized by the assemblage chlorite-calcite. Major

albite±Kfeldspar-quartz and minor to trace amounts of carbon-titanite-pyrrhotite-chalcopyrite-sphalerite ± epidote/prehnite, actinolite, pyrite, magnetite are also present. Locally, calcite partially replaces epidote/prehnite, particularly near the base of the zone and proximal to calcite-absent zones. Actinolite is rare and pyrite and magnetite partially replace pyrrhotite in some samples. Pyrrhotite forms up to 2 mm grains generally in felsic shards, less commonly in chloritic shards and transgresses grain boundaries between shard, matrix and lithic fragments. This suggests that some sulphides were introduced postdepositionally and that the sulphides are not all fragmental. Where titanite and calcite coexist in the same chloritic shard the morphology of the two are similar, yet there is no rutile present which might be a byproduct of the reaction: titanite + CO₂ → rutile+quartz+calcite (Ames et al., 1991).

Vitric shards are altered to calcite-chlorite- plagioclase-quartz-titanite ± epidote. In any one section there are various shard assemblages: 1) chlorite>>titanite, 2-3) felsic rim with chlorite or calcite core, 4) calcite core and chlorite-albite rim, 5-7) all calcite, chlorite or felsic minerals. Generally two “types” of alteration occur in one section with calcite-feldspar-quartz replaced shards and chloritic shards. Chlorite compositions in calcite-bearing versus calcite-absent shards in the middle units are similar. In calcite-absent zones within the regional semiconformable zone, epidote and epidote-chlorite comprise the shards. Chlorite compositions in the calcite zone are also similar to Sandcherry member units but have a slightly lower Fe# than the contact units (Figure 4-3).

Most shards are only partially replaced by calcite thereby revealing the relict textures. Calcite replaces former vitric shards in the middle and upper units of the Dowling

member. Calcite may replace epidote/prehnite and titanite and typically occupies shard cores along with chlorite and radiating and sector crystallized feldspar. Relict palagonite and perlitic textures are retained by calcite particularly near the base of the alteration zone (Plate 4-9). The outer rims of shards often show devitrification textures such as the parallel intergrowth of felsic minerals perpendicular to the shards walls that may be totally to partially replaced by calcite. The inner calcitic core may be brown in plane polarized light and display laminar growth, interpreted as a replacement of palagonite. Brown calcite in the core may form feathery, botryoidal growths adjacent to sector crystallized feldspar and the calcite around the margins of the shard is clear. Calcite alternating with feldspar is pseudomorphous after botryoidal growths along flow bands in vitric fragments (Plate 3-10). Calcite fills amygdales in chloritic shards, partially to totally replaces smaller shards and occurs in the matrix in zones of intense carbonatization. In the Simmons Lake area, calcite with relict inclusions of epidote indicate that locally calcite postdates epidote deposition.

These delicate textures replaced by calcite are present in the lower 500 m of the calcite alteration zone at Cow Lake, in the lower 200 m in Morgan Township and at the base of the zone at Simmons Lake (Plate 4-9). Above this most of the regional calcite zone is characterized by 1) abundant calcite that totally to partially replaces small 0.4 mm shards; 2) minor calcite in large, 1-2 mm devitrified feldspathic shards and 3) trace amounts in the 1-2 mm chloritic shards. Totally replaced shards locally resemble fragments although they contain relict amygdales.

Calcite-free zones within regional semiconformable calcite alteration zone:

Calcite-free zones within the regional calcite alteration zone are discordant areas up to 200 m wide along strike with syndepositional faults (Morgan Township) and 75-200 m wide semi-concordant zones near the base or top of the regional zone (Maps 1 and 5). Trace amounts of calcite may be present near the contact with the regional zone. Calcite-free zones have abundant actinolite and titanite and/or epidote as replacement of shards (Plate 4-9). Epidote is present mainly in the calcite-free zones within the larger zone of regional carbonatization in Morgan Township and is associated with actinolite and chlorite. Actinolite-titanite pseudomorph glass shards in the Simmons Lake area.

Epidote mineral compositions indicate a moderate Fe and Al epidote which is intermediate between the base metal associated epidote at the Limerick and Simmons showings and epidote within the basal silicification zone (Figure 4-5).

Fe-Mg-Ca Carbonate alteration zones:

Localized Fe-Mg-Ca carbonate alteration zones were mapped west of the Vermilion mine (Gray, 1995) in the Dowling member upper units. The lateral extent of these alteration zones is unknown in the North Range due to overburden cover at the top of the Onaping Formation. These alteration zones are small, approximately 150 x 500 m and poorly constrained due to lack of outcrop. Fe-Mg-Ca carbonate alteration zones are spatially associated with minor base metal showings more than 500 m west of the Vermilion Zn-Pb-Cu deposits and were observed east of the Vermilion mine. They contain ankerite/dolomite and calcite which were identified through XRD. Carbonate concretions

range from 2 mm to 2 m within the upper 100 m of Onaping Formation strata in the bedded upper units beneath the Vermilion Formation. The large concretions are restricted to the uppermost 5 m (Gray, 1995). The carbonate zone sampled in this study is situated ~1.4 km east of the Vermilion mine in the stratigraphically highest exposed Onaping Formation above the Gordon Lake Road peperite (Figure 2-12).

Geochemistry

Semiconformable calcite alteration: Mass balance calculations of the calcite alteration zone were subdivided to examine mass change associated with calcite alteration in the Lower units, contact units and middle units. The least altered vitric precursor was used (Tables 4-3; 3-1; Appendix 4-1e). Volumetrically, the middle units contain the most calcite and, in general, are characterized by gains of Ca, CO₂, Fe, Pb, Mo, S, C, and Mn and losses in Na, K and Ba.

Calcite-absent zones within regional carbonate alteration: The calcite-absent zones within the regional semiconformable alteration zone have significant gains in Ca, Mn, Fe⁺³, Zn, Pb, C and S and loss of Na, Fe⁺² and Cu relative to the vitric precursor (Table 4-3; Appendix 4-1).

Local Fe-Mg-Ca carbonate: The carbonate zone east of the Vermilion deposit has significant relative gains of Ca, CO₂, Fe, Mn, C, Mg, Zn, Pb and S (Table 4-3) and losses of Na, K, Ba and Cu. The only other zone showing significant gains of Mg is the zone of

weak chloritization in the contact units approximately 1 km below the top of the Onaping Formation. Major losses of Na are also evident in the discordant calcite-free corridors through the regional, semiconformable, calcite alteration zone.

Discussion

Implications

Although carbonate has been observed in various parts of the Onaping Formation (Martin, 1957; Arengi, 1977; Muir and Peredery, 1984; Paakki, 1992; Bunch et al., 1997), particularly near the Errington-Vermilion base metal deposits, the regional alteration zone was only recently identified through a Falconbridge reconnaissance program (Gibbins et al., 1992). Carbonate has been interpreted as fragments (Muir and Peredery, 1984; Bunch et al., 1997) and replacement of feldspar (Gibbins, 1994). Muir and Peredery (1984) noted “fine-grained, carbonate-bearing rocks, some of which contain oval, amygdale-like structures, and some of which are shard-like” as miscellaneous fragments with an unknown source and origin but suggested country rock fragments. Prior to this study the distribution and timing relative to other alteration types and possible origins were poorly constrained.

There are numerous possible sources of CO₂ in the Onaping Formation 1) impact-released CO₂ from carbonate target rocks (Bunch et al., 1997) 2) mantle- magma degassing 3) seawater 4) oxidation of matrix C in the Onaping Formation ($\delta C_{13} = -30.10$ to -31.06 ; Avermann, 1994; Heymann et al., 1997; Bunch et al., 1997; Gray, 1995), 5) mixture of 3 and 4, 6) metamorphic decarbonation, 7) SIC degassing or 8) later brines. Isotopic studies combined with field observations constrain the origin of the CO₂ and are

presented in Chapter 6. However, the distribution of the carbon constrains the source of CO_2 .

Distribution/Timing: The widespread preservation of palagonitic textures in calcite near the base of the regional calcite alteration zone shows that calcite is pseudomorphous after glass. Therefore CO_2 was initially introduced to the Onaping Formation while the middle units still contained glass. This suggests that the regional calcite alteration is due to syndepositional alteration broadly coincident with emplacement of the middle units. Therefore, the regional carbonate is not a product of regional metamorphism or a precipitate from late brines.

In sediment-covered mid-oceanic ridge hydrothermal systems calcite is derived from the host carbonaceous sediments (Bowers et al., 1985; Von Damm, 1985, Peter and Shanks, 1992). The presence of calcite in carbon-poor rocks and as amygdales associated with sulphides throughout the entire Onaping Formation implies that oxidation of the carbonaceous matter to form calcite is unlikely, although not impossible. Calcite and carbonaceous matter occupy different sites when they coexist; calcite in shards and carbon in the matrix.

Temperature constraints on carbonate formation in active geothermal systems are provided through a combination of direct measurements of well temperatures compared with alteration assemblages as well as fluid inclusion studies. In well constrained geologic environments the calcite-chlorite assemblage forms at temperatures ranging from 165-222°C and averages 195°C (Reydarfjördur, Iceland; Mehegan et al., 1982). Calcite

alteration zones in halos on volcanic centres formed in a late stage of the cooling hydrothermal system. Modern ocean floor studies have calcite (plus clays or chlorite) alteration to 800-1000 mbsf with temperature constraints on calcite precipitation from 100 to 200°C (Alt et al., 1986). These carbonates were also produced late in the evolution of the system from cooler, off-axis solutions. In the absence of clay minerals to provide minimum constraints on the temperatures of formation of the regional calcite alteration zone assemblages comparisons with these other geothermal systems provide at least maximum temperatures of formation (<230°C, likely <<150°C). The similar depth of the calcite alteration zone in the modern oceanic crust (Alt. et al., 1986) and the distance from the paleoseafloor in the Sudbury crater fill suggests that temperatures likely extended well below the chlorite-smectite to chlorite transition (ca. 230°C: Schiffmann and Smith, 1988). The transition from the regional NaCa (albite) alteration to chlorite-calcite with increasing stratigraphic height in the Onaping Formation may reflect decreasing temperature and increasing $f\text{CO}_2$ during a gradual cooling of the Upper hydrothermal system in the Sudbury Structure.

The sodium depleted, discordant calcite-free zone within the regional calcite zone represents a relatively higher temperature upflow zone in which feldspar has been destroyed by low $f\text{CO}_2$, calcic, silica-saturated and metal bearing fluids. The temperatures were likely in excess of 260°C, using the assemblage actinolite-epidote. If the regional calcite zone formed by collapse of a hydrothermal system with an influx of cold seawater the prograde discordant alteration would be overprinted by late retrograde alteration and calcite should replace the epidote-rich shards. In contrast, the textures imply that the

discordant calcite-absent zones overprint the regional calcite-chlorite alteration perhaps due to reactivation of NW faults in the Sudbury Structure allowing the expulsion of hotter, more evolved metal bearing fluids from deeper in the pile (Map 1B, note association of base metal sulphides).

If magma or mantle degassing were invoked for the formation of calcite in the Onaping Formation the gas would have to pass through the strata and alteration assemblages lower in the pile. Calcite is present locally along syndepositional faults associated with pyrrhotite-sphalerite-chalcopyrite cutting the albitized zones and in amygdales of the basal intrusion; however, the prehnite/epidote in the “layer-cake transition zone” is not carbonatized. There should be calcite veining, mariolitic cavities at the top of the degassed intrusion and discordant calcite zones in the overlying strata. Mariolitic cavities are common in the granophyre (J. Cowan, pers. comm.) and are present in the basal intrusion. The distribution and textures of calcite in the Onaping Formation are compatible with the source (s) of CO₂ being seawater, a mixture of seawater and organic carbon and mantle-magma degassing including degassing of the SIC (?) or degassing of the basal intrusion within the Onaping Formation. Carbon isotopic data place constraints on these possible sources (see Chapter 6).

4-2g. (K-Ba feldspathization)

Schandl et al. (1986) proposed that the Onaping Formation cooled as a single unit and was zoned with respect to Na and K due to metasomatism. Gibbins (1994) noted that

a pronounced increase in the amount of K_2O/TiO_2 occurred only within the upper 200-300 m and may represent an upper semiconformable alteration zone enriched in Kfeldspar.

Potassic alteration at the top of the Onaping Formation proximal to the Vermilion base metal deposit and ~25 km east of the deposits has been observed (Whitehead et al., 1992 and Gray, 1995) and related to the presence of authigenic Kfeldspar. Whitehead et al., (1992) noted in one drillhole <2.5 km west of peperite locality C in Azilda (Figure 1-2), that K-Ba distribution is not related directly to K-addition. Geochemical data for K_2O was not shown and the restricted sampling is inadequate to suggest that the alteration is a regional zone.

Gray (1994) described 1-5 m discrete zones with elevated K_2O only in the upper 10-50 m of the Onaping Formation and observed dominantly sodic alteration (albite) proximal to the Vermilion deposit with Kfeldspar increasing distally. A semiconformable zone of alkali feldspar alteration was proposed (Gray, 1995).

In this study K (Ba) alteration has been observed 1) associated with peperites in the middle units and upper units both distal to and below the known ore deposits, 2) in the Onaping Formation immediately below the Errington deposit, 3) proximal to intra-Onaping base metal showings, and 4) in and between the Errington and Vermilion deposits. The spatial distribution of this zone is difficult to determine due to poor exposure at the top of the Onaping Formation in the North Range, coupled with intense deformation and faulting in the South Range. Evidence to suggest the presence of a regional semiconformable potassic or alkali alteration zone at the top of the Onaping

Formation is lacking. Therefore the potassic alteration observed in this study will be described with discordant peperite-associated and VMS-associated alteration below.

4-2h. Carbon

Various types of carbon exist in the Onaping Formation: 1) a regional semi-concordant carbonaceous zone, 2) pre-existing carbonaceous fragments and 3) remobilized carbon in stringers and veinlets (Plate 4-10).

Regional semi-concordant carbon zone:

The most obvious regional carbon zone is slightly discordant to strata (Gibbins, 1994) in which carbon is finely disseminated in the matrix. Subdivision of the Onaping Formation into “Gray” and “Black” members (Muir and Peredery, 1984; Peredery, 1972) was based on the absence or presence of carbon. Muir (1983;1984) noted that carbon does not define the “Black member” because it is locally absent from the “Black member” and it is present in the “Gray member”. Gibbins (1994) through detailed mapping and sampling found that generally, the carbon contact lies metres below the upper contact of the Dowling member contact unit but locally the carbon contact transgresses the Sandcherry member strata and locally may extend 350 m below the Sandcherry member/Dowling member contact.

In Morgan Township (Map 1) the carbon contact slightly transgresses strata with local pockets of carbon-bearing equant shard units (Sandcherry member) and carbon-poor and carbon-bearing contact units (Dowling member) (Figure 2-4B). Generally, the upper 1

km (true thickness) of the Onaping Formation including the lower, middle and upper units of the Dowling member are carbonaceous. Contact units are only locally carbonaceous. Carbon is absent in 0.1-1.0 m wide halos surrounding aphanitic dykes and bodies of basal intrusion that intrude carbonaceous rocks. In the Joe Lake map area (Map 2), carbon-bearing Sandcherry member strata occurs at the base of the Onaping Formation adjacent to the SIC (Ames et al., 1997; Plate 4-10a, b). Therefore, there are not only undulations in the carbon contact that are diachronous but also isolated pockets of carbonaceous rocks deep within the Sandcherry member.

Most carbonaceous Onaping Formation is non-conductive. Rocks that are conductive include the carbonaceous Sandcherry member (Conductive unit of Gibbins, 1994) and the uppermost 10-50 m of the Onaping Formation (Gray, 1995).

Carbonaceous fragments:

Carbon also occurs as subrounded lithic fragments throughout the Dowling member (Plate 4-10c, d). Carbonaceous fragments are most common in the middle units and are less common in the contact units. The middle units contain 2-4 mm, subrounded carbonaceous fragments that show relict laminations or are epidote-bearing. Locally the contact units contain subrounded carbonaceous fragments (up to 2 cm).

Discordant stringers and veinlets:

Carbon is irregularly distributed within most of the Dowling member. Fine veinlets and stringers of carbon at the thin section scale indicate that carbon has been remobilized.

Stringers of carbon crosscut chloritic shards and carbon is concentrated in low permeability zones such as the margins of shards.

Geochemistry:

The amount of organic carbon (C_{org}) necessary to change the colour from grey to black is very little (0.08 wt. %; Gibbins, 1994). Carbon-bearing Sandcherry member contains on average, 0.3 wt.% C_{org} (Table 3-1). The lower, middle and upper units of the Dowling member are typically black, carbon bearing and average 0.4-0.47 wt. % C_{org} (Table 3-1). The upper units are typically much more carbon-rich containing up to 1.6 wt. % C_{org} in the majority of the unit (300m) and up to 6.0 wt. % in the uppermost 10-50 m (Gray, 1995).

Implications:

The origin of carbon in the Onaping Formation has been controversial with hypotheses suggesting a single carbon source including, the bolide (buckminster fullerenes; Becker et al., 1994), reduced carbonate target rocks (Bunch et al., 1997), carbonaceous target rocks (Masaitis et al., 1997; Grieve, pers comm., 1997; Bunch et al., 1997), biogenic activity (Avermann, 1994; Heymann et al., 1997), fumarolic activity (Burrows and Rickaby, 1930) and the transformation of CO to $CO_2 + C$ in the cooling impact plume (Heymann et al., 1996). The important factor is that there are multiple types, and therefore possible sources, of carbon in the Onaping Formation. Prior to this study there was no distinction between various types of carbon.

Biogenic origin: A biogenic origin has been proposed for carbon in the Onaping Formation, specifically algae in a local euxinic basin (Avermann, 1994) and algae from a photic zone (Beales and Lozej, 1975). The identification of algal relicts observed in thin section is tentative until microbial identification by SEM/TEM methods are forthcoming. Heymann and Dressler (1997) favour a biogenic origin based on C isotopic data combined with Raman spectroscopy and suggest that Avermann's (1994) algal blooms were synchronous with rapid deposition of the Onaping Formation under sedimentary conditions. They suggest that the carbon contact is time stratigraphic and that the carbon was deposited at the surface synchronous with sedimentation based on previous workers mapping (1:50,000 map). The explanation of this hypothesis is not compatible with the observations of 1) the presence of isolated pockets of carbonaceous rocks deep in the Onaping Formation near the SIC in the Sandcherry member, 2) the transgressive, undulatory nature of the carbon contact which cuts major stratigraphic units and members and is thus time-transgressive, and 3) the non-sedimentary stratigraphy of the Dowling member units, excluding the clearly, bedded upper units. Only the upper 200 m of the 1400 m Onaping Formation, (14%) is clearly reworked this accounts for only 20% of the carbonaceous Onaping Formation. Therefore the carbon could not have accumulated at the surface by algal and (cyano) bacterial activity in competition with sedimentation.

Carbonaceous target rocks: The target rocks have also been suggested as a source of carbon for the semi-concordant carbon zone in the Onaping Formation ("Black Member") (Masaitis et al., 1997; Grieve, 1997 pers. comm.). Heymann and Dressler (1997)

emphasize that the regional target rocks contain little carbonaceous matter and certainly not enough to deposit carbon over a distance of >60 km by 1 km represented by the upper Onaping Formation. The paucity of carbonaceous host rocks in the Huronian sequence in the Sudbury area is certainly a factor. Bunch et al., (1997) suggest that the C inventory in the Sudbury Structure comes from both the target and impactor. The target rocks are clearly a source of carbon in the Onaping Formation based on the presence of C-rich (<26 wt.%) siliceous shale fragments initially identified in the "Black Member" (Bunch et al., 1997), (Plate 4-10) and impact diamonds (Masaitis et al., 1997), although this does not prove therefore that carbonaceous target rocks should be the source of the regional carbon zone. The distribution of fullerenes (Becker et al., 1994) in the Sudbury Structure requires further definition.

The subrounded microscopic carbonaceous fragments in the contact and middle units indicate that there was a preexisting carbonaceous unit (s) in the target rocks. The carbonaceous target rock is proposed here to be the source of the small subrounded carbonaceous fragments and diamonds only, but not the source of the regional carbon.

Impact evaporation/dissociation of C from carbonate target rocks: The reactions involved in this process are poorly understood. A small scale experiment at the Ames Research Center vertical gun range (Bunch et al., 1997) produced graphite from impacting a limestone target and it was therefore suggested that the carbon precipitated from the impact vapor plume and was deposited as carbonaceous fallback matter in the Sudbury Structure.

Carbon patches in the lower Sandcherry member have diffuse contacts and within one unit, the carbon is patchy. This and the transgressive nature of the regional carbon contact are incompatible with “fallout” from target and impactor carbon sources.

Fumarolic activity: Peredery, (1984) rules out the fumarolic hypothesis (Burrows and Rickaby, 1930) as the source of the regional carbon in the Onaping Formation suggesting that 1) feeder structures are absent, and that 2) fumarolic activity does not agree with the present (1984) distribution pattern of carbon. Heymann et al., (1997) dismisses the hypothesis of CH₄-producing fumaroles suggesting that they contain too little reducing matter. Methane-bearing vent fluids are common in modern hydrothermal systems (i.e., Guaymas Basin, Escanaba Trough, Middle Valley) with the methane derived from the thermal cracking of terrigenous and/or marine organic matter in the buried sedimentary rocks (Von Damm, 1985b; Simoneit, Peter et al., 1991). The methane in these cases is converted to carbon and CO₂ by bacterial oxidation which regenerates organic matter in the surface sediments. The distribution pattern of the regional carbon in the Onaping Formation is not commensurate with purely fumarolic activity however, syn-depositional structures and fumaroles are present.

This study has defined numerous syn-depositional structures that focused both hydrothermal fluid and melt (Chapter 2: analogous to syn-volcanic faults infilled with igneous dykes).

Evidence for prolific fumarolic or hydrothermal activity includes:

- 1) the presence of regional hydrothermal alteration; silicification, albitization, chloritization and carbonatization;
- 2) carbonate “sinter”, the Vermilion Formation
- 3) major chemical additions of Zn, Pb, S and Mg at the base of the Dowling member and the top of the Onaping Formation. Zn-Pb-Cu deposits and occurrences.

The presence of syn-depositional or feeder structures, is indicated by:

- 1) the distinct structural control of aphanitic dykes, North and northwest set, locally feeders to fluidal fragment units
- 2) hydrothermal alteration focused around fluidal breccia complexes i.e., Joe Lake, Garson, Capreol, Nelson Lake, (Maps 1-3)
- 3) discordant calcite absent zones within the regional calcite alteration
- 4) long-lived feeder structures allowing dyke injection and formation of peperite when the Onaping Formation was still water saturated and likely when the Onwatin Formation was being deposited.

Although the fumaroles or hot-springs did not produce the regional carbon these structures and hydrothermal fluids were important for remobilizing carbon during the formation of the Errington and Vermilion Zn-Pb-Cu deposits (Chapters 5 and 6).

Alternate hypotheses: The pattern of distribution of carbon in the Onaping Formation is not compatible with the preceding proposed sources of carbon. The source proposed must be compatible with the field observations i.e.: the significance that the

surface that separates rocks with and without carbon is diachronous and that pockets of carbon-bearing rocks within the Sandcherry member are present within 50 m of the SIC. The amount of carbon in the pockets of carbon-bearing rocks is minor ($<0.5\%$). Carbon is found in the matrix of the Onaping Formation and is not present in the altered shards.

There is considerable evidence for sulphide deposition, fumarolic activity and deposition of carbonaceous matter in the subsurface or upper 1 km of the impact crater-fill sequence. Modern seafloor systems and attendant black smoker environments are hosts to prolific macro- and microbiological communities (Deming and Baross, 1993; Stetter et al., 1990; Jannasch, 1995 and references therein). There is a relatively recent but well known belief that there is a vast thermophilic biosphere beneath the earth's surface (Corliss, 1979; Deming and Baross, 1993; Baross and Hoffman, 1985; Fredrickson and Onstott, 1996). Microorganisms inhabiting water-bearing rock formations in the subsurface have been found at depths up to 2.8 km. The limiting factor is increasing temperature as these microbes flourish between 50-80°C as the lower limit and 113°C to 150°C as the upper temperature limit (Huber et al., 1990; Karl et al., 1988; Stetter et al., 1990; Brock, 1985; Delaney et al., 1998; Baross et al., 1982; Elsgaard et al., 1994). Autotrophic microbes derive nutrients and energy from inorganic chemicals and exist in the fractures and pore space between minerals. The amount of microbial activity is dependent on the capacity of the local environment to promote and support a niche whose critical factors are porosity and permeability, the presence of water, C, N, P, S, Fe and Mn (i.e., the same factors that control alteration). These nutrients are found in a number of environments including submarine volcanic craters and hydrothermal vent areas from volcanic gases, mantle

degassing or abiotic water-rock reactions (Jannasch, 1995; Huber et al., 1990; Baross et al., 1982). As depth and pressure increase the distribution becomes patchy as microbes are transported by flow of groundwater upon cooling of magmas and rock piles to an appropriate temperature limit ($<150^{\circ}\text{C}$) (Fredrickson and Onstott, 1996).

The possibility exists for analogous hyperthermophilic (microbial activity in the subsurface of the Onaping Formation. Hydrothermal systems induced by meteorite impact may generate, supply and convect nutrients and create an environment suitable for prolific growth of microbes that may be preserved as filamentous carbonaceous matter. Detailed and regional mapping of the complex stratigraphy, carbon distribution and various hydrothermal alteration zones show that there is no relationship between carbon and stratigraphy or carbon and any specific alteration zone. Patches of carbon-bearing Sandcherry member rocks are present in areas of weak albitization and carbon is present with or without carbonate although carbon is absent in areas of silicification. The distribution of carbon is probably mainly controlled by factors such as permeability controlled partially by the precipitation of alteration minerals, temperature and the presence or absence of water.

Field observations of initial reworking of the Onaping Formation during middle unit deposition (Figures 2-9, 10) suggests that external water was re-introduced into the crater. Water may not have been added everywhere in the crater at the same time but perhaps as streams or seeps along specific parts of the crater walls. The ability of water to permeate the fragmental Onaping Formation is variable for different units. The units along the carbon contact which separates rocks with and without carbon are most important.

The contact units which are locally incipiently welded are usually carbon-poor not unlike welded ash flow tuffs that are known to be barriers to gas and fluid escape causing alteration zones to develop (Ross and Smith, 1961). The Sandcherry member strata are typically variably albitized and the lack of carbon is likely a combination of an impermeable matrix due to precipitation of earlier alteration minerals and/or higher temperatures. The carbon contact may represent an isotherm.

Isolated carbon-bearing patches deep in the pile could be interpreted as follows: 1) the entire Onaping Formation once was carbonaceous but carbon was partially removed from the lower part; the process involved in remobilizing carbon may have been incomplete leaving isolated pockets of carbon, or 2) permeable areas with low amounts of hydrothermal alteration were conducive to microbial growth at higher temperatures and pressures than the regional carbon zone (i.e. Cowan, 1995).

In light of this new hypothesis as a possible source of carbon in the Onaping Formation and the definition of hydrothermal alteration zones, the tentative conclusions drawn here should be followed up with further research. Is there a relationship between hydrothermal alteration and the presence of carbon? Do specific types of alteration control the emplacement or removal of carbon? Is there a temperature control on the distribution of carbon in the Onaping Formation and can this be defined? Are there filamentous carbonaceous remains in the carbonate depositing fumaroles (Vermilion Formation) and in the subsurface carbonaceous zones in the Onaping Formation? Is the carbon modification/remobilization due to secondary processes such as hydrothermal fluid circulation or variations in temperature due to hydrothermal or magmatic activity?

The relationship between regional calcite alteration and carbon distribution in the Onaping formation and the mineralogically complex carbonate mounds of the Vermilion Formation is constrained using isotopes, Chapter 6.

4-3. Local Hydrothermal alteration

Zones(<10m) of epidote-pyrite and Kfeldspar-quartz-actinolite alteration are local and spatially restricted in the Onaping Formation. These and peperite-associated alteration types are documented and their significance discussed.

4-3a. Epidote-pyrite

An isolated, 2 x 1m epidote-pyrite pod, trending 100° was trenched near the top of the contact units in the Simmons Lake area (Map 5). This pod, approximately 260 m from a galena-sphalerite vein (Drake, 1992) is likely unrelated to the veins (Map 5). The epidote-pyrite pod is situated at the contact between, the contact and lower units, in a ~100-110° trending zone with anomalous pyrrhotite-sphalerite-chalcopryrite replacement of shards (Plate 4-11) and dykes in the overlying lower units. Sulphides, predominantly pyrrhotite, are associated with carbonate, replace shards and fragments, occur as 20 x 40 cm gossanous zones or as southeast trending pyrrhotite-chalcopryrite stringers and are spatially associated with isolated dykes and pods of the Basal intrusion. Massive dykes contain chlorite-quartz filled amygdales and disseminated pyrrhotite. Cavities filled with coarse, 6 mm-1 cm euhedral quartz are disseminated within the contact units proximal to the epidote-pyrite zone.

The gossan contains 20-25% pyrite, 20% Ba-Kfeldspar, 5% chlorite-titanite in a fine granular mass of epidote, minor Ba-Kfeldspar and trace quartz (Plate 4-11). There are two morphological types of compositionally similar pyrite. The first type is skeletal pyrite occurring within delicate veinlets, that in samples distal to the pyrite pod partially replace pyrrhotite that has replaced shards (Plate 4-11). The second type is euhedral pyrite that overgrows skeletal pyrite (Plate 4-11). This secondary, euhedral pyrite is associated with chlorite and titanite in aggregates that reach 8 mm. Titanite is disseminated in the chlorite, concentrated at the edge of chloritic shards and forms colloform grains within pyrite.

Epidote occurs as a fine polycrystalline matrix to <2 cm, coarse pyrite grains in the core of the mineralized zone and lines cavities within the less intensely altered wallrocks. The Simmons epidote is the most Fe-rich within the Onaping Formation (Figure 4-5). Fine Ba-Kfeldspar in the matrix is rimmed by fine-grained epidote. Coarser Kfeldspar occurs as discontinuous rims on the epidote, and 4-8 mm arcuate, lenticular forms possibly representing replaced shards. The Ba content of Kfeldspar in the shards is much less than that in the matrix, 0.42 and 2.0 wt.% BaO respectively (Appendix 4-2).

Geochemistry

The epidote-pyrite zone is characterized by significant mass gains of Ca, Ba, Fe, Co, Pb and S; a minor gain of V; significant loss of Si, Na and Cu and minor loss of CO₂ and Ni (Table 4-4). Negligible mass change is evident for K, Mn, Mg and Zn.

Implications

Paragenetic relationships indicate that the epidote-pyrite zone overprints and is late relative to the pyrrhotite-sphalerite-chalcopryrite disseminations in the lower units. Fe-rich epidote associated with a Ba-Kfeldspar-pyrite-Mg-chlorite assemblage strongly suggests a low temperature, relatively oxidizing environment (Gillis and Thompson, 1993; Holland and Malinin, 1979). This epidote-pyrite pod is located within a discordant, 120° trending zone with numerous dykes of basal intrusion, chalcopryrite stringers and a calcite-absent zone. This discordant zone is roughly orthogonal to bedding (025°). The permeability control on the distribution of the epidote alteration at a stratigraphic contact and overprinting relationships suggests that the higher temperature, relatively reducing environment with po-cpy-sph mineralization is locally overprinted by lower temperature, relatively oxidizing Ca-Fe-Ba rich fluids.

4-3b. Kfeldspar-quartz

Morphology, contact relationships, controls on distribution: Kfeldspar-quartz ± actinolite occurs as 1) coarse pegmatitic patches, 2) cavity and vein fillings in the Onaping Formation, 3) a breccia hosted by the basal intrusion, and 4) as alteration halos on epidote veins in the granophyre (Plate 4-12). Cavities filled with coarse, pink Kfeldspar and quartz although not common, were observed in less altered fluidal-fragment units and the basal intrusion of the North Range

Kfeldspar-quartz assemblages in coarse pegmatitic patches, veins and hydrothermal breccias in the Onaping Formation were observed in the Joe Lake area (Map 2; Ames and Gibson, 1995 see Figure 11). Quartz - Kfeldspar patches in the intensely

albitized Sandcherry member are restricted to an area < 50 m around a hydrothermal breccia (described below) and were also observed in the granophyre of the SIC. A pipe-like body of quartz-Kfeldspar-trace actinolite observed in the granophyre (SIC) is of similar mineralogy and orientation (300-315) to a subvertical vein within the Onaping Formation (Map 2). The subvertical vein, 2.5×0.8 m, is composed of Kfeldspar-quartz and cuts the contact between a proximal fluidal-fragment unit and a flow-banded dyke (Map 2B, inset). In the granophyre, epidote is a common constituent that is absent in the Onaping Formation. The potassic alteration is aurally restricted and volumetrically insignificant.

Hydrothermal breccia: A spectacular 9×5 m stockwork breccia whose long axis trends 295° is hosted by the Basal intrusion at Joe Lake (Plate 4-12; Ames and Gibson, 1995). The basal intrusion at this locality intrudes a massive to autobrecciated aphanitic dyke which is part of a discordant fluidal breccia complex with associated intense albitization. Actinolite-filled amygdales $\pm$ bleached halos at the margin of the basal intrusion are abundant (10%). Patches, 30 cm in diameter, consist of a 6 cm core of coarse quartz rimmed by Kfeldspar and quartz and occur within 3 m of the hydrothermal breccia.

The Basal intrusion is most intensely brecciated in a zone $3 \text{ m} \times 5 \text{ m}$. The breccia consists of angular fragments of variably bleached basal intrusion in a matrix of pink Kfeldspar-quartz-actinolite and minor titanite/leucoxene (Plate 4-12,14). Bleached halos on fragments are asymmetric, symmetric and have abrupt terminations against the veins. This alteration is multi-staged as revealed by early bleaching of the Basal intrusion and

fragments which are derived by its brecciation. These are cut by quartz-Kfeldspar-actinolite-titanite veins which in turn are cut by at least one late quartz vein stage.

Mineral chemistry, assemblages

Distal to the hydrothermal breccia in the Joe Lake area, the basal intrusion consists of albite-Kfeldspar-actinolite-quartz- titanite. The mineralogy of the less altered basal intrusion within the hydrothermal breccia consists of 70% quartz, 10% Kfeldspar, 20% actinolite and trace rutile, zircon (Plate 4-13). The bleached margins on fragments of basal intrusion contain more Kfeldspar (25-35%) and similar amounts of quartz, rutile/leucoxene and zircon but actinolite is absent (Plate 4-13). The matrix to the breccia consists of coarse Kfeldspar and quartz, Kfeldspar-quartz-actinolite and a late stage of clear coarse quartz. The Kfeldspar is stoichiometric (Appendix 4-2, sample AV-515d).

Implications:

The timing of Kfeldspar-quartz alteration in the Joe Lake area is late. It overprints the intense facies of albitization and cuts all rock types. The genetic relationship of this type of local alteration and the regional alteration is unknown.

4-3c. Peperite proximal alteration.

Alteration characteristics and types

Alteration types associated with peperite formation are complexly distributed in detail and in any one hand sample a variety of alteration types may coexist (i.e.,

silicification of tuff and muscovite-Kfeldspar alteration of the intrusion or magma), (Appendix 2-5; Plates A2-5.1 to 5). Alteration types associated with peperite formation are silicification, carbonatization (Fe-Mn-Mg), K-Ba feldspathization, chloritization, sericitization and Mn-alteration with base metal sulphide associated with carbonatization. In general, the peperite occurrences have 1) a chlorite-rich footwall, 2) an intensely silicified tuff with jigsaw puzzle fit of weakly brecciated fragments in the footwall, 3) a core with Ba-Kfeldspar $\pm$ sericite alteration of the magma/melt component and silicification and subsequent carbon removal of the host tuff and 4) manganiferous oxides $\pm$ carbonate halo either below or above the peperite in amygdale and cavity fillings (Figures 4-13 and 4-14).

In the two blocky peperites near the top of the Onaping Formation (Gordon Lake road and Azilda occurrences), the dominant alteration type of the host tuff is silicification. Alteration of the andesitic component is potassic manifested as barian Kfeldspar and phengitic muscovite. The lower part of the peperite showing is chlorite-carbonate altered (Figure 4-13).

The lensoidal peperite in the middle units (Figure 4-14), shows similar silicification of the host tuff and Ba-Kfeldspar-chlorite-Kfeldspar alteration of the “magma” but without sericite. The magma is dominated by spherulites rimmed by Fe-oxides, rutile, ilmenite, allanite, zircon, monazite in a chloritic groundmass. Tuff in the hangingwall of the peperite showing is much better exposed and reddish-brown, mm to cm scale Mn-oxide pods and 50 x 100 cm cavity fillings.

Mineral chemistry and assemblages:

Tuff component: Middle and upper unit tuff weathers brown to reddish brown except in areas of silicification where it weathers whitish grey. At the A&M peperite, pervasive silicification occurs discordant to bedding in the footwall (Figure 4-14). This discordant silicification defines a ~10 m wide northerly trending zone that extends for a minimum of 500 m into the footwall (Figure 4-14). Tuff, at the hangingwall contact between less altered middle unit and A&M intense peperite has a narrow (1 cm) intensely silicified halo and wider (10-20 cm) zone of less intense brown weathering weak silicification. The tuff component of the lensoidal and blocky peperite is strongly silicified.

Silicified tuff is composed dominantly of felsic lithic fragments in a quartzofeldspathic carbonaceous matrix (Table 4-2). The very fine polycrystalline quartzose matrix comprises 70-80% of the tuff. In contrast, the matrix of the less altered tuff contains chlorite, quartz, feldspar and fine needles of actinolite-hosting chlorite-epidote shards. Ferromagnesium minerals are absent in the silicified tuff. Black carbonaceous matter is 1) finely disseminated in the matrix, 2) fills interstices between fine polycrystalline grains with larger accumulations more common adjacent to the coarser 0.1 mm quartz/feldspar grains, 3) in quartz-carbon veinlets and 4) along foliation planes which cut the 'magma component'.

Magma component: "Magma" within the A&M lensoidal peperite is now dominantly spherulitic and composed of intergrown albite-barringerite Kfeldspar and Kfeldspar, chlorite and trace zircon, monazite, titanite, Fe-oxides and rutile. Amygdales are lined with radiating feldspar with growth perpendicular to vesicle walls and cored by quartz.

Amygdales in the discordant spherulitic lobes that intrude peperite have similar feldspar linings but are cored by Mn-calcite. Amygdales in discordant lobes in the hangingwall tuff again are rimmed by feldspars but cored by Mn-Fe dolomite and sphalerite.

The “magma” component of the intense blocky peperite at Gordon Lake road consists of muscovite-chlorite-albite-Kfeldspar-barian (2.8 wt. % BaO)-Kfeldspar-biotite $\pm$ carbon. On the footwall side of the intense blocky peperite, a less intensely altered assemblage consists of albite, Kfeldspar, barian (<1.5 wt. % BaO)-Kfeldspar, Mn-calcite, chlorite, biotite and calcite $\pm$ carbon. The “magma” component at the stratigraphically higher Azilda occurrence at the top of the Onaping Formation contains barian (<3 wt. % BaO)-Kfeldspar, Kfeldspar, muscovite, biotite, chlorite, Fe-Mn dolomite, Mn-calcite, calcite, Fe-dolomite and trace albite. Amygdales have Kfeldspar linings and dolomite cores.

Chlorite compositions in the lensoidal peperite at the A&M occurrence are similar in both the magma component of the most intense mixing zone and interstitial to spherulites within intrusive andesitic lobes (Figure 4-3). These chlorite compositions are only slightly more Mg-rich than the regional (background) middle unit tuff chlorite composition.

Chlorite compositions at the Gordon Lake road peperite are variable. Chlorite in the footwall chlorite-calcite alteration zone (AV-150,151) is pycnochlorite-ripidolite which is compositionally similar to the regional chlorite (Figure 4-3). Chlorite within “magma” fragments in the blocky peperite zone (Plate A2-5.4; AV-147) is much more Mg-rich; a magnesian pycnochlorite (Figure 4-3). This chlorite is more Mg-rich than that

in the basal silicification zone and similar to some chlorite at the Limerick intra-Onaping base metal showing (Figure 4-3). These represent some of the most Mg-rich chlorite compositions in the Onaping Formation.

Feldspar compositions in the A&M lensoidal peperite are barian Kfeldspar and end-member albite and Kfeldspar (Figure 4-6; Appendix 4-2). They are intergrown with no consistent growth history (paragenesis). The BaO content of Kfeldspar, although variable, is highest in the peperite at 0.1 to 3.4 wt.%. The BaO content of Kfeldspar filling amygdales in intrusive lobes is low (<0.8 wt.%).

Feldspar compositions in the magma component in the Gordon Lake road blocky peperite are end-member albite, Kfeldspar and Ba-Kfeldspar (Appendix 4-2, AV-147). Fine Kfeldspar in the matrix is BaO poor (~.7 wt. %) whereas Kfeldspar at the edge of, or in the sericitic foliation plane, is BaO enriched (2.1 to 2.8 wt %). In the footwall of the intense blocky peperite (AV-150) coarse radiating feldspars emanate from the edge of the angular "magma" fragments. BaO poor Kfeldspar is intergrown with albite and is rimmed by calcite and is likely a devitrification product. Minor barian (1.5 wt. %) Kfeldspar rims albite.

At the very top of the Onaping Formation at the Azilda peperite, coarse twinned Kfeldspar is intergrown with Mg-chlorite and pyrrhotite and is partially replaced by phengite. In the 'magma' component Kfeldspar rims the fragments, is isolated as coarse grains within biotite and fills amygdales. In intensely amygdaloidal andesite, biotite defines the foliation and partially replaces chlorite along the outer margin of chlorite-Ba-Kfeldspar pods. Vesicle fillings are feldspar and calcite. The BaO content of Kfeldspar is

variable, 0.2 to 3.0 wt. %, with no distinct populations associated with pyrrhotite, chlorite or biotite. Albite occurs in trace amounts.

The white micas in the Onaping Formation are predominantly phengitic with high Si/Al ratios (Figure 4-15). Phengite is present only in the blocky peperite showings. At the Gordon Lake road peperite, it occurs as an alteration mineral within the “magma” component where it replaces chlorite and fills vesicles. Coarse, 4 mm, phengite partially fills vesicles whereas fine matted phengite rims spherulites, occurs in the foliation and less commonly partially replaces Kfeldspar. This phengite is the most magnesian and siliceous (Figures 4-15 and 4-16; Appendix 4-2) and contains an average of 0.5 wt. % BaO and 0.5 wt. % F.

At the Azilda peperite, phengite is more abundant and commonly replaces coarse Kfeldspar crystals and less commonly chlorite. Phengite occurs as coarse 4 mm grains randomly oriented in low strain zones, is associated with carbonate and pyrrhotite, and replaces coarse Kfeldspar along the lining of amygdaloids which are infilled with pyrrhotite and dolomite. Fine grained phengite also occurs in the matrix of the tuff. The Azilda phengite have more Fe and less Si than those in the stratigraphically lower peperite although all of the peperite-associated phengite has $Mg > Fe$ (Figure 4-15). The Azilda phengite has similar $Fe/(Fe+Mg)$ values to muscovite in the Errington Zn-Pb-Cu deposit (Figure 4-15). The Azilda phengite averages 0.66 wt. % BaO and 0.1 wt. % F (Figure 4-16; Appendix 4-2).

Carbonates fill the core of vesicles, occur as fine fractures and locally replace epidote. In general, calcite occurs in the Gordon Lake road peperite, dolomite in the

Azilda peperite and calcite and ferroan dolomite at the A&M peperite (Figure 4-12a). At the A&M peperite, carbonate in amygdaloids within the discordant intrusive lobes is more Fe and Mn- rich in the hangingwall (2.4 to 5.3 wt. % MnO in dolomite) than those in the core of the peperite (0.6 to 4.1 wt % MnO in calcite).

Carbonate is associated with sphalerite, pyrite and chalcopryrite in the footwall of the main blocky peperite zone at the Gordon Lake road peperite. Carbonate is absent from the main intense blocky peperite and likely forms a halo around it. Manganiferous-calcite with <2.7 wt. % MnO dominates in the footwall with trace to rare calcite and/or ankerite. The Azilda peperite contains Fe-Mn dolomite, with less than 3 wt.% MnO, in the core of amygdaloids along with sulphide.

Carbon is a secondary phase that 1) surrounds spheres of chlorite in the core of “magma fragments”, 2) fills void spaces between adjacent chlorite spheres, 3) is interstitial to matted phengite grains and 4) is concentrated along foliation planes that cut the “magma fragments”. It has been remobilized from the carbonaceous tuff host into the “magma” during deformation and late quartz vein development but may also have been partially remobilized during formation of the peperite.

Geochemistry of alteration

The SiO₂ values for silicified tuff associated with peperite formation range from 80.6 to 88.5 wt. % and averages 84 wt. % (n=8; Appendix 4-1). Mass balance calculations comparing the least altered Onaping Formation (Table 3-1) as a precursor with the average Dowling member upper unit as the protolith (Appendix 4-1; Figure A4-1.7) show

that the erratic behaviour of many of the elements is minimized when the local host rock is used as the protolith. Using the average composition of three samples collected near the Gordon Lake road peperite, the silicified Dowling member tuff in the peperite is characterized by gains in Si, K, Ba, C and CO₂ and loss of Ca, Na, Fe, Mn, Mg, Cu, Zn, Pb, S, Ni and Co (Table 4-4). Many of the chemical losses are reflected in the absence of chlorite-actinolite and epidote and the presence of quartz, calcite, remobilized C, and barian phengite.

Mass changes during alteration of the “magma” component of the peperite rocks at the three localities were determined (Figure A4-1.8; Appendix 4-1). There are minor differences reflected in the presence or absence of barian phengite however this alteration is generally characterized loss of Na, Ca, Rb and Sr. Mg, K and Ba are variable depending on the peperite occurrence. Zn and Pb are generally lost and K, Ba and Rb gained at the Gordon Lake road peperite and Zn, Pb, Fe, Mg and Mn gained at the Azilda and A&M peperites (Appendix 4-1h).

A comparison of the massive cores of penecontemporaneous intrusions into the peperite from the top of the sequence with the least altered vitric Onaping Formation protolith from the base of the sequence essentially shows variations with the composition of intrusion with stratigraphic height. Negligible change is noted for most elements however gains and losses are evident in Zn, Mn, Ba, Cu, S, CO₂, Pb and Cu (Figures A4-1.8c and d).

Implications

Peperite and associated intrusive activity is significant in the Onaping Formation because 1) it defines conduits for magma delivery to the near surface associated with periods of extension in the basin during burial of the Onaping Formation and synchronous with Onwatin sedimentation (Chapter 2) and 2) it provides clues to the composition of the fluids in the Sudbury basin at ~1850 Ma. Although there is considerable literature on the physical features of peperite formation, the alteration assemblages are not well documented and chemical changes even less so. Silicification, chloritization and palagonitization are briefly noted alteration types in the literature (McPhie et al., 1993; Brooks et al., 1992).

Alteration minerals produced during dyke injection into wet, poorly consolidated sediment should provide information on the composition of the pore fluids in the Sudbury basin. The rapid intrusion of magma into wet rock results initially in, expanded porewater flow away from the dyke into lower pressure regimes until pressure differences decrease and hydrothermal convection starts (Delaney, 1982). Silicification of the host tuff likely resulted during the initial rapid temperature increase of the pore water during intrusion. Under low confining pressures (<700 bars) the retrograde solubility curve indicates temperatures above 375°C are required for rapid SiO₂ saturation and precipitation (Fournier, 1983; Kennedy, 1950). SiO₂ values of peperite associated tuff are high, averaging 84 wt. %, and significant mass gains in Si are evident (Table 4-4).

Andesite fragments in the peperite are lined with Kfeldspar-albite and cored by chlorite and/or paragenetically later phengite. MgO addition at the A&M and Azilda peperite is reflected in chlorite and dolomite, whereas the Gordon Lake peperite is

dominated by phengite. Phengite in the Gordon Lake road peperite has more F, Mg and Si and is associated with calcite whereas the Azilda phengite has more Fe, Ba, Mn and is associated with dolomite and pyrrhotite. The anomalous magnesium composition of chlorite and phengite in the Gordon Lake road peperite suggests that the pore fluids were magnesian and is consistent with modified seawater.

Halos of ferroan and manganiferous minerals reflect a low temperature hydrothermal stage likely due to cooling of the peperitic dykes.

Peperites in sill/sediment complexes may produce traps for high temperature fluids and may refocus and redirect hydrothermal fluid into focused discharge sites (i.e., Guaymas Basin, Rio Tinto: Boulter, 1993). Many of the alteration minerals associated with the Onaping/Vermilion-hosted base metal deposits have been identified in the alteration halos associated with the blocky peperite in the footwall of the ore deposits (Chapter 5). The spatial association and similarity in alteration mineralogy together suggest a link between peperite emplacement and formation of the Errington and Vermilion base metal deposits.

4-4. Geochronology of regional alteration

Establishing the age of hydrothermal alteration in the Sudbury crater-fill sequence was important as it clearly identified the age of the hydrothermal system and constrained the depositional age of the Onaping Formation (Ames et al., 1998).

Previous U/Pb age dates from Onaping Formation samples were obtained from Archean xenocrystic zircons (Krogh et al., 1984; Krogh et al., 1986). The variably

shocked, metamorphosed zircon grains showed impact-related Pb loss along a discordia line and a lower intercept of 1850 Ma supporting an impact origin for the Onaping Formation (Krogh et al., 1996). U/Pb geochronology was used in this study to establish the age of the hydrothermal system because field relationships suggest that most of the alteration is syndepositional with the Onaping Formation.

Planar discordant zones of intense albitization (section 4-2c) are relatively late in the evolution of the hydrothermal system; they crosscut the syn-depositional albite alteration proximal to fluidal breccia complexes and cut the basal intrusion in the Joe Lake area. Details of the distribution, mineral assemblages, compositions, and chemical gains and losses in this type of alteration were presented in Section 4-2c.

Coarse hydrothermal titanite was separated from these planar discordant zones of albitization in the Joe Lake area (Plate 4-6), (Ames et al., 1996; Ames et al., 1997; Ames et al., 1998). U/Pb dating was by conventional methods at the Isotope Laboratory at the Geological Survey of Canada outlined in Ames et al., (1998) and references therein. Analytical data is given in Table 4-6 and isotopic results are illustrated in Figure 4-17 for six multigrain titanite analyses. Regression of all six analyses yields an upper intercept with concordia of $1848 \pm 3.8/-1.8$ Ma.

Implications of geochronology

The new age data clearly establishes constraints on the cooling history of the Sudbury crater-fill deposits and the role of hydrothermal processes in impact structures. The geochronologic results on shocked zircon Ma (Krogh et al., 1996) and hydrothermal

titanite, together with field data indicate that the Onaping Formation was emplaced at 1852-1846. The age of titanites in the Onaping Formation (1848 Ma) clearly demonstrates the rapid evolution of rock generation and alteration following the Sudbury event.

The geochronology also demonstrates that the discordant albitized zones within the Onaping Formation are unrelated to the 1700 Ma albitite dyke event observed in the Sudbury area (Schandl et al., 1994). The ca. 1848 Ma age for albitization in the Onaping Formation is compatible with the heat source for the Sudbury crater-fill hydrothermal system being the ca. 1850 Ma SIC, sublayer and offset dykes (Krogh et al., 1984; Corfu and Lightfoot, 1996; Ostermann et al., 1996) (Figure 2-1).

Figure 4-1: Simplified stratigraphic and alteration section for the Onaping Formation, Sudbury Structure illustrating the distribution and vertical stacking of regional basinwide hydrothermal alteration zones. Brackets denote alteration types with poorly constrained regional distribution patterns (modified from Ames et al., 1998). See Map 1B, Figure 2 for the distribution of the major alteration zones in the Sudbury basin.

Figure 4-2: Distribution of regional alteration zones in the Onaping Formation, over a 15 km strike length, North Range. Calcite absent zones transect the regional semi-conformable carbonate alteration. Compilation of Map 1 (pocket) and Falconbridge Ltd. mapping, Gibbins (1994).

Peperite

- x A + M (n=9, 1)
- o Azilda (n=12, 2)
- Gordon Lk. rd. (n=36, 4)

Sandcherry member

- + Basal silicification (n=12, 1)
- ▲ Fludal autobreccia and Equant shard (n=17, 2)

Dowling member

- o Contact Units (n=36, 4)
- o Middle Unit (MU) (n=95, 8)
- Limerick Cu-Zn showing in MU
- Upper Unit (UU) (n=9, 1)

Mineralization

- Errington stringer veins (n=7, 2)

Figure 4-3: Chlorite composition diagrams, n=408 (modified after Hey, 1954) A, B) Chlorite from a transect through the Onaping Formation in Morgan township, C) Chlorite from altered andesite in peperite zones and stringer veins in the Errington deposit, D) Chlorite from silicified equant shard unit, Hammer powerline and contact units (Peredery, 1972), E) Chlorite associated with pyritized epidosite zone, Simmons Lake, F) Chlorite from silicified equant shard unit, Capreol and albitized rim on mafic clot, Joe Lk.

Fracture-controlled albitization

- $\bullet$ Joe Lake, AV-512
- $\bullet$ Capreol, AV-486
- $+$ AV-488

Contact unit, Simmons area

- $+$ chl-ep-Ba. Kspar-py, AV-647
- $\bullet$ <<chl-alb-Ksp-act.hb-tnt-mn.ilm AV-650

Δ Hanmer powerline, AV-356

- $\bullet$ Highway 144 (Peredery, 1972) samples P117-68, DW 479A-70

Figure 4-3: (cont'd):

Figure 4-4: Pyroxene mineral compositions within the basal intrusion, the basal silicification zone and fluidal-fragment units, Onaping Formation.

Figure 4-5: A) Epidote compositions from alteration zones at various stratigraphic levels within the Onaping Formation. The Fe-poor, Al-rich epidotes are indicative of the lowest part of the Onaping Formation adjacent to the SIC whereas the Fe-rich, Al-poor epidote compositions correspond to alteration zones in the upper half of the Onaping Formation. B) The Fe/Fe+Al in epidote increases with increasing stratigraphic height in the Onaping Formation and increasing distance from the SIC.

A Regional alteration

B Errington mine proximal alteration

Figure 4-6: Ternary plots for feldspar compositions in the Onaping Formation n=379.

figure 4-7: Morphology of actinolite and/or chlorite fragments, clots and associated alteration alos. S=station number, AV=sample number, ts=thin section, chl=chlorite, act=actinolite, p=epidote, fsp=feldspar, q, qtz=quartz, cc=calcite, tnt=titanite, moly=molybdenite, F1=uidal fragment unit, EQ=equant shard unit, tr=transitional unit, fba=flow banded andesite, lt=pilli tuff.

Figure 4-8: Amphibole mineral chemistry from the Onaping Formation. Nomenclature based on atomic Si versus $Mg^{2+}/(Mg^{2+}+Fe^{2+})$, (Leake, 1978, IMA, 1978). Symbols represent the average composition based on 5 methods of amphibole calculations (Appendix 4-3). Trends in D, from McCollom and Shock, 1998.

Figure 4-9: Rose diagrams of fracture controlled alteration in the Joe Lake area (Map 2B). HPL=Hanmer powerline area A) U-Pb dating of titanite in albitization ~1848 Ma; Table 4-6, Figure 4-17.

Figure 4-10: Schematic cross-section illustrating the albiteization alteration facies proximal to fluidal breccia complexes. Chlorite alteration is fault bounded, generally restricted to the contact units and is overlain by transition-type alteration. The lower and middle unit rocks in the transition zone are some of the least altered units.

Figure 4-11: Amphibole mineral chemistry showing variations in A) Si versus Ti and B) Si versus (Na+K) in Site A. Compositions were recalculated from microprobe data based on 6 different methods (Appendix 4-3) and the data points represent the average composition.

A Regional carbonatization, peperite and intra-Onaping showings

B Errington deposit

Figure 4-12: Mineral compositions of carbonates within regional and local alteration zones and the Errington deposit, Sudbury Structure. n=427.

Figure 4-13: Generalized alteration map for the blocky, Gordon Lake road pepelite, Upper Units, Dowling member, Onaping Formation. Chl=chlorite, cc=calcite, sph=sphalerite, cpy=chalcopyrite, qtz=quartz, Ba-Ksp=barian Kfeldspar. Map and description of geology in Appendix 2-5.

Figure 4-14: Generalized alteration map for the A&M lensoidal peperite. Geology map and text in Appendix 2-5.

Figure 4-15: Variations in $Fe^\#$ and Si/Al in muscovite and phengite from the Zn-Cu-Pb deposits, showings and peperites in the Whitewater Group. CBX= cherty breccia, CHM= carbonate hosted mineralization, BPZ= basal pyrite zone.

Figure 4-16: BaO and F (wt%) content of phengite in the Onaping Formation and Errington Zn-Cu-Pb deposit. White bars indicate average composition.

Figure 4-17: Geochronology of albitization, Sandcherry member, Onaping Formation. U-Pb-data in Table 4-6.

- A) Discordant fracture controlled albitization, equant shard unit, Sandcherry member. Outcrop station 422, Joe Lake area. Red magnet is 12.5 cm long.
- B) Polished slab showing intense albitization in fracture-controlled discordant zones. Note relict quartzose lithic fragments and brown titanite specks in the altered equant shard unit. Sample AV-33=J8, outcrop station 422.
- C) Back-scattered electron image of euhedral, hydrothermal titanite with relict ilmenite in core; sample AV J8.
- D) U-Pb concordia plot for hydrothermal titanite from discordant zones of albitization. Error ellipses effect 95% confidence limits. Sample AV-J8, outcrop station 422.

Table 4-1: Summary of the relative mass changes of the Least altered Onaping Formation relative to the felsic norite. Major>50, minor=25-50.

GAINS

Major	Ba, Rb
Minor	Na2O, MnO, K2O

LOSSES

Major	CaO, Fe2O3, CO2, Cr, Ni, Sr, Zn
Minor	Co
Constant	Ti, Al, Nb, Zr, Y

SILICIFICATION TYPE/ZONE	MINERALOGY	PRINCIPAL TEXTURES	PARAGENESIS
Basal silicification n=8 Morgan (AV-181, 182, 185, 186 194, 201, 206, 715) HPL (AV-365)	alb-act-qtz-chl-tnt Ksp-ep +- cc, pyx, mu, bio << cpy-po-covellite-sph-mt ilm<<< ap, ser	Qtz-fine polygonal, local dessication-like cracks, replacement front edge stylolitic band of amphi-chl-tnt. SEM image analyses one side of front qtz:albite estimate= 21.79, other side Q:A=66/34. Alb-subhedral 50-100 um, contains anhedral 1-25um Kspar grains Amygdales filled with quartz-actinolite, may have ep rims po-ep-cpy association shards= alb-qtz-amph-tnt (Ksp, chl) predominantly = minor mafic shards-amph matrix= fine polycrystalline Qtz-plag-act epidote= rims vesicles/shards, associated with po-cpy, minor dusting on plag, in matrix and as 2 mm anheda	early Ksp overprinted by albite-quartz-epidote later silicification overprint albite-quartz covellite secondary
Fracture-controlled Morgan-Middle units n=3 (AV-257-259) -Contact units (AV-268)	Qtz-plag-chl-tnt Qtz-alb-chl-tnt-cc-py	chlorite-titanite stylolitic stringers cut fine polygonal qtz-alb matrix matrix grain size is inhomogeneous, 5-30% chl rosettes, rare ghost-like shards, axiolitic growth of fsp in shards shards recrystallized, fine qtz and plag, matrix=chl-alb-qtz, coarse (0.2 mm) euhedra, fine polygonal qtz rims on monocrystalline qtz grains. matrix is fine polycrystalline quartz and plag (chl removed) shards= qtz-plag-tnt +- chl-cc shard plag is coarse, inhomogeneous mottled extinction, coarse tnt subhedra 0.1mm moderately altered samples contain more chl in the shards, the chl is evenly distributed in the shard with plag/qtz, no rim of plag core of chl relationship. SEM image analyses of matrix 32Qtz/68Alb	cc-open space filling -partial shard replacement precursor chl shards altered to qtz and plag, most of plag remnant.
Peperite associated Gordon Lake Road n=4 (AV-151, 152, 147, 145)	Qtz-plag-C +- chl, se tnt	Quartz is very fine, polycrystalline with C wisps defining the weak foliation, se occurs in and out of foliation	radiating crystals (?) on quartz. relative to less altered <<chl-cc
A&M showing n=2 (AV-153, 157)	Qtz-C-plag, tr. chl, mt, cpy +- chl, bio, se, cc	Qtz-fine polycrystalline, inhomogeneous grain size, embayments on quartz lithic grains with polycrystalline fine qtz, Carbon occurs in patches and is remobilized to intergranular spaces between qtz grains	

Table 4-2: Summary of silicification petrography

SILICIFICATION TYPE/ZONE	MINERALOGY	PRINCIPAL TEXTURES	PARAGENESIS
Basal silicification n=8 Morgan (AV-181, 182, 185, 186 194, 201, 206, 715) HPL (AV-365)	alb-ad-qtz-chl-tnt Ksp-ep +- cc, pyx, mu, bio -< cpy-po-covellite-sph-mt ilm<<< ap, ser	Qtz-fine polygonal, local desiccation-like cracks, replacement front edge stylolitic band of amph-chl-tnt. SEM image analyses one side of front qtz:albite estimate= 21:79, other side Q:A=66/34. Alb-subhedral 50-100 um, contains anhedral 1-25um Kspar grains Amygdales filled with quartz-actinolite, may have ep rims po-ep-cpy association shards= alb-qtz-amph-tnt (Ksp, chl) predominantly = minor mafic shards-amph matrix= fine polycrystalline Qtz-plag-act epidote= rims vesicles/shards, associated with po-cpy, minor dusting on plag, in matrix and as 2 mm anhedral	early Ksp overprinted by albite-quartz-epidote later silicification overprint albite-quartz covellite secondary
Fracture-controlled Morgan-Middle units n=3 (AV-257-259) -Contact units (AV-268)	Qtz-plag-chl-tnt Qtz-alb-chl-tnt-cc-py	chlorite-titanite stylolitic stringers cut fine polygonal qtz-alb matrix matrix grain size is inhomogeneous, 5-30% chl rosettes, rare ghost-like shards, axiolitic growth of fsp in shards shards recrystallized, fine qtz and plag, matrix=chl-alb-qtz, coarse (0.2 mm) euhedra, fine polygonal qtz rims on monocrystalline qtz grains. matrix is fine polycrystalline quartz and plag (chl removed) shards= qtz-plag-tnt +- chl-cc shard plag is coarse, inhomogeneous mottled extinction, coarse tnt subhedra 0.1mm , moderately altered samples contain more chl in the shards, the chl is evenly distributed in the shard with plag/qtz, no rim of plag core of chl relationship. SEM image analyses of matrix 32Qtz/68Alb	cc-open space filling -partial shard replacement precursor chl shards altered to qtz and plag, most of plag remnant.
Hammer powerline n=3 (AV-353A, B, 355, 356)	Qtz-alb-chl-tnt-cc		
Peperite associated Gordon Lake Road n=4 (AV-151, 152, 147, 145)	Qtz-plag-C +- chl, se tnt	Quartz is very fine, polycrystalline with C wisps defining the weak foliation, se occurs in and out of foliation	radiating crystals (?) on quartz. relative to less altered -< chl-cc
A&M showing n=2 (AV-153, 157)	Qtz-C-plag, tr. chl, mt, cpy +- chl, bio, se, cc	Qtz-fine polycrystalline, inhomogeneous grain size, embayments on quartz lithic grains with polycrystalline fine qtz, Carbon occurs in patches and is remobilized to intergranular spaces between qtz grains	

Table 4-3: Summary of relative mass changes in regional alteration zones.
 (- negligible, m=20-50%, M=>50%)

ALTERATION ZONE	Si	Ca	Na	K	Ba	CO ₂	Fe ₂₊	Fe ₃₊	Fe _{3+tt}	Mn	Mg	Cu	Zn	Pb	Ni	S	C
Carbonate n=3	- +(8)	M (-81)	-M (-53)	-m	-m	M	m	M	M	M	m	-M	M	M	-	M	+M
Calcite n=15, MU	- +(8)	M (99)	-m (-45)	-m	-m	M	-	m	-	M	-	-M	M	M	-	M	+M
n=3, LU	-	+M	- to -M	-	+m	M	-	+mM	- to +M	M	-	+	M	m	-	M	+M
n=1, CT	-	M (124)	-	-	-	M	-	-	-	M	-	-	M	M	-	M	+M
no-calcite n=7	- +(9)	M (58)	-M	-m	-	-	-m	m	m	M	-	-M	M	M	m	M	+M
Transitional n=5	- +(9)	M 54	- 8	-	-m	m	-	m	-	M	-	-M	M	M	-	M	+M
Chloritization Contact units n=15	- +(10)	m 48	- 18	-M	-M	M	-	-	-	-	m	-M	-m	-	-	m	- to +M
Albitization Lower units n=3	- +(9)	M 80	-	-	-m	M	-M	-	-	M	-	-M	-	M	-	M	-
Contact units n=15	- +(12)	m 28	-	-M	-M	-	-	-	-	-	m	-M	-	-	-	M	-
Sandcherry member strong, n=10	- +(17)	M 56	M	-M	-M	-	-m	-m	-m	-m	-	-M	-M	-	-	-M	-
moderate, n=4	- +(16)	M 88	m	-M	-M	M	-m	-m	-m	-m	-	-m	-M	-	-	-m	-
weak, n=18	- +(15)	m 30	-	-m	-m	-	-	-m	-	-	-	-m	-m	M	-	m	-
Basal silicification Sandcherry member n=6	-	m 25	-	-m	-M	M ₁	-	-	-	-m	-	M	-	M	-	M	-
Basal intrusion	19																

1. negligible to minor loss, major gain in one controls average chemistry.

Table 4-4: Summary of relative mass changes in discordant alteration zones.
Vitric least altered protolith except italicized with Dowling member upper unit as protolith.
(- negligible, m=20-50%, M=>50%)

	ALTERATION ZONE	Si	Ca	Na	K	Ba	CO2	Fe2+	Fe3+	Fe3+t	Mn	Mg	Cu	Zn	Pb	Ni	S	V	Co
Onwatin	Silicification peperite associated	M	-M	-M	+M	M	M	-M	-M	-M	-M	-M	+M	+M	+M	-M	-M	-	-M
	(with DMUU protolith)	M	-M	-M	+M	M	+M	-M	-M	-M	-M	-M	-M	-M	-M	-M	-M	-m	-M
	no-calcite n=7	- +(9)	M (58)	-M	-m	-	-	-m	m	m	M	-	-M	M	M	m	M	m	-m
	Fracture-controlled silicification-DMMU	M	-M	-M	M	M	-	-M	-M	-M	-M	-M	-M	-M	M	-	-M	-M	-M
DM	Silicification Limerick area-DMMU	m	-M	-	-M	-M	-m	-m	-m	-M	-m	-m	-M	-M	M	-	-M	-	-m
SM	Epidote-pyrite zone	-M	M	-M	-	M	-m	-M	-M	M	-	-	-M	-	M	-m	M	m	M
	Silicification Hammer powerline-SM	M	-M	-	M	-m	-m	-M	-M	-M	-M	-M	-M	-M	-m	-M	-M	-m	-M
	Capreol-SM	m	-m	M	-m	-m	-m	M	-M	-M	-M	-M	-M	-M	M	-M	-M	-M	-M
	Albitization Basal intrusion-Joe Lake	m	-M	M	-M	-M	M	-M	-M	-M	-M	-M	-M	-M	-M	-M	-M	-M	-M
SIC	Sandcherry member-Joe	m	-M	M	-M	-M	-	-M	-M	-M	-M	-M	-M	-M	-	-M	-M	-M	-M
	Silicification Fluidal breccias	m	-	-	-	+ -	-m	-m	-m	-m	-M	-	-M	-m	+M	-	+ -	-	-m

Table 4-5: Characteristics of alteration facies for albitization.

	Weak	Moderate	Intense
Field characteristics	Weathers greenish grey Minor thin feldspathic rims on shards Shard dominantly chlorite Vugs filled with coarse Ksp-qtz	Weathers grey with distinctive 2-5mm pinkish beige rims on shards. minor total replacement of shards by feldspar.	Weathers pinkish beige Total to partial replacement of shards by feldspar Feldspar alteration of lithic fragments and matrix Actinolite rims/cores shards, fragments and fills amygdales Minor veining/feldspar or actinolite Act. clots, fragments and amygdules with bleached haloes. Albite-actinolite-quartz-chlorite titanite
Alteration assemblage	Chlorite-albite-Kfeldspar-quartz titanite prehnite-pumpellyite-actinolite tr. po	Albite-Kfeldspar-chlorite-actinolite -titanite-quartz	
Textures	Shards dominantly chloritic with fine <1 mm clear rim Chlorite mass with radiating sector birefringent chlorite Shards composed of spherulites Spherulitic quartzofeldpathic grains, minor spherulites/Fe-Ti oxide bands after palagonite Shards heterogeneous in one section Amygdales-quartz/actinolite +- prehnite in core chlorite near top of SM-Morgan	Shards distinctively zoned albite-ksp tr quartz forms coarse grains lining shard rims and fractures growth perpendicular to shard walls some sector crystallization core is chlorite-titanite	Shards with coarse actinolite and albite intergrown set in fine felsic matrix Kfeldspar relict fine <5 micron grains in coarse albite Titanite-coarse hydrothermal Amygdales-actinolite quartz-actinolite quartz with pre-ep?/act core quartz-titanite euhedra

Table 4-6. UPb Analytical data

Fraction ^a	wt ^b (μg)	U (ppm)	Pb ^c (ppm)	206Pb ^d 204(Pb)	Pb ^e (pg)	Th U	206Pb ^f 238U	207Pb ^f 235U	207Pb ^f 206Pb	206Pb ^g 238U(Ma)	207Pb ^g 235U(Ma)	corr. coef.	207Pb ^g 206Pb(Ma)	dsc ^h (%)
AV-108: Hydrothermal alteration, albittization														
Titanite														
A	78.8	72.15	44.25	6755	17.2	3.59	0.3293±0.09	5.130±0.10	0.1130±0.03	1835.2±2.8	1841.1±1.7	0.94	1847.8±1.2	0.8
B	100.4	33.36	20.79	3451	19.9	3.7	0.3301±0.09	5.143±0.11	0.1130±0.04	1838.7±3.0	1843.2±1.8	0.93	1848.2±1.5	0.6
C	168.9	20.48	10.51	3743	19	2.39	0.3295±0.09	5.137±0.10	0.1130±0.04	1836.5±2.8	1842.1±1.7	0.92	1848.5±1.4	0.7
D	97.8	45.4	22.55	4550	20	2.19	0.3292±0.09	5.132±0.10	0.1130±0.04	1834.6±2.8	1841.3±1.7	0.93	1849.0±1.4	0.9
E	27.7	68.29	35.75	645	60.2	2.63	0.3234±0.24	5.054±0.36	0.1134±0.36	1806.3±7.6	1828.5±6.1	0.34	1853.8±13.0	2.9
F	147.6	27.69	16.35	2237	37.8	3.27	0.3315±0.09	5.168±0.10	0.1131±0.08	1845.7±1.7	1847.3±1.7	0.69	1849.2±2.7	0.2
AV-162: Spherulitic dike contemporaneous with peperite														
Zircon														
As	3.0	431.3	171.3	783	41.0	0.015	0.3892±0.42	7.823±0.46	0.1458±0.17	2119.2±15.0	2210.8±8.2	0.93	2236.9±5.8	9.1
BS	3.0	153.5	107.8	810	17.0	1.59	0.5038±0.19	12.13±0.22	0.1747±0.10	2630.2±8.1	2614.7±4.0	0.89	2602.8±3.3	-1.3
CS	2.0	75.09	48.06	369	13.4	1.09	0.5022±0.42	12.19±0.44	0.1761±0.17	2623.1±18.1	2619.1±8.3	0.92	2616.0±5.7	-0.3
DS	2.0	187.4	102.4	973	10.2	0.48	0.4850±0.22	11.86±0.24	0.1774±0.10	2548.8±9.1	2593.5±4.4	0.91	2628.6±3.2	3.7

a s, single grain

b Weighing error = ± 1 mg

c Radiogenic Pb

d Measured ratio, corrected for spike and Pb fractionation of 0.03%±0.03% AMU.

e Total common Pb in analysis corrected for fractionation and spike

f Corrected for blank Pb and U, and common Pb (Cunningham and Richards (1975) model Pb composition equivalent to the interpreted age of the individual zircons); errors are 1 standard error of the mean in percent for ratios.

g Corrected for blank and common Pb; errors are 2 standard errors of the mean in Ma

h Discordance in percent

Zircon and titanite were analyzed by conventional UPb methods (Parish et al., 1992; Roddick, 1987; Roddick et al., 1987) after abrasion (Krogh, 1982).

Plate 4-1: Diagenetic and devitrification textures. A) Chlorite-prehnite altered fragment. Prehnite (dark) 0.3 to 0.4 mm radiating aggregates with radiating chlorite spheres (light). Base of the lower units, Dowling member. Transition zone alteration, AV-76. B and C) Sector crystallization of feldspar around outer margin of altered glass shards. Chlorite-prehnite cores. Note sector crystallization along fractures in shards in C.

PLATE CAPTIONS

Plate 4-2: Photographs of silicification

- a) Polished slab of silicified fluidal fragment unit, Joe Lake area. Station 416, sample AV-524.
- b) Polished slab of pervasively silicified equant shard unit, basal silicification zone, Morgan township. Station 129, sample AV-186.
- c) Angular fragment of intensely altered equant shard hosted in relatively unaltered equant shard unit, Dowling township.
- d) Patchy silicification at the contact between the middle units and contact units, Dowling member, crossed by quartz veins. Limerick area, Morgan Township, station 232, AV257-259.
- e) North trending fracture-controlled silicification with local perturbation. It cuts the contact between the Sandcherry member and Dowling member at hammer head, Hanmer powerline. station 502, AV-353.
- f) Polished slab showing textural features of fracture-controlled silicification from locality shown in photo E, Hanmer powerline. Note strong silicification of the equant shards. station 502 AV-353.

PLATE CAPTIONS

Plate 4-3: Microphotographs of silicification textures

a) Back scattered image of silicification fronts crossing a quartzose lithic fragment (qtz) in the basal zone of silicification, Morgan Township. In crossed polars the lithic fragment is monocrystalline above the stylolitic line whereas the quartz lithic is polycrystalline in the silicified zone below the line marked by chlorite, amphibole and titanite. sample AV-182, station 125.

b) Microphotograph of 3 mm feldspar-epidote shard rimmed by fine polycrystalline quartz, equant shard unit, Sandcherry member, basal silicification zone, Morgan Township. AV-194, station 139.

c) Flow banding in fluidal fragment is replaced by fine polycrystalline albite. In plane polarized light the albite has an irregular fracture pattern that cuts grain boundaries. Amygdales filled with actinolite. Upper part of the basal zone of silicification, Morgan Township. Sample AV-201, station 149.

d) Etched thin section with recessive shards in a matrix (white) dominated by quartz, from the basal silicification zone, Morgan Township. Sample AV-184, station 127.

e) Back scattered image of early, albite-Kfeldspar alteration of Sandcherry member equant shard unit overprinted by silicification which is quartz dominant. Alteration front marked by fine amphibole and titanite. Basal silicification zone, sample AV-182, Morgan Township, station 125.

PLATE CAPTIONS

Plate 4-4: Outcrop and polished slab photographs of regional albitization zone, Type 1 albitization.

- a) Weak albitization characterized by thin pinkish white weathering rims on some shards. Shard cores are composed of chlorite and the weakly albitized rocks weather greenish gray. Morgan Township, Station 142, AV-195.
- b) Polished slab of weakly albitized equant shard unit. As in a) note the thin pinkish white feldspathic rims on chloritic shards, station 409, Sample AV-508. GSC 1995-077T.
- c) Moderately albitized equant shard unit. Note the majority of shards have distinctive feldspathized shard outlines and chloritic cores. Outcrops weather pinkish gray. Morgan Township, station 079, sample AV-97.
- d) Intense albitization characterized by partially albitized lithic fragments, matrix and shards. Shards are actinolite-rich. Actinolite occurs in patches rimmed by albite and vice versa. Station 416, Joe Lake area.
- e) Intense albitization proximal to aphanitic dyke just outside of photo. Note pervasive albitization at scale card and pervasively albitized shards and fluidal fragments. Joe Lake area, station 413.
- f) Intense albitization within 1 m of aphanitic sill. Note distinctive pink weathering and pervasive replacement of matrix, fluidal fragments and lithics excluding the quartz fragments (qtz) Joe Lake area, station 422.

PLATE CAPTIONS

Plate 4-5: Outcrop photographs of albite and actinolite alteration.

- a) Ten centimeter pervasively albitized halo surrounds aphanitic dyke within fluidal breccia complex, Joe Lake area. Station 443.
- b) Actinolite veinlets with albite haloes within pervasively albitized zone extending 1 m along strike from the termination of an aphanitic dyke. The dyke is just out of the photo below the right side of the scale card. Nelson Lake west, station 603.
- c) Polished slab of intensely albitized equant shard unit with the matrix replaced by actinolite. Sampled proximal to aphanitic dyke, station 603, Nelson Lake west.
- d) Intense feldspathization of fluidal fragments and equant shards. Note multiple fluid pulses evident by alternating feldspathic and actinolite bands. Nelson Lake west, station 602.
- e) Actinolite-filled vesicles are common adjacent to small pods of basal intrusion (noted here) and aphanitic dykes. Morgan Township.

PLATE CAPTIONS

Plate 4-6: Discordant albitization, Type 2 albitization.

- a) Fracture-controlled albitization (1848 Ma) cuts equant shard unit, Sandcherry member. North is to the top of the photo. Note multiple overprinting zones with the pervasive albitization centred on a fracture. Shards are visible in the albitized halos. Same location as geochronology (Ames et al., 1998). Joe Lake area, station 422.
- b) Polished slab from location in a) of fracture-controlled albitization. Note patchy irregular alteration front. Joe Lake area, station 422, sample AV-535.
- c) Fracture-controlled albitization within the basal intrusion, Joe Lake area, station 402.
- d) Three metre in diameter zone of actinolite veins with pervasive albite-quartz alteration haloes in close proximity to a fluidal breccia dyke/sill complex. Capreol - Rockcut Lake area, station 361.
- e) Close up of of 1-2 cm actinolite veins and 12-18 cm pervasive alteration haloes from photo d). Capreol-Rockcut Lake area, station 361.
- f) Polished slab of actinolite vein and quartz-albite alteration halo in equant shard unit. Locality the same as photos d and e, sample AV-489.

A

B

C

D

E

F

PLATE CAPTIONS

Plate 4-7: Microphotographs of albitization textures

- a) Back scattered image of feldspathized margin to shard in Sandcherry member. The shard core is a mixture of chlorite (bright) and albite (Alb) and the margin is randomly distributed albite (dark) and Kfeldspar (medium gray, Ksp). sample 174, station 114, Morgan Township.
- b) Back scattered image of flow banded fragment within same sample as a). Note monomineralic bands of Kfeldspar in a matrix composed of subequal proportions of chlorite, albite and Kfeldspar. sample 174, station 114, Morgan Township.
- c) Back scattered image of shards within weakly albitized transitional unit, Sandcherry member. Some shards are albitic (centre, dark gray) and others have randomly distributed Kfeldspar, albite and chlorite. sample 174, station 114, Morgan Township.
- d) Back scattered image of albitized contact unit, Dowling member, Morgan Township. 1-2 mm shards have albitized margins (dark gray) and chlorite cores, light gray and some are monomineralic with chlorite, sample AV-284, station 274.
- e) Back scattered image of albitized contact unit, Dowling member, Morgan Township. Variable distribution of alteration minerals in the shards. sample AV-284, station 274.
- f) Back scattered image of Type 2 pervasive fracture-controlled albitization dated at 1848 Ma (Ames et al., 1998). Dark gray is albite (87%) and white anhedral domains Kfeldspar (13%).

PLATE CAPTIONS

Plate 4-8: Transition zone alteration

a) Polished slab of gossanous lower unit, Dowling member. Note white, devitrified margins to glass shards. Station 312, AV-410, Cow Lake. Scale 5 mm.

b) Polished slab of lower unit, Dowling member. Larger altered glass fragments (30%) are bluish white and strongly devitrified, finer shards are dominated by chlorite and/or feldspar. Weakly mineralized with chalcopyrite and pyrrhotite. AV-412, Cow Lake.

c) Polished slab of lower unit, Dowling member. Lapilli-sized fragment of flow banded andesite in lower part of photograph. Note bluish white altered vitric shards and fine lenticular chloritic (dark) shards. Chalcopyrite, sphalerite replace vitric fragments. AV-414, Station 318 Cow Lake.

d) Polished slab of gossanous lower unit, Dowling member. Note white, devitrified margins to glass shards. Pyrrhotite, pyrite (<1%), station 566, AV- 646, Simmons Lake area.

PLATE CAPTIONS

Plate 4-9: Textural features of regional calcite alteration zone

- a) Microphotograph of 1.2 mm calcite altered shard pseudomorphous after brown palagonite. Note the dark black to brownish material and white is calcite. The shard in the upper left corner has flow bands replaced by calcite. Lower unit, Dowling member, AV-412, station 312, Cow Lake area.
- b) Two mm shard with clear rim composed of feldspar and brown core calcite which likely replaced palagonite. Lower unit, Dowling member, AV-412m station 412, Cow Lake area.
- c) Epidote-chlorite shard with contained amygdale within calcite absent zone. Middle unit, Dowling member, AV-261, station 236, Morgan Township.

PLATE CAPTIONS

Plate 4-10: Outcrop and textural features of carbon

- a) Carbon-bearing equant shard lapillistone unit, Sandcherry member within 100 m of the granophyre contact. station 431, Joe Lake area.
- b) Polished slab of carbon-bearing, conductive equant shard unit as in a). Note alteration rims on fragments, sulphides and carbonaceous matrix. AV-539, station 433, Joe Lake area.
- c) Carbonaceous fragment (0.8 mm) from basement rocks within middle unit, Dowling member. station 272, Morgan Township.
- d) Carbonaceous lithic fragment (1.4 mm long) in the upper units, Dowling member. AV-318, Morgan Township.

Plate 4-11: Local epidote-pyrite alteration, Simmons Lake area.

Polished slab of pervasively epidotized contact unit, Dowling member. Rock is composed of predominantly epidote, pyrite and barian Kfeldspar. AV-647.

PLATE CAPTIONS

Plate 4-12: Features of local Kfeldspar-quartz-actinolite alteration

- a) Subvertical, north trending, Kfeldspar-quartz-amphibole vein crosses the contact between fluidal fragment unit and aphanitic dyke. station 416, Joe Lake area.
- b) Uncommon quartz-Kfeldspar patches in the Joe Lake area. Station 416.
- c) Hydrothermal breccia in basal intrusion with veins consisting of pink Kfeldspar-quartz-actinolite. Station 413, Joe Lake area.
- d) Polished slab of hydrothermal breccia displaying early bleaching and albitization of the basal intrusion cut by veinlets of Kfeldspar and quartz. Station 413, AV-515, Joe Lake area.
- e) Epidote veins with Kfeldspar-quartz halos cut the granophyre in the Joe Lake area. Station 436.

Plate 4-13: Textures of hydrothermal breccia, back scattered electron images.

Mineralogical changes from A)less altered Basal intrusion to (B) bleached Basal intrusion to the (C) vein core

Chapter 5

BASE METAL MINERALIZATION AND ASSOCIATED DISCORDANT ALTERATION

5.1 Introduction

The purpose of the field, petrographic and mineralogical study of the sulphide occurrences and deposits in the basin is to determine the controls on mineralization and compare and contrast the mineralizing fluids with fluids responsible for regional semi-conformable alteration within the Onaping footwall rocks. Zn-Cu-Pb mineralization occurs at intra-Onaping showings generally situated in the lower units and at the base of the middle units in the Dowling Member, and as deposits at the top of the Onaping Formation, hosted dominantly by the Vermilion Formation (Figures 5-1, 1-2). The Errington and Vermilion massive sulphide deposits comprise an 8.7 Mt reserve within multiple sulphide lenses at the top of the Onaping Formation and within carbonates of the Vermilion Formation in the southwestern part of the Sudbury Basin (Figure 5-1; Plate 5-1). The production and reserve history of the deposits are summarized in Table 5-1. An historical account of exploration within the Whitewater Group, including the Errington and Vermilion mines, was compiled by Ames (Ames et al., 1997).

The stratigraphic, alteration and structural setting of the intra-Onaping mineralization was defined through mapping of the Limerick, Ryan, Cow, McNunes and Simmons showings (Figures 5-1, 5-2: Maps 1B, 4B, 5B). The Vermilion deposit, LW

showing (Gray, 1995) and the Errington deposit (Paakki, 1992) were mapped by Falconbridge Ltd. staff. Knowledge of the proximal alteration and mineralization in the Errington deposit was enhanced through a detailed mineralogical study of samples collected from Falconbridge's metallurgical drillholes that penetrated the orebody.

5-2. Intra-Onaping Formation base metal showings

Base metal showings within the Onaping Formation occur as replacement of lapillistone beds and fragments, sulphide veins, stringer zones, disseminations and sulphide fragments and are most abundant in the carbonaceous upper Onaping Formation (Muir, 1980; Rousell, 1984b, c; Gibbins et al., 1992; Ames, 1997). Significant North Range showings occur at 1) Simmons (Map 5B) 2) Limerick (Map 1B); 3) Ryan, (Figure 5-2); 4) Cow Lake (Map 4B); and 5) McNunes showing (Map 4B). Two of these showings were drilled. At Limerick, 11 drill holes totaling 2162 m (INCO, 1953) intersected stockwork veins and disseminated base metal mineralization with narrow <1 m intersections at 7.83 % Cu, 2.68 % Zn, 0.43 % Pb, 0.02 % Ni, and 0.06% Cu, 14.47 % Zn, 0.32 % Pb and 0.14 % Ni (DDH IN-10671 in Gibbins et al., 1992). In 1988/9, Falconbridge Ltd. drilled the Cow Lake showing (DO45-1) (Gibbins et al., 1989). Characteristics of the base metal showings are listed in Table 5-2.

5-2a. Geologic controls

Important controls on the base metal showings are syndepositional faults (i.e., those synchronous with deposition of the Onaping Formation) and paleotopographic highs

in the footwall Sandcherry member units. These are classic controlling factors for the localization of more typical VMS deposits (Franklin, 1986). Both the NE and NW orientations of syndepositional faults (see Section 2.4d) in the Onaping Formation focus hydrothermal fluid flow.

The Limerick occurrence overlies a 020° syndepositional fault structure (“Limerick fault”) which is the locus for magmatism (units 8 and 9) and mineralizing fluids. This zone contains anomalous disseminated chalcopyrite, pyrrhotite and lesser sphalerite and calcite (Map 1B). In the immediate footwall of the Limerick showing, aphanitic dykes and pods are coarsely spherulitic and have peperitic contacts. Peperite suggests that the magma was emplaced into wet strata at shallow levels.

Similarly, the Ryan mineralization is situated above a paleotopographic high and fault (Figure 5-2). The McNunes showing is along strike of a 295° trending syndepositional fault that is responsible for a complex geometry between units due to apparent sinistral movement. Small pods of basal intrusion (Unit 9) are aligned along this trend, as well as a steeply east dipping flow banded aphanitic dyke (Unit 8). Amygdales in small pods of basal intrusion are filled with pyrrhotite, chalcopyrite and calcite. The 295° syndepositional fault is likely part of the larger 340° Gibson fault system described by Gibbins et al. (1989). The control on sites of mineralization by paleotopographic highs in the Sandcherry member, syndepositional faulting, intrusions and regional alteration are not apparent for the Cow Lake showing and are unknown for the Simmons showing owing to lack of mapping.

5-2b. Relationship to regional alteration zones

The major intra-Onaping Formation base metal showings occur at or near the base of the regional semi-conformable calcite zone within carbonaceous strata in localized calcite-absent zones. Insignificant mineralization occurs in the basal silicification zone near the granophyre contact. Showings within the regional semi-conformable calcite zone form localized calcite-absent pockets and discordant corridors as carbonate-sulphide veinlets or replacement zones (Ryan, McNunes, eastern Morgan Township), (Figure 5-2; Maps 4B, 1B). Near the Limerick and Simmons showings, the base of the semi-conformable alteration zone is deeper in the stratigraphy around the calcite-absent showings (Maps 1B, 5B).

The Simmons area hosts several mineralization styles (Map 5B). These include galena-sphalerite-chalcopyrite veins, disseminated pyrrhotite-sphalerite-chalcopyrite and epidote-pyrite (Section 4-3a). The galena veins in the Simmons area differ from the other showings in that they are solid sulphide veins whose presence does not disrupt the regional semi-conformable calcite zone. In contrast the disseminated mineralization occurs in a local calcite absent zone and is spatially associated with intrusive activity (Unit 9b). A magnetic mafic dyke also occurs in this area. The Simmons area likely has multiple generations of mineralization and magmatic activity.

5-2c. Mineralization and alteration

The mineralization in the Onaping Formation is dominated by sphalerite, chalcopyrite, pyrrhotite, minor galena, arsenopyrite and later pyrite and anglesite, and alteration

minerals include, calcite, ankerite, siderite and trace Fe- or Mg- chlorite, muscovite, barian Kfeldspar and epidote (Table 5-3). Sphalerite contains 6-14 mole % FeS (Figure 5-3) suggesting that the hydrothermal fluids were buffered close to the pyrite-pyrrhotite fO_2 condition (Hannington et al., 1995). Secondary pyrite replaces pyrrhotite and is nickeliferous (Table 5-3), a feature also observed by Desborough and Larson (1970).

Barium anomalies associated with some intra-Onaping base metal occurrences and the Errington and Vermilion Mines (Rousell, 1984c; Paakki, 1992; Gray, 1995; Gibbins, 1994) are due to the presence of barian Kfeldspar and phengite in mineralized veinlets, ore gangue and proximal alteration haloes (Tables 5-3; Figures 4-6, 4-15). Muscovite, spatially restricted to veins and immediate wallrocks is phengitic, and is the most Mg-rich observed in the Onaping Formation (Figure 4-15, 16). Chlorite associated with pyrrhotite and/or muscovite in the Limerick stringer and in lobes of spherulitic andesite in the footwall is generally more Mg-rich than the background chlorite of unmineralized Middle units (Figure 4-3). A second phase of chlorite spatially associated with ankerite and chalcopyrite is Fe-rich and similar to chlorite in chalcopyrite-rich veinlets in the Errington deposit (Figure 4-3). Carbonate restricted to stringers in the Limerick showing consists of calcite, dolomite and siderite (Figure 4-12). Sideritic brecciation infiltrates calcite-dolomite veins. Siderite is paragenetically late and forms thin rims on dolomitic carbonate, similar to that observed in the Errington deposit (Plate 5-1). Epidote is Fe-rich (>25 Fe/Fe+Al) and, as in the Simmons epidote-pyrite pod, represents the most Fe-rich epidote analyzed in the Onaping Formation (Figure 4-6a). High Fe^{3+} in epidote commonly reflects lower temperature, oxidized conditions of formation (Liou, 1981).

5-2d. Mass balance calculations for mineralized showings

The Ryan and Limerick alteration show similar relative mass changes. Chemical changes relative to the least altered Onaping Formation are manifested by the significant addition of Cu, Pb, S, Fe, Mn, variable Zn and losses of Ca, Rb, Sr, H₂O and Cr (Appendix 4-1). The McNunes showings show similar gains and losses except that Zn is gained and Cu shows only negligible change.

5-3. Errington and Vermilion Zn-Cu-Pb Deposits:

5-3a. Local geologic setting

Metal deposition at the Errington-Vermilion deposits is largely within the carbonates of the Vermilion Formation associated with a footwall sequence of hydrothermally altered Onaping Formation and hangingwall carbonaceous argillites of the Onwatin (Martin, 1957; Paakki 1992; Gray, 1995). The origin of the massive sulphide deposits has been ascribed to syn-tectonic replacement or syngenetic exhalation (Card and Hutchinson, 1972; Whitehead et al., 1990; Rousell, 1984) and as the sub-seafloor replacement of a carbonate host - the currently favoured model (Martin, 1957; Paakki, 1992; Gray et al., 1992; Gibson et al., 1996).

The Vermilion Formation consists of 1) The Lower Carbonate Member, subdivided into a proximal hydrothermal carbonate mound facies and a distal, finely laminated carbonate facies (Plate 5-1) the Grey Argillite Member composed of distal turbidites; and 3) the Upper Carbonate Member which contains vent specific,

concretionary carbonate units (Stoness, 1994; Gray, 1995). The carbonates have been interpreted as hot spring sinters (Martin, 1957; Card and Hutchinson, 1972; Whitehead et al., 1990; Gray and Gibson, 1993; Stoness, 1994) or products of clastic sedimentation (Arengi, 1977).

The Errington and Vermilion deposits are situated at the same stratigraphic level underlain by a laterally extensive sodium depletion zone extending over 10 km east of the Errington deposit and 5 km to the west of the Vermilion deposit (Figure 5-4). The deposits are characterized by a marked increase in Ba, Si and Zn near the orebody and a zone of Mn depletion within the Vermilion Formation (Figure 5-4) (Paakki, 1992; Gray, 1995; Rogers, 1999). The Ca-Mg carbonate sinter vent complex grades laterally into Mn-Fe rich carbonates (Gray, 1995) interlaminated with albite, barian Kfeldspar, muscovite and quartz (Plate 5-1). Regional alteration haloes extend into the overlying Onwatin Formation to form a broad 25 km² target enriched in Zn, Cu, V, Cd, Ag and Ni (Rogers, 1995) (Figure 5-4). The Zn halo is more extensive than Cu, which forms discrete haloes in the hangingwall Onwatin Formation but the anomalous metal zones are less extensive in the host Vermilion Formation (Rogers, 1999).

The 2.44 Mt Vermilion deposit (Table 5-1) has a lower discordant chlorite alteration zone, an upper discordant silicification zone and a stratiform Ca-Mg carbonate sulphide-rich stockwork (Gray, 1995). The deposition and preservation of the carbonate host is attributed to boiling and precipitation in an alkaline anoxic basin and rapid burial by turbiditic sediments (Gray, 1995; Stoness, 1994). In contrast, the 4.36 Mt Errington deposit does not contain a chloritic footwall alteration zone (Figure 5-5; Paakki, 1992).

Paakki (1992) reported a siliceous cap rock beneath which metal-bearing hydrothermal fluids replaced the carbonate host rock. Deformation within the area of these deposits along the South Range is manifested by tight isoclinal folding and numerous axial planar and thrust faults. The ore lenses occur within tight inclined and locally overturned folds. The deposits are deformed and occur within 3 parallel anticlines with the ore concentrated in the crest of each anticline (Figure 5-6).

Mineralization and alteration characteristics of the Errington deposit were determined by systematic sampling of two metallurgical holes of Falconbridge Ltd. that penetrated the orebody (Figure 5-6, 5-7). DDH E79-7 penetrated the Rheume No. 1 orebody described by Martin (1956). The carbonate mineralogy was assessed by a combination of staining of drillcore (Evamy and Shearer, 1962), microprobe analyses and SEM observations. Mineral analyses are compiled in Appendix 4-2.

5-3b. Errington deposit mineralogy and mineral chemistry

The Errington deposit includes from base to top: 1) the conductive andesite tuff in the footwall Onaping Formation; 2) massive basal pyrite zone (basal pyrite zone) of the Onaping Formation; 3) carbonate-hosted mineralization, the main ore zone hosted by the Lower Carbonate Member, Vermilion Formation; 4) silicified “cherty” zones referred to as chert breccia at top of the orebody within the proximal facies of the Lower Carbonate Member (locally at the base) and 5) an upper pisolitic carbonate unit defining the Upper Carbonate Member, of the Vermilion Formation (Paakki, 1992; Stoness, 1994) (Figures 5-5, 5-7). Underground observations showed that pyrite comprises 30% of the ore at the

Errington deposit and that the massive pyrite has been replaced by chalcopyrite-pyrrhotite (Martin, 1957). Vuggy ore in the cherty breccia occurs as irregular replacement masses at the edge of the orebodies in both the Vermilion and Errington deposits. Gray (1995) also documented spectacular open-space filling textures with sparry dolomite. Some of the carbonate is interpreted to be of hot spring origin while some is epigenetic (Martin, 1957).

The deposit is mineralogically simple, containing pyrite, chalcopyrite, sphalerite, galena, marcasite, pyrrhotite and arsenopyrite with only trace amounts of freibergite and argentite. The Errington gangue is dominated by various types and generations of Fe-Mg-Mn-Ca carbonate, quartz, hyalophane, celsian, barian muscovite, pyrobitumen and traces of barian stilpnomelane and rare Fe-chlorite (Table 5-4). Carbonates are dominantly ankerite, dolomite and late siderite at the base of the deposit, but calcite dominates in the carbonate-hosted mineralization. Barium within the Errington deposit is distributed between feldspar and muscovite in the Basal Pyrite Zone, Onaping Formation, in muscovite in the lower part of the carbonate hosted mineralization of the Lower Carbonate Member, Vermilion Formation and in minor amounts within stilpnomelane in the upper part of the orebody (Figures 4-6, 4-16). Ba-feldspar is also locally present at the top of the deposit in the silicified upper part of the Errington orebody.

Basal Pyrite Zone, Onaping Formation:

The basal pyrite zone replaces the top of the Onaping Formation and comprises the lowermost 2.5-6 m of the massive sulphide deposit which averages 2% Cu, 1.34% Zn and 0.31 % Pb (Paakki, 1992). The lower contact of the basal pyrite zone is defined by a

marked increase in the abundance of 5 mm spherical pyrite grains, up to 70%. The basal pyrite zone is characterized by the assemblage, pyrite, sphalerite, quartz, ankerite-dolomite, Ba-Kfeldspar, chalcopryrite, Ba-muscovite (phengite), arsenopyrite and galena, and a later stage of calcite, ankerite and euhedral pyrite (Table 5-4; Figures 5-8 to 10).

The main sulphide precipitation stage is characterized by 500 μm spheres of pyrite-sphalerite-chalcopryrite-ankerite and a later crosscutting phase of Fe-rich chl-cpy-ankerite-siderite-pyrrhotite veins. Pyrite spheres are rimmed by ankerite and Fe-chl, and partially replaced by pyrrhotite (Plate 5-2) as described also by Martin, (1956), Paakki, (1992) and Rogers, (1999). Pyrite contains radiating laths of barian phengite, chalcopryrite sphalerite, and trace galena (Plate 5-2). Pyrite is rimmed and cored by quartz. Pyrite is associated with Cd-poor sphalerite with an FeS content between 10-12 mole percent (Figure 5-3, 5-8).

A late stage of euhedral pyrite are overgrowths on the earlier spherical pyrite-ankerite-barian Kfeldspar assemblage. Ankerite with distinctive growth zones forms the matrix to fine pyrite grains. Calcite-ankerite-chalcopryrite-quartz-galena assemblages also occur in pressure shadows around the pyrite and were therefore remobilized synkinematically. Late calcite-pyrite veins also cut the main basal pyrite zone assemblage.

Ankerite is the dominant carbonate in the basal pyrite zone coeval with sulphide deposition (Figure 4-12). Minor calcite is late and overprinting. Fine compositional zones in ankerite are controlled by the symmetry of the crystals. These growth zones are characterized by differences in the Fe/Mg ratio of the carbonates (Plate 5-2, Figure 5-9, Figure 4-12; Appendix 4-2).

Barian Kfeldspar occurs as <300 μm , skeletal, anhedral grains associated with quartz in the matrix. Barium concentrations in Kfeldspar reach 38.1 wt. % but are generally < 18 wt % (Figure 4-6, Appendix 4-2). The analyses of the Ba-feldspars are very similar to that of cymrite (Table 5-5) a hydrous mineral, but powder XRD identified the feldspar in the basal pyrite zone as celsian.

The barium distribution in celsian is inhomogeneous and locally displays growth zoning characterized by variations in the Ba/K ratio (Plate 5-2). The dominant inclusions in the Ba-feldspars are quartz, Kfeldspar and minor pyrite-sphalerite-galena. Barian Kfeldspars are also overprinted by pyrite, Fe-chlorite, chalcopyrite and ankerite (Plate 5-2). The celsian is an early alteration phase that is overprinted by higher temperature assemblages.

Barian muscovite partially replaces celsian at the top of the Onaping Formation directly below the basal pyrite zone (plate 5-2). Less than 5% barian muscovite is finely disseminated as 5-200 μm blades in quartz in both the basal pyrite zone and the top of the Onaping Formation. The muscovite at the top of the Onaping Formation spans a range of Fe/Fe+Mg and Si/Al ratios, but is dominated by Ba-Mg-rich phengite with 0.36-1.4 wt. % F (Figure 4-15 and 4-16). In the basal pyrite zone, muscovite is dominantly barian muscovite with a broader range of Fe/Fe+Mg ratios and on average higher Fe content than those in the conductive unit in the immediate footwall (Figure 4-15 and 4-16).

Carbonate Hosted Mineralization, Lower Carbonate Member, Vermilion Formation:

The carbonate-hosted mineralization at the Errington deposit forms a zone with an apparent thickness of 35 m above the basal pyrite zone (Figure 5-7, 5 -5). Sphalerite, chalcopyrite and galena are the principal ore minerals associated with pyrite, along with accessory arsenopyrite, freibergite, argentite and pyrrhotite. Common gangue minerals are calcite, minor ankerite-dolomite and locally quartz, trace siderite, stilpnomelane and barian muscovite.

Red brown to orange sphalerite and chalcopyrite are the major sulphide phases. The compositional variation of the major elements, Zn and Fe, in sphalerite within a given sample equals that between samples (Appendix 4-2). Distinguishing features between samples are high Cd levels in the sphalerites near the top of the ore zone compared to those at the base and middle (Figure 5-8).

Chalcopyrite occurs as veins and pods in carbonate and is commonly associated with galena which occurs as inclusions in the chalcopyrite and as isolated grains. Carbon inclusions also occur within some chalcopyrite grains and along grain boundaries (Plate 5-3). Stilpnomelane may overgrow chalcopyrite. Compositional differences in chalcopyrite are confined to variations in Ag and As (Table 5-4; Appendix 4-2). Two samples show the beginning (E79-7-25) and progressive (E79-7-18) replacement of chalcopyrite by argentite, which is visible initially as bluish-red tarnish on chalcopyrite and finally resulting in black, porous aggregates of acicular argentite. Freibergite (a Ag-rich tetrahedrite: $\text{Ag}_5(\text{Cu Zn})_2(\text{Sb,As})_4\text{S}_3$) with up to 30 wt. % Ag and 25 wt. % Sb occurs as fairly large (<145 x 50 μm) grains associated with chalcopyrite, arsenopyrite, pyrite and galena near the top of the orebody, (E79-7-18; Plate 5-3). Locally within the freibergite grains are

patches with tiny 1-2 μm Ag-sulphides. These locally transect the freibergite-chalcopyrite grain boundary extending along fractures in the chalcopyrite. Freibergite contains inclusions of chalcopyrite and calcite.

Pyrite generally occurs as small, anhedral to euhedral grains associated with chalcopyrite and galena and has relatively constant compositions. Galena is a minor but common constituent throughout the carbonate zone (Figure 5-8).

The carbonate minerals display a complex paragenesis. Although the dominant carbonate by far is Mn-poor calcite, this has replaced an earlier phase of Mn-bearing ankerite (Figure 4-12 and 5-9). Less than 3% fine-grained, (<2 mm), ankerite-dolomite forms the matrix to 10 x 4 mm pyrite cubes. It is texturally inhomogeneous but without distinct cores or rims. Areas of oscillatory zoning range from almost dolomitic compositions to very Fe-rich ankerite (Plate 5-3; 79-1-17).

Two silicified zones near the top of the carbonate-hosted mineralization have a narrow zone of carbonate-hosted sulphide separating them (Figure 5-7, E7-16). This zone contains a complex mixture of 55% carbonate (dolomite-ankerite, siderite and calcite), 25% quartz, 15% muscovite and $<3\%$ sulphides (Plate 5-3). Siderite forms rims on the dolomite and locally on sulphides. There are at least 2 phases of calcite; one dominant phase that stains a deep mauve (Fe-rich) and a coarse grained deep red stained phase. Calcite forms the matrix to the sulphides and contains 15% fine, inhomogeneous siderite (Plate 5-3). Thus calcite is the latest carbonate phase overprinting dolomite-ankerite and siderite.

The pisolitic Upper Carbonate Member is composed dominantly of manganiferous siderite (Stoness, 1994) which stratigraphically overlies this zone. The deposit is generally zoned with respect to carbonates with an ankeritic base (basal pyrite zone), calcitic core (carbonate-hosted mineralization) and sideritic top (chert breccia and Upper Carbonate Member) (Figure 5-9).

Barian muscovite persists into the main zone of mineralization above the basal pyrite zone as subhedral to euhedral inclusions in massive chalcopyrite (Figure 4-15 and 4-16). It also occurs in the matrix at the top of the orebody where it comprises up to 15% of the calcite-quartz-dolomite matrix to minor disseminated sulphides. In the main part of the orebody, the Ba content of the muscovite is high and variable (3.74-6.86 wt%; Figure 4-16) locally with Ba-rich cores. These micas are phengitic, and compositionally form a tight cluster with relatively constant $\text{Fe}/\text{Fe}+\text{Mg}$ at ~ 0.32 (Figure 4-15). This zone of mineralization contains micas with the highest Ba and F contents in the crater-fill hydrothermal system with 0.74-1.48 wt% F (Figure 4-16).

Acicular, $<200\ \mu\text{m}$, yellowish-brown crystals of stilpnomelane were found as overgrowths on calcite and sphalerite and are intergrown with chalcopyrite and galena near the middle and top of the orebody (Plate 5-3). The chalcopyrite-stilpnomelane intergrowths are cut by euhedral pyrite of possible metamorphic origin. All stilpnomelanes analyzed have comparatively low K ($<2\ \text{wt.}\%$), Mg and relatively low Ba and F (0.27-0.63 wt.%) (Figure 5-10). Very rare pale green chlorite is Fe-rich (Figure 4-3).

Silicified zone, top of Lower Carbonate Member, Vermilion Formation

Silicification in the upper part of the Errington deposit has produced a cherty, sulfide carapace at the top of the deposit known as the “cherty breccia” (CBX; Paakki, 1992), (Figures 5-7, 5-5). It consists of a very fine matrix with subequal amounts of pyrite (with trace galena) and quartz that is cut by stringers, pods and veins. Fine (1-2 μm), euhedral to subhedral pyrite and trace galena occur in 10-20 μm aggregates in fine microcrystalline quartz (Plate 5-4). Galena occurs as generally $<10\ \mu\text{m}$ grains within pyrite and along pyrite grain boundaries. Veins are composed of pyrite, chalcopyrite, galena, arsenopyrite in calcite, siderite and stilpnomelane gangue.

Chalcopyrite occurs as 400 μm anhedral grains intergrown with galena and trace sphalerite and may contain inclusions of arsenopyrite, calcite, carbon, muscovite and quartz. Anhedral carbon inclusions are 130 μm . Pyrite, a dominant constituent, occurs as 20-30 μm euhedral crystals or ragged anhedral grains within the calcite-siderite gangue. Galena, a minor constituent, occurs as $<200\ \mu\text{m}$ grains typically associated with chalcopyrite. This galena has the highest Ag content (Figure 5-8). Se, in galena, is elevated relative to the underlying carbonate-hosted mineralization but lower than that in the basal pyrite zone (Figure 5-8). Sphalerite shows a decrease in the mole % of FeS in this upper zone as well as relatively high Cd levels (Figure 5-3, 5-8)

All of the carbonates in the silicified upper zone of the orebody are manganiferous in contrast to Mn-poor carbonates analyzed below this zone (Figure 5-9). The dominant carbonate is calcite. Calcite contains zoned manganoan ankerite with dolomitic cores and may contain subhedral to euhedral grains of inhomogeneous siderite (Plate 5-4). Chemical variations in the siderite are due to irregular patches with more MgO-rich portions.

Siderite also forms rims on sulphide minerals and locally contains inclusions of calcite, quartz and pyrite.

Stilpnomelane is associated with the Fe-rich minerals in the silicified zone such as sulfides and siderite and is locally hosted by calcite (Plate 5-4). It occurs as 100 μm randomly oriented to radiating aggregates of blades typically associated with galena in chalcopyrite grains. Trace amounts of barian Kfeldspar (4-6.9 wt% Ba) occur as inclusions in chalcopyrite. Trace barian phengite is also disseminated in the silicified cap rocks and has relatively high F and Ba contents (Figure 4-15, 4-16). The Si/Al ratios of the barian phengites are high and similar to those in the Azilda peperite and LW showings laterally distal to the deposits (Figure 4-15).

5-4. Discussion

5-4a. Implications of the assemblages and mineral compositions

Hydrothermal fluids are chemically buffered by fluid-rock reactions in the subsurface which control the pH and redox state of the fluid (Bowers et al., 1988). The elemental exchange between hydrothermal fluid and the vitric andesitic footwall strata of the Onaping Formation likely exerted a strong control on the exiting hydrothermal fluid and therefore the composition of the overlying water column similar to observed processes in modern seafloor studies (Edmond et al., 1979). The presence of, carbonaceous (<6 wt% Corg) sediments in the upper 10-50 m of the OF, carbonate mounds of the Vermilion Formation and carbonaceous argillites of the Onwatin Formation implies a restricted

anoxic basin environment (Rousell, 1984a, b; Whitehead et al., 1990, 1992). The presence of hydrocarbons in the ore may buffer the hydrothermal fluid to low fO_2 and thus should affect the resultant sulphide assemblage (Hannington et al., 1995; Ames et al., 1993).

Mineral assemblages in the Errington deposit are dominated by low temperature phases such as barian minerals, argentiferous tetrahedrite, galena and arsenopyrite (Barnes, 1979). In general, the deposit has a Ba-K-Zn-rich base and a Si-Ag-As-Sb-Cd-Pb-Mn -rich top (Figure 5-5). The upper zone of feldspathization at the top of the Onaping Formation contains Kfeldspar with minor albite overprinted by celsian, reflecting low-temperature seawater-rock reactions in the shallow sub-seafloor. The paragenetic sequence from Kfeldspar to barian Kfeldspar to celsian which is overprinted by muscovite and sulphides with decreasing distance from the ore deposit could suggest that the barian feldspars within the Basal pyrite zone and in the proximal footwall are a product of 1) diagenetic alteration which would be conformable or 2) a low temperature discordant alteration zone. The Kfeldspar alteration occurs in the footwall of the deposits and reaches up to 20-90 m into the stratigraphic hangingwall (Rogers, 1999). Diagenetic alteration zones would progress through the sediment column as strata accumulated forming broadly concordant zones, however the distribution of Kfeldspar at the top of the Onaping and in the Onwatin Formations, is difficult to ascertain due to lack of exposure. The presence of barian Kfeldspar spatially restricted to the intra-Onaping showings (i.e., Limerick Cu-Zn veins) lends credence to the latter hypothesis (#2). The barian Kfeldspars are likely cogenetic with deposition of the carbonate mound in focused discharge areas, whereas barian muscovites are related to the overprinting mineralizing stage.

The Ba-rich nature of proximal alteration is the direct result of the composition of the feldspathic footwall rocks, from which barium was leached during fluid-rock interaction (Von Damm et al., 1985; Scott et al., 1990). However, the preservation of barian Kfeldspar as early phases in the basal pyrite zone and in the siliceous cap rock at Errington, is compatible with low-temperature ($<200^{\circ}\text{C}$) deposition (Barnes, 1979). The Errington deposit lacks evidence of vigorous high temperature venting necessary to either 1) keep barium soluble in the hydrothermal fluid to be dispersed by a hydrothermal plume in the overlying water column or 2) to flush earlier deposited barium from the deposit during reworking. Late crosscutting pyrrhotite-chalcopyrite-Fe-rich chlorite assemblages, typical of relatively high temperatures are relatively rare. The transition from Ba-Kfeldspar to Ba-phengite only in the core of the deposit suggests local changes in pH and/or aK⁺ conditions (Barnes, 1979; Heald et al., 1987).

Barian Kfeldspar has been identified in VMS deposits but there has been little explanation of its origin (Rosebery and Que River deposits, Tasmania; Zaw et al., 1995; McGoldrick and Large, 1992; Tulks prospect, Nfld., Jambor and Barbour, 1986; McKenzie et al., 1993). At the Que River deposit, the barian (0.5-2 wt. % BaO) Kfeldspar is restricted to gold-rich zones and is interpreted to be hydrothermal and indicative of boiling (McGoldrick and Large, 1992). Celsian ($\text{Ba}_{0.75}\text{K}_{0.25}$) in the sphalerite-pyrite-galena ores in the felsic volcanic-hosted Rosebery deposit were used to suggest that replacement sulphides formed under neutral to slightly alkaline pH conditions (Zaw et al., 1995).

Diagenesis and/or regional metamorphism of a barite-rich unit are common origins reported for barian -feldspar and -muscovite (Pan and Fleet, 1991; Fortey and Beddoe-Stephens, 1982; Jiang et al., 1996; Willan, 1980; Coats et al., 1980; Chabu and Boulegue, 1992; Hendry, 1981). Barian feldspars (hyalophane-celsian) and barian phengite compositionally similar to those in the Errington deposit occur in carbonate-hosted Zn-Pb-Cu deposits in Zaire and Tasmania (Chabu and Boulegue, 1992; Zaw et al., 1995). In these studies, the replacement of barite is suggested as a possible origin for celsian supported by mineral textures; there is little evidence for a the diagenetic-metamorphic origin with a cymrite precursor. Nevertheless, possible barite pseudomorphs reported in the Errington deposit (Paakki, 1992) suggests that barite may have been present in the vicinity of the carbonate mounds. Celsian and pyrite could be produced during reduction of barite, which might explain the distribution of barian (Cn₈₅₋₈₇) feldspars at the base and top of the orebody associated with pyritic zones.

Sulphide mineral assemblages are sensitive to the redox (fO_2 , fS_2) and T conditions of the hydrothermal fluid (Barnes, 1972). The dominance of pyrite and the replacement of pyrrhotite by pyrite in the deposit, coupled with the pyrrhotite-pyrite transition 20 m below the Errington deposit (Figure 5-5) suggests that the fluid composition is buffered close to the pyrite-pyrrhotite boundary. The compositions of sphalerite range from 9-13 mole percent FeS in all deposits of the crater-fill sequence (Figure 5-3). Sphalerite compositions in a variety of modern seafloor deposits range from 0-55 mole percent FeS with low temperature assemblages (pyrite-marcasite-sphalerite-galena-arsenopyrite) commonly contain <10 mole percent FeS_{sph} and high temperature pyrite-chalcopyrite

assemblages with up to 35 mole % FeS_{sph} (Hannington et al., 1995). In contrast, very iron-rich sphalerite (up to 55 mole % FeS) is found in deposits in sedimented, carbonaceous environments compatible with the low $f\text{O}_2$ of the hydrothermal fluid (Ames et al., 1993; Koski et al., 1988; Peter and Scott, 1988).

In areas of hydrothermal activity in the Guaymas basin, Gulf of California there is <500 m of sediment cover with 4-3 wt. %, total organic carbon (TOC) (Peter and Scott, 1988), 450 m with 0.4 wt% TOC in Middle Valley sediments (Davis et al., 1992); 500 m with 0.4 wt% TOC in Escanaba Trough (Fouquet et al., 1998) whereas 1 km of the Onaping Formation has 0.47 wt.% TOC and 10-50 m at 6 wt% TOC immediately beneath the deposits. The influence of carbon on buffering the hydrothermal fluids at the Errington deposit was not as significant as that at modern sediment-hosted hydrothermal systems. Errington sphalerite compositions are comparable to the low temperature assemblages on the outer carapace of the Middle Valley chimneys (Ames et al., 1993). However, the pyrite-pyrrhotite-siderite assemblage is all indicative of relatively low $f\text{O}_2$ conditions for formation of the Errington deposit (Barnes, 1979).

Rapidly changing chemical conditions and disequilibrium textures are reflected by the mineralogically complex fine laminar textures in the Lower Carbonate Member, Fe/Mg/Ca zonation of carbonate and K/Ba growth zonation of barian feldspar. Reaction of acidic metal-bearing solutions with carbonates results in dissolution of the carbonate increasing the pore space for the low temperature, low $f\text{O}_2$ metal-rich fluids to deposit metals in response to the increased pH (Barnes 1979). During the formation of the main ore zone (carbonate-hosted mineralization), Mg is released during replacement of

dolomite by calcite, Kfeldspar is replaced by muscovite with the resulting mica assemblage becoming Mg and Ba -rich due to the release of elements during alteration.

The origin of the metal-bearing hydrothermal fluids can be fingerprinted using stable and radiogenic isotopes of hydrothermal minerals (Chapter 6); however, trace elements in mineral assemblages provide clues. Possible sources of F for the micas in the Errington deposit may include seawater (Von Damm, 1995) or a magmatic source. The rapid alteration of the fragmental vitric sequence may induce F adhesion onto clay surfaces. During subsequent hydrothermal alteration, F could be remobilized and redeposited at a fluid discharge site. The relationship of high F in micas from massive sulphides has been noted in Tasmania (Hendry, 1981) although there is no discussion of its possible source. F contents are also high in the overlying Onwatin Formation (Whitehead et al., 1992) suggesting a probable seawater source.

Textural and paragenetic observations are compatible with the proposed replacement origin of the Errington and Vermilion Zn-Cu-Pb deposits (Martin, 1957; Gray et al., 1992; 1995; Gibson et al., 1996). However, dolomite is replaced by calcite not vice versa as proposed earlier (Gray, 1995; Paakki, 1992). Early dolomite of the carbonate mounds is replaced by calcite-sphalerite-chalcopyrite-pyrite assemblages. The formation of phengite and celsian is compatible with replacement of Ba-Kfeldspar, similar to that suggested for carbonate-barite hosted VMS deposits in Australia (Hendry, 1981; Zaw et al., 1995). The sedimentary exhalative origin proposed for the Errington and Vermilion deposits (Whitehead et al., 1990; Davies et al., 1990) is inconsistent with the form and morphology of the deposits, the textures of the ore (no interlaminated carbonate and

sulphide, sulphide replaces laminated carbonate) and the SEDEX hypothesis is largely based on isotopic data. This aspect will be discussed further in Chapter 7.

5-4b. Relationship between the intra-Onaping showings and Errington-Vermilion deposits.

Controls on sites of mineralization: Characteristics of the two levels of mineralization in the Sudbury basin are summarized in Table 5-6. The significant intra-Onaping base metal showings are usually situated above basement highs in the Sandcherry member, are associated with syndepositional fault systems, and are close to the base of the regional calcite zone as stringer zones and replacement of coarse permeable units. The Simmons galena veins differ from the others in the lack of carbonate association, and have an epigenetic style of mineralization. Although most of the base metal showings are broadly coincident with the 1848 Ma hydrothermal system in the Onaping Formation some later mineralizing events have likely been superimposed on the Proterozoic event (Marshall et al., 1999).

Paleofaults on the South Range proximal to the ore deposits are evident from the linear distribution of peperite (Chapter 2; Appendix 2-5), the linearity of Lower Carbonate Member sites, and variations in the thickness of the Gray Argillite member of the Vermilion Formation (Stoness, 1994). The paleofaults may be related to possible sub-basins along the paleoseafloor.

The spatial association of peperite with the main ore zones in the SW Sudbury basin is not entirely fortuitous. Peperite in the footwall to ore deposits have been noted in

the Iberian Pyrite Belt and Guaymas Basin (Boulter, 1993; Gieskes et al., 1982). The intrusion of magma close to the paleoseafloor is known to trigger hydrothermal activity and displace large volumes of pore-water, super-heated seawater and hydrothermal fluids releasing hot fluids from deep reservoirs along fault systems to the paleoseafloor (Baker et al., 1987, 1989; Baker, 1994; Embley and Chadwick, 1994). The intrusive activity associated with peperite formation in the Onaping Formation is an unlikely heat source for productive hydrothermal convection, owing to the small volume of magma and shallow level of emplacement in the entire hydrothermal system. However, heat supplied by the melt could induce shallow lithification of the sediments and thus alter convective fluid flow patterns and focus fluid flow to the paleoseafloor and/or favourable traps in the subseafloor. Typically low temperature siliceous-carbon fluids ($<200^{\circ}\text{C}$) are expelled onto the seafloor due to shallow sill injection with the higher temperature systems resulting from a deeper level heat source (Gieskes et al., 1982). The higher temperature pyrrhotite-chalcopyrite-Fe-chlorite veinlets cutting the Errington deposits (Paakki, 1992; Gibson et al., 1996; this study) may be due to the release of deeper, hotter fluids.

Mineral assemblages: There are no major differences in mineral assemblages in the two levels of mineralization, except that the Intra-Onaping occurrences lie in the pyrrhotite field whereas the Errington and Vermilion deposits lie in the pyrite field. Trace amounts of cuprite, bornite, covellite, pentlandite, hematite, magnetite, native gold and silver have been reported in the Vermilion deposit along with distinct chlorite-rich discordant alteration (Gray, 1995). Textural, mineral chemical and paragenetic

observations are needed to explain the apparent differences in the alteration and sulphide assemblages between the Errington and Vermilion deposits.

5-4c. Relationship of mineralization with regional semi-conformable alteration zones

Field and petrographic observations clearly show that the intra-Onaping showings and ore deposits overprint the regional zone of carbonatization. The following features are significant. 1) the relatively late timing of the metal-bearing semi-conformable silicification overprinting the metal-leached regional zone of albitization, 2) discordant mineralized silicification zones cut the regional calcite alteration zone, 3) intra-Onaping base metal showings have local carbonate-absent zones indicating overprinting of the regional calcite alteration 4) significant base metal showings occur near the base of the regional calcite zone. The localization of metal deposition is closely linked with carbonate boundaries causing metal deposition.

The low temperature of the Zn-Pb-Cu mineralization is consistent with the relatively low temperature ($<260^{\circ}\text{C}$) regional hydrothermal system in the subsurface of these deposits.

Figure 5-1: Location map for Zn-Cu-Pb deposits and showings studied.

A) Western half of the Sudbury Structure indicating locations for the Vermilion-VD and Errington deposits-ED, LW showing and intra-Onaping Formation showings. SFC-Sandcherry Creek Fault, FLF-Flack Lake Fault, SRSZ-South Range shear zone. GF-Gibson's Fault. Inset shows location for Figure B.

B) Geologic setting of the Limerick, Ryan, Cow and McNunes Onaping showings. (compiled from Gibbins, 1994; this study).

Figure 5-2: A) Geological setting of the Ryan Zn-Cu showing, North Range, Sudbury Structure. The replacement mineralization is situated above a paleotopographic high in the Sandcherry member, within a local carbonate-absent area in the regional semi-conformable calcite zone. Sample locations AV-670-678. (modified, Gibbins et al., 1994). See Map 1 for legend. B) Polished slab of mineralization. Pyrite-pyrrhotite-chalcopyrite impregnated lapillistone, DMMU, Ryan showing.

Errington Zn-Cu-Pb deposit

- BPZ py-sph
- ORE py-sph-cpy-ga-fr

Zn-Cu-Pb Showings

- Simmons sph-po-ga-anglesite
- Limerick po-sph-cpy
- LW showing sph-py

Figure 5-3: Histogram of mole % FeS in sphalerite from the Errington deposit and intra-Onaping Zn-Cu-Pb showings, Sudbury Structure. The associated sulphide phases are noted. Symbols: sph, sphalerite, cpy, chalcopyrite, py, pyrite, po, pyrrhotite, ga, galena, fr, freibergite.

Figure 5-4: Distribution of regional semiconformable and deposit proximal, footwall alteration zones and metal enrichment halos in the hangingwall Onwatin Formation, South Range, Sudbury Structure. Vermilion deposit=VD, Errington deposit=ED. Zn anomaly in hangingwall Onwatin Formation, 1000 ppm increments from red >5000 to blue 1000-2000 ppm (Rogers, 1999). Data compiled from Rogers (1999); Paakki (1992); Gray (1995) and Falconbridge Ltd data.

Figure 5-5: Schematic diagram of the proximal alteration, sulphide mineralogy and trace element variations, Errington Zn-Cu-Pb deposit (modified from Paakki, 1992).

Figure 5-6: Geology and location map for metallurgical drillholes through the Errington deposit used in this study (highlighted). A) Surface projection of the Errington deposit projected to surface. B and C) Geologic cross-sections through the Errington deposit with locations of the two drillholes analyzed (compiled from Paakki, 1992).

Figure 5-7: Simplified geology logs of metallurgical holes E79-7, E79-1, through the Errington deposit, Sudbury Structure. Sample locations for this study are bold and those circled have isotopic data (Chapter 6), (geology compiled from Paakki, 1992).

Figure 5-8: Trace element profiles for galena and sphalerite through the Errington deposit., Composite section of E79-7 and E79-1. Se, Ag and Cd (wt%), Appendix 4-2 table 11.

Figure 5-9: MnO (wt. %) and carbonate distribution profiles through the Errington Deposit. Composite section of E79-7 and E79-1. Data in Appendix 4-2.

Figure 5-10: Major element and silicate mineral distribution through the Errington Deposit. Composite section of E79-7 and E79-1. Microprobe data, Appendix 4-2, wt%.

Table 5-1: Production and Reserve History of the Errington and Vermilion mines
(data from Martin, 1957; Young, 1996)

ERRINGTON MINE	TONS	Zn %	Cu %	Pb %	Au oz/t	Ag oz/t	
Production 1926-1931, tonnage through mill							
1926-1928	32,708	5.75	1.02	1.12	0.029	1.79	Treadwell Yukon Co. Ltd.
1928-1929	89,221	4.49	1.04	0.99	0.028	1.64	"
1929-1930	64,859	-	-	-	-	-	"
total tons 1	186,788	-	-	-	-	-	1= (Young, 1996)
total tons 2	186,172	4.60	1.07	1.10	0.030	1.70	2=(Martin, 1957)
Reserves							
1929	833,000	5.47	2.44	1.20	0.027	1.84	Sudbury Basin Mines Ltd.
1954	7,513,007	3.24	1.02	0.75	0.017	1.49	Consolidated Sudbury Basin Mines Lt
1957-Errington #2	10,432,477	3.82	1.10	0.97	0.021	1.58	Ontario Pyrites Co. Ltd.
1957-Errington #3	1,437,500	4.79	1.05	1.96	0.017	2.22	"
1991	6,900,000	4.21	1.22	1.09	-	-	Falconbridge Ltd.
VERMILION MINE							
1954	2,819,220	4.56	1.43	1.10	0.020	1.78	Consolidated Sudbury Basin Mines Lt
1957-Vermilion #4	5,077,779	3.92	1.26	0.97	0.025	1.40	Ontario Pyrites Co. Ltd.
1957-Vermilion North	862,500	3.73	0.34	1.30	0.020	1.64	"
1991	2,700,000	5.11	1.49	1.37	0.032	1.93	Falconbridge Ltd

Table 5-2: Summary of Base metal showings in the Onaping Formation

Showing	Location	Host unit	Style	Mineralization	Alteration
Simmons	NR SW Dowling T.	DM-Contact unit near sm/ dm contact (Map 5)	veins 5 veins in 2m 167o/80	ga-sph-cpy-po,py	regional: chl-cc
				py replaces po ga-cpy cores secondary anglesite sph (12-14 mole% FeS) (Fig. 5-3)	proximal: shards- alb-Ksp (70-80%) chl (15-20), pre-tnt. distal: (~10 m) alb-Ksp (50-60) act-Hb (30-40) cc, Mn-ilm, tnt cpy-ga in wallrocks
		DM-Lower unit -spatially with very amygdaloidal BI pods and dykes	disseminated gossans 20x40 cm stringers	sph-cpy-po	cc-absent local zones some silicification.
				cpy-py cut diss'd	
Limerick	NR Morgan T.	base of DM-middle units above topographic high and close to 020o syndepositional fault mineralized "fault" (Map 1)	stringer	cpy, po, sph vein gangue: barian-Ksp, quartz, muscovite, ankerite calcite, siderite (Plate 5-1) sph (10-13 mole% FeS) (Fig. 5-3) phengitic muscovite, low Ba and F (Figs. 4-15, 16) calcite, ankeritic dolomite and late siderite (Fig. 4-12;	Regional: calcite-absent zone at base of chl-cc 100x300 m gossan Mg-rich chlorite assoc. with po and/or muscovite (Fig. 4-3) Fe-rich chlorite associated with ankerite and cpy (Fig. 4-3) Fe-rich epidote (Fig. 4-5a) Muscovite: phengitic (Fig. 4-15) low Ba and F (Fig. 4-16)

Table 5-2: Summary of Base metal showings in the Onaping Formation (cont'd)

Showing	Location	Host unit	Style	Mineralization	Alteration
Ryan	NR SW Morgan T B4.	DM-Middle units above topographic high formed by proximal fluidal breccia complex along trajectory of 305o (Fig. 5-2)	replacement of lapillistone beds (Chubb, 1990)	po-py (2-15%) cpy (<3%), sph (<3%), tr. ga grab samples 6200 ppm Cu, 1900 ppm Pb, 3980ppm Zn (Gibbins and Nunes, 1989) Early po-red sph-cpy overprinted by py, marcasite, honey sphalerite. Second phase colloform textured fills open spaces with prehnite/epidote, tr. mica	In a 100 m2 calcite-absent zone 600 m above base of regional chl-cc zone. Relict shards are micro-spherulitic and/or chlorite altered.
Cow Lake	NR NE Dowling T.	DM-Middle units 500 m above SM-DM ct. (Map 4)	veins, gossans N-trending joint control (Map 4B) inset	Gossans: 10-20% po-cpy -sp-ga impregnated matrix and cut chloritic shards Po-cpy-ga calcite veins Secondary py rims po and is colloform in open spaces Tertiary, coarse py euhedra.	Local calcite absent zone within regional calcite-chlorite zone, veins are filled with calcite.
McNunes	NR NE Dowling T.	DM-Middle units 295o syndepositional fault control (see text for details) lithic-rich lapilli tuff.	gossans and replacement of coarser beds gossans 330o and 060o (Map 4B)	20% po-cpy-sph. 1.9%Zn and 0.2% Cu grab samples (Gibbins et al., 1989)	Localized calcite absent zone 20 x 60 m, 140 m above an offset base of the Regional chl- cc zone (Map 4B).

Table 5-3: Summary of the petrographic, textural and chemical features of minerals in the intra-Onaping Formation base metal occurrences.

Sample	DDH	Sulfides	Textures	Chemistry	Carbonates	Textures	Silicates	Textures	Chemistry
LW SHOWING-hosted in Upper units									
92LW-2	Stringer	Py, Cpy, Sph, Gal	cpy in sph, gal in py remobilized gal	low Cd-sph	Ank dlmt sid	granular, euhedral with galena	Musc		Ba (0.23-0.39) Mg (0.4)
92LW-3	Stringer	Py, Sph, Gal, Asp	Asp in sph or gal sph in gal, py-sph	low Cd-sph Ni-py, Ni, Se-asph	Ank-sid		Alb Ba-ksp Musc		Ba (1-1.6) Ba (0.24-0.72) Mg (0.9-1.4)
LIMERICK SHOWING -at the base of the middle units									
AV-LIMW	Stringer	Po, Py, Cpy, Sph	Sph in po, cpy in po	Mn-sph, low Cd	Sid Cc	rim sph, in vein, lathes in po large coarse in vein	Fe, Mg chl Fe-chl Ba-ksp Musc Ep	in musc or w po w ank / sid in po in vein w musc inclusion in ksp	ripidolite Ba (1.1-3.8) Ba (0.14-1.2) Mg (2.5-7)
SIMMONS SHOWING-at the base of the contact units									
AV-652	Vein	Po, Py, Gal, Sph, Cpy Anglesite	Po in py anglesite in galena Sph in gal, po in sph ga-po PbCo3 rims galena	Ni, Bi-py mod Cd-sph Bi-py	Anglesite Cd	secondary along fractures coarse with amph. needles	Alb		
AV-650	Alteration	Po, <<Py	Po rimmed by pyrite	Ni, Bi-po, Bi-py			Chl act-hb Ba-poor ksp Alb Mn-ilrn Tnt		pycnochlorite act-hb to magnesio-hb Ba (0.7) Mn (11.4-12) F
SIMMONS EPIDOTE-PYRITE ZONE-at contact unit/lower unit interface									
AV- 647	Alteration	Py					Chl Ba-ksp Tnt Epidote	in shards, py, ep-ksp matrix colloform in py in matrix with ksp	pycno-diaban Ba (0.6-5.5) F FeO (8.8-14.4)

Table 5-4: Summary of the petrographic, textural and chemical features of minerals in the Errington deposit.

Formation	Sample	DDH depth(m)	Sulfides	Textures	Chemistry	Carbonates	Textures
Vermilion Formation Top of ore between cherty breccia	E79-7-16 IK	89.49	Cpy, Sph, Gal, Py	Sph w cpy-ga-py euhedral py	Cd-sph Ag, Se galena As, <Ag-cpy	Cc-major Ank-dlmt	massive, coarse zoned Mn-ank w dlmt cores, dlmt relicts
Ore in cherty breccia	E79-7-17 IK	90.53	Cpy, Sph, Py, Gal	Sph w cpy-ga-py fgd py, rounded py	Cd-sph Ag-galena As-cpy	CC-sid	cc host to inhom sid grains, massive cc Mg-sid in siderite
Ore	E79-7-18	93.12	Cpy, Py, Gal, Sph Argentite, Freibergite Asp.	Sph in cpy, py in cpy argentite overgrows cpy cpy host of Arg and Frei Frei w cpy and py galena in fribergite	Cd-sph loss of Cu, gain Ag Co, As-py As, Ag-cpy Freib (<30%Ag, 25% Sb)	Cc	Massive
Ore	E79-7-25	101.96	Sph, Py, Cpy, Ag-cpy	Cpy rimmed by sph Sb in galena assoc. w Ag-cpy Ag-cpy in cpy w rim of sph	low Cd-sph Co-py Ag-cpy	Cc-all	Massive
Ore (near base)	E79-7-29	109.27	Py, Sph, Ga	Gal rims sph and contained within, euhedral py	low Cd-sph As-py	Cc	Massive, coarse
Onaping Formation BPZ (top)	E7-35		Sph, py, ga, cpy			Cc-all	
	E79-7-38	122.47	Py, sph, cpy, ga	late ga-cpy-ank vein		Ank	vein w ga-cpy vein cuts py and is cut by py in matrix-rhombs
BPZ	E79-7-39	124.24	Py, Sph, Cpy, Gal	Radiating py, contains sph and gal Cpy radial in pyrite sph-ga-qtz on outer rim py Late py euhedra Gal in fr'e xc py-sph	low Cd-sph	Ank	Cataclastic matrix w pyrite in pressure shadow w qtz contains inclusions of qtz In matrix w Ba-Mu and sph

Table 5-4: Summary of the petrographic, textural and chemical features of minerals in the Errington deposit.

Formation	Sample	Chemistry	Silicates	Textures	Chemistry
Vermilion Formation Top of ore between cherty breccia	E79-7-16 IK	Fe(3.7-22.4 %)	Stilpnomelane Musc, Qtz	host cpy Mn-ank	BaO (0.44-0.62), MgO (2.7-3.2) low K(1-1.2)
Ore in cherty breccia	E79-7-17 IK	Mn-cc Mn-sid Mg, Mn sid	Stilpnomelane Qtz Ba-Musc Chlorite trace Ba-ksp	host Qtz, cpy, sid in cpy w chl	BaO (.07-.27), MgO (2.2-3.3) K2O (.8-1.4) BaO (5), MgO(2.2-3.3), F(1.3) Ba (4.1-6.9), F
Ore	E79-7-18	Mn, Fe	Ba-Musc		
Ore	E79-7-25		Stilpnomelane	host sph, cpy, carb	BaO (.02-.40), MgO (1.7-1.8), low K (1.4-1.8)
Ore (near base)	E79-7-29 E7-35		 Ba-musc		
Onaping Formation BPZ (top)	E79-7-38	Mn-ank	Ba-ksp Ba-Musc	w py, matrix, contains py, ga in py	BaO(16.1-19.2) BaO (3.7-6.2) MgO (0.6-2)
BPZ	E79-7-39	Mn	Ba-ksp Ba-Musc	matrix inter w sph-py "-ga-ank in late py-epy, coarse in matrix Qtz/carb, w cataclastic pyrite in early sphere py	Ba O(12.6-16.1) BaO(3.2-6.1), MgO (0.8-13.7) F

Table 5-4: Summary of the petrographic, textural and chemical features of minerals in the Errington deposit

BPZ (base)	E79-7-41	128.41	Py Sph	pseudomorphous after fsp spheres contains fsp inclusions, Ba-Mu forms matrix to fsp spheres contains fsp inclusions (early)	Cc Ank-dlmt	Late, fg rd in pressure shadow Intergrown w Ba-Mu, ratty in pyrite, Early
UU	E79-7-45	133.65			Ank-dlmt Cc	rhombs in matrix skeletal grains in qtz vein w py-qtz-fchl-ser-fluorite
UU	E79-7-48	136.35				
Vermillion Formation Ore	E79-1-17	189.74	Cpy, Sph, Gal		low Cd-sph Ank-dlmt	inhomogeneous, subhedral
Onaping Formation BPZ (top)	E79-1-31	203.61			Ank	Matrix between py, adjacent to albite
BPZ (mid)	E79-1-33.6	205.59	Py, Cpy, Asp Po-cpy	Colloform py, contains asp and cpy, cpy in qtz adjacent to celsian Py composed of numerous tiny py spheres Pyrite cubes in celsian po relicts in later pyrite	Co,Cu,Se-Asp	
UU	E79-1-34	206.35	Py, Cpy, Sph, Gal, Po	Py partially replaces po Ga in py-sph cpy in Fe-chl stringer Py rimmed by ank/chl	Ni-po Ag-galena Ag-cpy Ank	Rim on py, w qtz, authigenic feldspar, rimmed by chl-ser

Table 5-4: Summary of the petrographic, textural and chemical features of minerals in the Errington deposit

BPZ (base)	E79-7-41	128.41 Mn	Ba-ksp	ass. sph, py in py, authigenic py replaces ksp in spherical py in cc, sph, py	BaO (6.5-13.9)
			Ba-Musc fluorite		BaO(2.3-4.9) Mg) (1-3.1), F
					Fe-rich
UU	E79-7-45	133.65 Mn	Ba-Musc Chl	in pelast, veins, w ksp coarse assoc. with qtz spheres	
UU	E79-7-48	136.35			
Vermilion Formation Ore	E79-1-17	189.74	Ba-musc	in sph, sulphides	BaO, MgO, F BaO (3.5-6.7) MgO (2.1-2.7) Fe-rich
			Chl	in sph	
Onaping Formation BPZ (top)	E79-1-31	203.61 Mn-ank			
BPZ (mid)	E79-1-33.6	205.59	Ba-ksp	in matrix, intergrown with py, authigenic. inclusions of cpy	Ba (14.3-38.1)
UU	E79-1-34	206.35 Mn	Ba-ksp Chl Vein	in matrix, spherical large grains composed of tiny spheres w cpy vein, inclusions in Ba-ksp Po-cpy xc late pyrite stage Fechl-ank-sid	Ba (2.2-38.1) Ba (1.4) Fe

Table 5-5: Comparison of cymrite composition with barian feldspars in the Errington deposit.

		Basal Pyrite Zone		Top of Onaping Formation	
	Cymrite (Hsu, 1994)	Average 1-33-6	Std Dev n=6	Average 1-34	Std Dev. n=3
SiO ₂	31.76	33.17	1.83	32.75	0.46
Al ₂ O ₃	26.77	25.21	0.53	24.17	2.314
SrO	0.03	0.01	0.03	0	0
BaO	37.44	36.68	0.99	35.17	4.77
K ₂ O	0.38	1.3	0.32	1.54	0.97
H ₂ O	3.67	3.3	0.4	5.96	5.54

Table 5-6: Mineralogical summary for mineralization in the Sudbury Basin.

ERRINGTON Zn-Cu-Pb DEPOSIT

A Carbonate-hosted mineralization

Pyrite	Ankerite-dolomite
Arsenopyrite	Siderite (replaces sulphide)
Argentite	Graphitic carbon
Galena	Muscovite (Ba)
Tetrahedrite (Freibergite; Native silver)	Stilpnomelane
Sphalerite (Low-Fe 9 mol%)	Calcite (170°C; Davies et al., 1990
Chalcopyrite	

B Basal Pyrite Zone

Pyrite	Ankerite-dolomite
Sphalerite (High-Fe 12mol%)	Ba-Kfeldspar
Chalcopyrite	(+- Phengite)
Pyrrhotite	(+- Chlorite [high Fe])
Galena	
Arsenopyrite	

INTRA-ONAPING MINERALIZATION

A Limerick Cu -Zn showing

Chalcopyrite	Ankerite-dolomite
Pyrrhotite	Siderite
Sphalerite (High Fe 13mol%)	Kfeldspar (Ba)
	Epidote
	Muscovite (Ba)

B Simmons Pb-Zn-Cu showing

Galena	Dolomite
Sphalerite (High Fe 14mol%)	

C LW showing

Arsenopyrite	Ankerite-siderite
Pyrite	
Sphalerite (Low Fe- 6mol%)	

PLATE CAPTIONS

Plate 5-1: Textural characteristics of carbonates in the Vermilion Formation and Limerick Cu-Zn showing. For sample locations refer to Figure 5-7.

- a) Back scattered image of vein carbonate from the Limerick Cu-Zn showing, Morgan Township. Note that siderite is a late phase and forms thin rims on ankerite. Sample AV-265.
- b) Vein carbonate associated with chalcopyrite-sphalerite stringers in the Limerick showing. Siderite (bright) is the latest phase after ankerite. Small bright areas in siderite are zincian. Sample AV-265.
- c) Back scattered image of carbonates from the distal lower carbonate member, Vermilion Formation, DO 3502, 250-251 m depth. Siderite (bright) forms rims on MnCa carbonate (medium gray) hosted by FeMn calcite in the matrix (light gray). Dark is ferroan dolomite. Note the consistent timing of siderite in the base metal showings and the Vermilion Formation.
- d) Polished slabs of the Lower Carbonate Member, Vermilion Formation. Left, distal LCM composed of alternating barian feldspar-quartz bands and Fe-Mn carbonates (AV-581). Centre, proximal LCM consisting of alternating pink bands of carbonates and white bands. Right sulphide mineralization partially replacing laminae of the proximal LCM; in mine terminology -carbonate-hosted mineralization.
- e) Polished slab of laminated carbonate-feldspar of the distal Lower Carbonate Member, Vermilion Formation. Gordon Lake Road, Vermilion Lake sample AV-581A.
- f) Outcrop photograph of silicified LCM or in mine terms the “cherty breccia”. Tourgney trench, South Range.

PLATE CAPTIONS

Plate 5-2: Back scattered images illustrating the textural characteristics of the basal pyrite zone, Errington deposit. For sample locations refer to Figure 5-7.

- a) Photomicrograph of barian muscovite lathes and chalcopyrite hosted within pyrite in the basal pyrite zone. Pyrite is x mm wide. Sample E79-7-39.
- b) Back scattered image of the core of microphotograph in a. Late pyrite forms overgrowth on barian muscovite-phengite laths. Carbonaceous matter is contained within the pyrite. Sample E79-7-39.
- c) Pyrite partially replaces pyrrhotite. Fe-rich chlorite forms the matrix to zoned ankerite and celsian in the uppermost Onaping Formation. Celsian partially replaces Kfeldspar which occur as relicts in celsian. Zoning in ankerite is due to variations in Fe:Mg ratios with the carbonate Fe-rich in contact with the pyrite. Sample E79-1-34.
- d) Alternating bands of arsenopyrite-galena with chalcopyrite (medium gray) in a matrix consisting of pyrite, ankerite and Ba-Kfeldspar. Middle basal pyrite zone, Sample E1-33.6.
- e) Fe-rich chlorite vein transects barian feldspars within the basal pyrite zone and is associated with chalcopyrite. Note the pyrite-pyrrhotite association (c) in the same section. Uppermost Onaping Formation, sample E79-1-34.
- f) Varying Fe:Mg ratios in ankerite-dolomite forms zoning in carbonates. Note the growth zones follow the grain boundaries of the pyrite grains. Middle basal pyrite zone, sample E1-33-6.
- g) Celsian with variations in brightness due to Ba:K. Celsian hosts minute grains of Kfeldspar and quartz and is hosted in quartz with minute lathes of barian muscovite. Top of the basal pyrite zone, sample E7-38.
- h) Skeletal ankerite hosted in a quartz-barian muscovite matrix. Outer margins of ankerite are the most Fe-rich. Uppermost Onaping Formation, sample E7-45.

PLATE CAPTIONS

Plate 5-3: Back scattered images illustrating the textural characteristics of the carbonate-hosted mineralization, Errington deposit. For sample locations refer to Figure 5-7.

- a) Inhomogeneous chalcopyrite with variations in the Fe:Cu ratio. Cu-rich areas are brighter than Fe-rich. Chalcopyrite is associated and contains black carbonaceous matter and is hosted in a complex mixture of calcite and dolomite-ankerite. Galena and stilpnomelane are hosted by the carbonates. Top of the carbonate hosted mineralization, sample E7-16.
- b) Freibergite, a Ag-rich tetrahedrite is associated with galena and arsenopyrite in chalcopyrite near the top of the orebody. The associated carbonate is calcite. Bright spots at the top of the right freibergite grain is fine native silver. Top of the carbonate hosted mineralization, sample E7-18.
- c) Fine growth zoning of ankerite-dolomite. The core is dolomitic whereas the brighter zones are more Fe-rich. Top of the carbonate-hosted mineralization E7-16.
- d) Matrix to the carbonate hosted mineralization. Euhedral to subhedral quartz and manganiferous calcite hosted in a fine matrix of ankerite-dolomite (55%), barian phengite (15%) and quartz (25%) with finely disseminated sulphide, dominantly chalcopyrite. Top of the carbonate hosted mineralization E7-16.
- e) Anhedral siderite hosted in manganiferous calcite near the top of the carbonate hosted mineralization, sample E7-18.
- f) Stilpnomelane lathes cut sphalerite, chalcopyrite and calcite, euhedral pyrite is late. Middle of carbonate hosted mineralization, sample E7-25

PLATE CAPTIONS

Plate 5-4: Back scattered images illustrating the textural characteristics of silicified zones, Cherty breccia, Errington deposit. For sample locations refer to Figure 5-7, all sample E7-17.

- a) The silicified lower carbonate member or “cherty breccia” consists dominantly of quartz and pyrite and has trace galena..
- b) Close up of image shown in a. The pyrite occurs as a series of 10-20 micron aggregates of 1-2 micron subhedral to euhedral grains. Galena (bright) is finely disseminated in the pyrite.
- c) Close up of the sulphidic part of a calcite-siderite-sulphide vein that cuts the silicified pyritic “cherty breccia”. The sulphides are dominated by chalcopyrite, galena and Cd-bearing sphalerite. This BSE image shows trace amounts of arsenopyrite and galena associated with pyrite euhedra.
- d) Stilpnomelane is associated with the sulphide veinlets that transect the silicified rocks.

Chapter 6

ALTERATION ISOTOPE GEOCHEMISTRY

6-1. Introduction

Stable isotope data of alteration minerals may provide information on possible source fluids, temperatures of formation and/or fluid chemistry with the quality of the interpretation strongly dependent on field, textural and paragenetic data. Previous stable isotope studies in the Sudbury basin focused on the carbon isotope values of the Onaping and Onwatin Formation carbonaceous matter (Heymann et al., 1997; Bunch et al., 1997; Avermann, 1994) and the O isotope values of alteration minerals in a drillhole 11 km east of the Errington deposit mineralization and Vermilion-Errington ore dump grab samples (Davies et al., 1990; Whitehead et al., 1990). Interpretation of the isotope data was predicated on a model of chaotic fallback breccia and wash-in theory for the emplacement of the Onaping Formation. Interpretation of published Rb-Sr and Sm-Nd isotope results are similarly model dependent and focus on the origin of the Sudbury Structure and SIC (Deutsch, 1989; 1994; Deutsch et al., 1995). This chapter describes a new well constrained alteration isotope study supported by new information on the stratigraphy, structure, regional and local alteration and ore deposits based on the field, petrographic and geochemical relationships documented in Chapters 2 to 5.

Oxygen isotope studies of synvolcanic base-metal producing hydrothermal systems have been used to map the paleohydrology and define alteration and isotherms in large subseafloor systems, thereby providing vectors to prospective high temperature fluid upflow zones (Cathles, 1993; Green et al., 1993; Munha et al., 1986; Paradis et al., 1993;

Hoy, 1993; Brauhart et al., 1998). The usefulness of the whole rock $\delta^{18}\text{O}$ technique to map paleohydrology in the Sudbury Structure crater-fill hydrothermal system was investigated.

The mineralogical nature of semi-conformable carbonate alteration zones in the footwall to VMS deposits have been used to distinguish a specific "type" of deposit, i.e.: the Mattabi-type shallow-water VMS deposits (Morton and Franklin, 1987). However, the ultimate source(s) of hydrothermal fluids (e.g., seawater versus mantle degassing) and processes responsible for VMS-related carbonate alteration are not well documented. A stable and radiogenic isotope study was initiated to identify the origin(s) and nature of the fluids responsible for carbonate precipitation in the Whitewater Group, specifically: 1) the district scale semiconformable calcite alteration zone in the Onaping Formation; 2) the Fe-Mg-Ca carbonates of the Vermilion Formation; 3) within a vertical section through the Rheaume #1 orebody (Martin, 1956), Errington Zn-Cu-Pb deposit; 4) in intra-Onaping Zn-Cu-Pb vein sulphide showings; 5) in alteration around peperite; and 6) within patchy carbonate in discordant zones through the Sandcherry member.

The origin of carbon in the Onaping and Vermilion Formation carbonates and its relationship to the regional carbonaceous carbon is examined. The carbon isotope signature of igneous (SIC/mantle degassing; $\delta^{13}\text{C} = -4.5$ to -8 ‰; Taylor, 1986) and reduced carbon in the Onaping Formation ($\delta^{13}\text{C} = -26.3$ to -39.9 ‰, averaging -31 ‰; Avermann, 1994; Heymann et al., 1997), are distinctive enough that the source of carbon for the regional scale carbonate alteration zone could perhaps be resolved.

6-2. Methods

Analytical techniques, sample descriptions and sample preparation are summarized in Appendix 6-1. Stable isotope ratios are reported in the usual per mil notation for $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$. Oxygen is normalized against SMOW (Standard Mean Ocean Water) and carbon is normalized against v-PDB. Whole rock $\delta^{18}\text{O}$ data and carbonate $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data are listed in Tables 6-1 and 6-2.

6-3. Whole rock oxygen isotope study

The preliminary oxygen isotope study investigated the value of whole rock $\delta^{18}\text{O}$ from regional and discordant alteration zones in the Onaping Formation (Table 6-1). In general terms, the whole rock $\delta^{18}\text{O}$ increases with stratigraphically higher alteration zones; however, this does not take into account differences in timing of the various zones. There is an overlap between the regional basal silicification, least altered Onaping Formation, discordant and regional albitization, transition zone, chlorite and calcite alteration (Figure 6-1).

The least altered Onaping Formation, represented by a proximal fluidal breccia (AV-233), has $\delta^{18}\text{O}$ values 0.7 to 0.9‰ lighter than the intense regional and discordant albite alteration. There are also subtle $\delta^{18}\text{O}$ differences between the regional albite zone and the overlying semi-conformable calcite zone (Figure 6-1). The discordant albitization dated precisely at $1848 \pm 3.4/-1.4$ Ma (Ames et al., 1998) has $\delta^{18}\text{O}$ similar to the regional syndepositional albite alteration.

The only major isotope differences are evident in the regional versus discordant silicification zones (Section 3-2b) with a maximum of 4.3 ‰ difference in values (Figure 6-1). The regional silicification zone ($\delta^{18}\text{O} = 6.9 \text{ ‰}$) are depleted in $^{18}\text{O}/^{16}\text{O}$ relative to the two discordant zones of silicification ($\delta^{18}\text{O}$ of 8.3 and 11‰) stratigraphically higher in the Dowling member (Map 1B). Occurrences of discordant silicification are very localized (<2-3 m) and although the $\delta^{18}\text{O}$ values are interesting, whole rock $\delta^{18}\text{O}$ mapping of the alteration system in the Onaping Formation would require much more data to determine the usefulness of using whole rock stable isotopes to distinguish upflow zones or help define paleo isotherms and alteration on the regional scale.

6-4. Carbon-oxygen isotope study of carbonate

Carbonate separates from 65 samples (23 whole rock, 42 mineral separates) from the Onaping and Vermilion Formations, were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (Table 6-2, Figures 6-2, to 4; Appendix 6-1). Carbonate-bearing samples from the well preserved North Range terrane, were selected to determine the isotope composition of, 1) the regional calcite alteration zone, 2) minor disseminated carbonate in the silicification, albitization and chloritization zones and 3) carbonate associated with Zn-Cu-Pb showings in the Onaping Formation. Sampling of the peperite- and massive sulphide ore -associated carbonates, and Vermilion Formation carbonates is restricted to the deformed and metamorphosed South Range terrane; however, there is strong geological control through detailed mapping, drillhole data and related information presented in Chapters 2 to 5 and appendices therein. Ore-related carbonates were sampled from metallurgical drillholes

E79-7 and E79-1 (Figure 5-7) providing vertical sections through the Errington #1 orebody.

6-4a: Stable isotope trends for carbonate in the Onaping Formation

Variation with stratigraphic height: In Morgan township, a trend to heavier $\delta^{18}\text{O}$ is evident with increasing distance above the SIC up to 1000 m, whereby the uppermost carbonates have $\delta^{18}\text{O}$ values similar to those at the base of Dowling member (Figure 6-3). The $\delta^{13}\text{C}$ values of carbonate in the basal silicification are slightly higher than that in the regional carbonate alteration zone and carbonate carbon in the basal intrusion is significantly lighter (Figure 6-3).

Variation with alteration type: The stable isotope values of calcite that pseudomorph vitric shards in the regional semi-conformable calcite alteration zone range from $\delta^{13}\text{C} = -9.3$ to -5.9 ‰, $\delta^{18}\text{O} = 9.6$ to 12.8 ‰ and average -6.9 , 10.5 ‰ respectively, forming a tight cluster (Figure 6-3). Vein calcite from the Limerick, Ryan and Cow lake Zn-Cu-Pb showings and Capreol vein alteration haloes also lie within or very close to this cluster, with the exception of one Cow Lake carbonate-sulphide vein sample. Calcite within the contact units proximal to the Simmons galena-sphalerite veins also lie within this cluster.

Late calcite microveinlets that cut the discordant zones of albitization in the Joe Lake area (ca. 1848 Ma), and carbonate patches in the basal silicification zone, are enriched in ^{13}C relative to the regional alteration (Figure 6-3). Calcite from patches within the Basal intrusion adjacent to the SIC in Morgan township have the lowest $\delta^{13}\text{C}$ values as

well as low $\delta^{18}\text{O}$. The lower units of the Dowling member typically contain no calcite; nonetheless in the Simmons area some calcite is present as a replacement of vitric shards. ($\delta^{13}\text{C} = -14, -15\text{‰}$, (Figure 6-3). In the Simmons locality, the black carbonaceous matter is remobilized along fractures (Chapter 4-2h).

Various carbonates from the upper units at the top of the Onaping Formation also have isotopically light carbon. These include samples located southeast of the Vermilion mine, dolomite lying 5 m below the Errington deposit and calcite in amygdales in the Azilda peperite (Table 6-2). Dolomite from the basal pyrite zone, which replaces the top of the Onaping Formation in the Errington deposit, is isotopically variable and may have strong ^{18}O -enrichment relative to the other carbonates (Figures 6-3 and 6-4).

6-4b: Isotope trends for carbonates in the Vermilion Formation and contained Zn-Cu-Pb Errington deposit.

Stable isotope ratios for carbonate from the Vermilion Formation have a large range (Figure 6-4). Calcite and siderite within the main ore zone ($\delta^{13}\text{C}$ at -3.8 to -4.6‰), have “normal” $\delta^{18}\text{O}$ values similar to the other calcite in the basin (Figures 6-4, 6-5). Dolomite in the orebody, in contrast, has high $\delta^{18}\text{O}$ with values greater than 20‰ . In the silicified cap to the orebody, calcite carbon is isotopically light, whereas both calcite and dolomite show ^{18}O -enrichment relative to the calcite in equilibrium with the ore fluids and the fluids responsible for regional calcite alteration (Figures 6-4, 6-5). Calcite in the Upper Carbonate Member above the silicified cap has $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope values similar to the regional semi-conformable calcite zone in the Onaping Formation (Figures 6-4, 6-5).

The finely banded LCM exposed on the Gordon Lake road is distal to any known mineralization. It consists of finely interlaminated albite-barric K-feldspar, quartz bands of light brown and darker bands of manganiferous ankerite-siderite and carbonaceous matter (Plate 5-1). These distal carbonates have high $\delta^{18}\text{O}$ and low $\delta^{13}\text{C}$ values (Figures 6-4,5). Similarly, finely laminated samples collected from dumps at the Errington and Vermilion mines show a range of isotope values for different carbonate bands within the same sample (Figures 6-4,5).

6-5. Radiogenic isotope study of carbonates.

Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were determined for 10 carbonate separates from the 1) regional semi-conformable calcite alteration zone, 2) carbonate alteration in footwall of the Gordon Lake road blocky peperite occurrence, 3) intra-Onaping carbonate-chalcopyrite-sphalerite $\pm$ galena veins, 4) carbonate-chalcopyrite-sphalerite-pyrrhotite filled amygdaloids, 5) carbonate associated with sulphide in the contact units and 6) the distal LCM, Vermilion Formation (Table 6-2; Table A6-1). These calcite separates have $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values that cluster with the regional calcite alteration values (Figures 6-3, 6-5). The Sr isotope study provides information for Sr isotope tracing for the fluid responsible for the regional calcite alteration zone (Fluid R). The Sr ratios of carbonates in the Sudbury Basin range between contemporaneous seawater values (0.7055; Veizer et al., 1992) and average continental crust (0.7170; Faure et al., 1963).

Onaping Formation: The regional calcite alteration zone is characterized by a Sr isotope ratio averaging 0.7139 and the peperite-associated carbonate at the Gordon Lake

road occurrence is similar. Calcite from the intra-Onaping Cow Lake and Limerick base metal occurrences is less radiogenic than the regional alteration zone. Similarly, Sr isotope ratios of calcite associated with sphalerite and chalcopyrite in a small intrusive body (basal intrusion) stratigraphically above the Cow Lake mineralized showing, and with chalcopyrite along the syn-depositional fault below the Limerick deposit, are less radiogenic. These samples all lie within discordant “mineralized” corridors in the Onaping Formation. Calcite from the Simmons galena showing differs from all other intra-Onaping occurrences, having a very radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7178 (Table 6-2).

Vermilion Formation: Carbonate from the distal LCM is more radiogenic than most carbonates in the Onaping Formation (Table 6-2).

6-6. Discussion

The stable isotope data of carbonates, silicification and albitization provide constraints on the origin of the alteration types. Interpretation of the isotope data is dependent on a strong understanding of the alteration distribution, paragenesis and relationship to stratigraphy as presented in Chapters 2 to 6.

6-6a. Fluid compositions

The C-O characteristics of fluids in equilibrium with various stages of calcite, dolomite and siderite in the Sudbury basin were determined (Table 6-3) using oxygen isotope fractionation equations for calcite-fluid (O’Neil et al., 1969), dolomite-fluid (Matthews and Katz, 1977) and siderite-fluid (Becker and Clayton, 1976) and temperature

estimates predominantly from fluid inclusion data of Sudbury basin carbonates (Davies et al., 1990). Fluid inclusion measurements were collected from a drillhole 11 km from known mineralization within calcite in the Upper units, Onaping Formation, the Vermilion Formation, the base of the Onwatin Formation and ore dump samples (Davies et al., 1990).

Changes in the $\delta^{13}\text{C}$ values may be due to variations in temperature, $f\text{O}_2$, pH and source. It is assumed that the carbonaceous matter present in the Onaping, Vermilion and Onwatin Formations buffers the $f\text{O}_2$ to a stable value, and in the ore fluid the pH would be buffered by dolomite from the Vermilion Formation. At temperatures less than $\sim 250^\circ\text{C}$, the $\delta^{13}\text{C}$ value of carbonate carbon can be used to estimate the source of carbon in the fluids (Ohmoto, 1986). Since, geologic and mineral chemical data from the carbonate bearing rocks in the Onaping Formation and ore deposits suggest that high temperatures ($>300^\circ\text{C}$) were not reached (Chapters 4 and 5), the measured carbonate carbon isotope values are valid for source and fluid considerations.

Variations in temperature with geologic setting of the carbonate in the alteration zones, orebodies, and veins change the $\delta^{18}\text{O}$ composition of the fluid in equilibrium with carbonate. Fluid inclusion temperatures of 100°C from veins in the Onaping Formation (Davies et al., 1990) were not used for calculation of fluid compositions in equilibrium with the regional or district-scale carbonate alteration due to the differences in texture and paragenesis (i.e., vein calcite versus glass replacement). The clustering of isotope values of the regionally disseminated calcite is compatible with a constant temperature of formation

(Figure 6-3, 5). For reasons outlined in section 4-2f on the regional semiconformable calcite alteration zone, a reasonable temperature range estimated for carbonate formation in this zone is between 100 to 180°C. This, coupled with Davies et al. (1990) fluid inclusion measurements of ore deposition at 170°C, led to the assumption of 100°C and 170°C to calculate a range of fluid isotope compositions in equilibrium with the regional calcite alteration. It is assumed that the focused ore fluids were hotter than the fluids responsible for the subsurface regional alteration zone ($\Delta^{18}\text{O}_{\text{calcite-fluid}} = -5.8\text{‰}$).

The fluid responsible for the regional semiconformable calcite alteration in the Onaping Formation has a calculated composition at 170°C of $\delta^{13}\text{C} = -7$, $\delta^{18}\text{O} = -0.5$ (Fluid R) (Figure 6-6). Vein calcite associated with the intra-Onaping Formation base metal showings and calcite in the peperite bodies is isotopically similar to the regional calcite. Calcite formed in equilibrium with Fluid R in a range of temperatures from 100 to 300°C evolve along a line with positive slope on the C-O plot (Figure 6-5). A comparison of this calculated line with the laminae from the proximal LCM (sample JA-JC) show that the latter is subparallel (Figure 6-5). This suggests that the proximal LCM, Vermilion Formation may have formed from calcite precipitated from Fluid R with fluctuations in temperature ranging from 100 to 225°C (Figure 6-5). Using this analogy, calcite from the UCM likely formed at ~170°C from the same fluid. Fluid R percolated through the upper half of the Onaping Formation forming the semiconformable alteration zone and locally breached the paleoseafloor along focused pathways to form proximal mounds of the Vermilion Formation. Dolomite from the distal LCM, Vermilion Formation has higher $\delta^{18}\text{O}$ and lower $\delta^{13}\text{C}$ than the proximal carbonates. This is consistent with lower

temperatures of formation and a larger contribution from an organic carbon source in the carbonatization process (Figure 6-5).

The influence of organic carbon in the system is evident for many carbonates in the Sudbury Basin including: 1) the localized Fe-Mg-Ca carbonate zones (Section 4-2f) at the top of the Onaping Formation within the upper units 2) the distal LCM on Gordon Lake Road, 3) the Basal pyrite zone and cherty breccia (silicified top) of the Errington deposit 4) the Simmons Pb-Zn showing 5) a Cow vein 6) calcite in proximal SMFL (Figure 6-5).

Calcite associated with mineralization was deposited from a fluid at 170°C (Davies et al., 1990) with an isotope signature of $\delta^{18}\text{O} = -1.7$, $\delta^{13}\text{C} = -4.3$ (fluid O) (Figure 6-6). The ore fluid (O) has a composition with lower ^{18}O and higher ^{13}C than Fluid R responsible for carbonates in the regional calcite zone, the LCM and UCM, peperites and most intra-Onaping showings. The ore fluid isotope composition is the same as that in calcite, associated with chalcopyrite and sphalerite in the basal silicification (section 4-2a) and in late microveinlets cutting the 1848 Ma albitization. Hydrothermal fluid compositions calculated from C-O isotope data of calcite in the Whitewater Group, differ from similar results from the Strathcona epidote zone and Fraser Cu-Ni deposits below the SIC (Farrow, 1994; Figure 6-5, 6-6).

6-6b. Sources of fluid responsible for carbonatization

Three main fluids are identified based on their stable isotope signature and can be characterized as, Fluid R- the regional calcite alteration fluid ($\delta^{18}\text{O} = -0.5$, $\delta^{13}\text{C} = -7$, $\text{Sr} = 0.714$), Fluid O- the ore fluid ($\delta^{18}\text{O} = -1.7$, $\delta^{13}\text{C} = -4.3$) and C- the fluid with an organic

carbon source ($\delta^{13}\text{C} < -11$) (Figure 6-6). The C-O-Sr values record different fluid source components.

Possible sources of carbonate carbon include any or all of:

- 1) impact-released CO_2 from carbonate target rocks (Bunch et al., 1997);
- 2) metamorphic decarbonation of local carbonate rocks;
- 3) oxidation of black carbonaceous matter in the Onaping Formation (Gray, 1995);
- 4) mantle- magma (SIC) degassing (Gray, 1995);
- 5) Early Proterozoic seawater (Davies et al., 1990; Whitehead et al., 1990);
- 6) later brines.

1) Impact-released CO_2 : Astroblemes that impacted into carbonate target rocks form 30% of earth's impact structures (Kieffer and Simonds, 1980) including such craters as Chicxulub (Hildebrand et al, 1991; Pope et al., 1991), Haughton (Martinez et al., 1994), and Popigai (Masaitis, 1994). Shatter cones are present in carbonates from the Haughton, Steinheim and Gosses Bluff craters (Robertson and Mason, 1975; Dietz, 1968). Preliminary studies on the importance of carbonate target rocks have focused on the isotope systematics and back-reactions (Boslough et al., 1982; Martinez et al., 1994), experimental, numerical and theoretical simulations of the volumes of CO_2 released into the atmosphere and pressure limits for complete decarbonation of carbonates (calcite, ~70 Gpa), (O'Keefe and Ahrens, 1989; Lange and Ahrens, 1986; Tyburczy and Ahrens, 1986; Ivanov et al., 1996), and shock experiments to identify the products lining the crater after impact (Bunch et al., 1997). Hypervelocity impact into dolomite produced a thin black

layer of graphite (Bunch et al., 1997); however, the fate of CO₂ is not discussed. The reactions of impact produced gases (Brett, 1992; Ivanov et al., 1996) with crystalline material in the plume and products deposited back in the crater requires investigation.

Experimental results from shock-induced (18 GPa) devolatilization of calcite demonstrate that there is no difference between carbon and oxygen isotope ratios from the shock-released CO₂ and the precursor calcite (Boslough et al., 1982). However, natural studies differ. Calcite is present in the matrix and in vesicle fillings along flow bands in the allochthonous polymict breccia at Haughton crater and is interpreted to be due to a large fraction of volatilized CO₂ that recombined to form secondary carbonates (Martinez et al., 1994). The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are higher in the shocked than unshocked carbonates and these natural studies of shock-induced devolatilization of carbonates result in the excursion of stable isotopes to higher values (+5 $\delta^{13}\text{C}$). Carbonates in the target rocks of the Sudbury Structure are heavier than the carbonate in the crater-fill sequence (Figure 6-5). This and the discordant distribution of calcite along faults and its transgressive nature show that impact-released CO₂ from target rocks is unlikely to be a source for carbonate carbon in the Sudbury Basin.

2) Metamorphic decarbonation: Natural studies of metamorphic decarbonation of marine carbonates result in a shift of $\delta^{13}\text{C}$ to higher values (0 to +5 ‰; Hoefs, 1997). The carbon in Proterozoic carbonates in the Sudbury area is isotopically heavier than that of the

Sudbury impact crater and therefore cannot account for the hydrothermal carbonate (Figure 6-5).

3) Organic source of carbon: The $\delta^{13}\text{C}$ -values of calcite, in equilibrium with the carbonaceous matter in the Onaping Formation ($\delta^{13}\text{C} \sim -30\text{‰}$; Avermann, 1994; Heymann et al., 1997), were calculated using the fractionation factors of Bottinga (1968) for temperatures between 100-300°C and range between -11 to -19‰ (Figure 6-5). At 170°C, the $\delta^{13}\text{C}$ -value of calcite in equilibrium with the Onaping Formation carbonaceous matter is -14.6 to -15.6 ‰.

The isotopic composition of carbonaceous matter in the Whitewater Group, as a source for carbonate-carbon is compatible with the stable isotope data of most dolomites and calcite in 1) the silicified cap (cherty breccia) in the Errington #1 deposit, 2) the Simmons showing area and 3) the Capreol actinolite-albite veins (Figure 6-5). Davies et al., (1990) proposed a Proterozoic seawater source for the distal Vermilion Formation carbonate; however, data presented here supports a different interpretation (Figure 6-6). The majority of dolomite has low $\delta^{13}\text{C}$ -values, particularly from the upper units of the Onaping Formation, the basal pyrite zone of the Errington deposit and the distal Vermilion Formation (AV-581) consistent with an organic source of carbonate-carbon.

On the other hand, the ore-bearing fluids and regional calcite alteration fluids generated isotope data that are inconsistent with derivation from reduced carbon in the Whitewater Group.

4) Mantle-magma (SIC) degassing and 5) Seawater source:

Data presented here for the carbonates in the Sudbury Basin are inconsistent with a single source from either magma degassing or seawater (Figure 6-6).

6) Late brines: Field and petrographic observations show that the calcite in the regional semiconformable calcite alteration zone formed early as the replacement of glass in the Dowling member. This is inconsistent with formation from late brines.

Fluid mixtures:

Fluid R is responsible for the regional semi-conformable calcite alteration zone, the proximal carbonate mounds in the Vermilion Formation, peperite-associated calcite and intra-Onaping Formation base metal associated vein calcite. Fluid O, the ore fluid, and Fluid R both have isotope signatures inconsistent with a single source of carbon derived from any of single possible source described above (Figure 6-5, 6). Davies et al., (1990) interpreted their $\delta^{18}\text{O}$ data for ore-forming fluid as a mixture of seawater and hot hydrothermal fluid (modified seawater). Data presented here supports the published interpretation for the generation of ore-forming fluid (O), but provides geologic and paragenetic constraints on ore carbonates and constrains the source of fluids for the regional semiconformable calcite alteration zone (R) (Figure 6-6).

Potential fluid sources for regional semiconformable calcite alteration zone. Fluid R for the regional calcite zone has a distinctly different isotope characteristics than the ore

forming fluid. C-O-Sr in peperite-associated calcite is similar to that in Fluid R which suggests that Fluid R was porewater and was present during peperite formation. The $\delta^{18}\text{O}$ carbonate (10.5 ‰) is greater than $\delta^{18}\text{O}$ whole rock of the least altered samples (7 ‰), (Figures 6-5, 6-1). Minerals formed by low temperature interaction are typically ^{18}O enriched with respect to their precursors (Muehlenbachs, 1987).

Fluid R has a $\delta^{13}\text{C}$ -value consistent with a contribution from a magmatic source (Figure 6-6). Seawater and magmatic fluids contain similar concentrations of oxygen but, the concentration of carbon is significantly less in seawater (Von Damm, 1990; de Ronde, 1995; Shanks et al., 1995). Mixing of these two fluids could result in a composition with $\delta^{18}\text{O}$ similar to seawater and $\delta^{13}\text{C}$ of magmatic fluids similar to composition R (Figure 6-6). Calcite replacement of glass suggests an early timing of carbonate precipitation in the Dowling member shortly after deposition of the mass flows of the middle units. This also occurred shortly before an active period of faulting and magma emplacement (aphanitic dykes into the lower and middle units). This active environment in the subaqueous crater is a likely scenario for seawater and magmatic fluid mixing.

The isotopic composition of carbon in Fluid R could also result from a mixture of oxidized carbon and seawater carbon, in an environment of broad scale convection of seawater into the carbonaceous Onaping Formation. The concentration of carbon in the Dowling member is low (0.40-0.47 wt. % Corg; Table 3-1) with an average $\delta^{13}\text{C}$ of -31 ‰ (Avermann, 1994). However, the regional extent of the calcite alteration and its near constant composition would imply that the two sources would have to mix in constant proportions around the entire circumference of the Sudbury Structure. A constant

water/rock ratio and temperature of reaction over a minimum of 60 x 1 km along the North Range, coupled with the presence of carbonate in carbon-absent rocks in the Onaping Formation, makes this scenario unlikely.

Potential fluid sources for ore carbonates: The isotope composition of the ore fluid (O) is intermediate between Proterozoic seawater and the “magmatic box” or the field of the Fluid R, illustrating a significant seawater component to the mineralizing fluids. Carbonate from the high temperature silicification zone at the base of the Onaping Formation adjacent to the granophyre of the SIC is also associated with sulphides such as chalcopyrite, pyrrhotite and sphalerite and has similar isotopic composition to the ore fluids in the Errington deposit. The late timing of the basal silicification zone relative to the regional albitization and the late timing of the mineralization relative to the deposition of the Vermilion Formation suggests that these fluids are related.

6-6c. Interpretation of Fluid evolution:

Isotopic data of carbonates in the Sudbury basin may be explained by various source mixtures including 1) seawater (Davies et al., 1990); 2) magma/SIC degassing (Card and Hutchinson, 1972), 3) organic carbon (Gray, 1995) and seawater modified through water/rock reactions. These complexities are amplified by multiple pulses of hydrothermal fluids; however, a repetitive paragenetic sequence of carbonates has been observed. Geologic and petrographic observations suggest that the fluid evolution responsible for carbonate deposition in the Onaping and Vermilion Formations progressed

from early seawater introduction into the Onaping Formation to low temperature water-rock interaction and subsequent development of pore and evolved ore fluids:

1) Fluid R, regional semiconformable carbonate alteration: Textural and paragenetic features including replacement of glass shards by calcite show that semiconformable calcite alteration was penecontemporaneous with deposition of the top of the Onaping Formation. Sr isotopes show that this fluid interacted with continental crust in the Sudbury area including possibly North Range Archean basement and Huronian strata present as lithic fragments in the Onaping Formation. Mariolitic cavities in the normal granophyre are filled with Kfeldspar and quartz (J. Cowan, pers comm., University of Western Australia) and mariolitic cavities are present locally in the Basal intrusion, Joe Lake area indicating local degassing. Variations in the composition of apatite have been attributed to degassing of the SIC (Warner et al., 1998).

Degassing of magmas below the Onaping Formation, perhaps seismically triggered, initiated percolation of magmatic volatiles through the fragmental water-soaked pile. Modification of the isotopic composition of the bicarbonate fluid due to mixing with seawater in porefluids during ascent is likely. Interaction of this bicarbonate fluid with the glass of the newly deposited middle units produced the regional semiconformable calcite alteration zone (Fluid R, Figure 6-6). The source(s) preferred is that of a magmatic fluid diluted by seawater resulting from CO₂ degassing from the SIC and reaction with calcic hydrothermal, seawater-dominated fluids in the Dowling Member.

2) Fluid R was focused to the paleoseafloor to deposit proximal mounds of the LCM, Vermilion Formation. Carbonate precipitated onto the paleoseafloor around warm

springs forming low mounds of the Vermilion Formation (i.e., the proximal Lower Carbonate Member) that are linearly distributed. Diffuse fluid flow and low temperature dispersal of hydrothermal plumes resulted in the deposition of the Fe-Mn-rich distal Lower Carbonate Member of the Vermilion Formation. Carbonate within the Upper units of the Onaping Formation and the distal LCM of the Vermilion Formation both show an organic signature for the carbonate carbon which is likely from the reduced carbon in the Whitewater Group (Figure 6-5).

3) This was followed by deposition of turbidites of the Gray Argillite Member and diffuse continued hydrothermal emissions deposited the Upper Carbonate Member local to vents. Carbonaceous argillites of Onwatin Formation were deposited likely due to deepening of the crater.

4) Fluids responsible for intra-Onaping base metal occurrences occur in mineralized corridors which overprint the regional semi-conformable calcite alteration zone. These carbonates have slightly lower $\delta^{13}\text{C}$ than the regional semiconformable alteration zone possibly indicating a minor organic component.

5) Errington #1 deposit: The composition of hydrothermal Fluid O is compatible with a mixed source with possible inputs from Proterozoic seawater, magmatic degassing of the SIC and hydrothermal fluid-seawater mixtures. The mineralizing fluids plot closest to Proterozoic seawater (Figure 6-6). The patchy carbonate in the basal silicification zone adjacent to the granophyre, as well as discordant calcite veinlets in the albitized zones, are isotopically similar to the ore-forming fluids.

The formation of the Basal Pyrite Zone results from a more vigorous introduction of a silica bearing hydrothermal fluid (organic contribution to carbon) precipitate silica forming the Cherty breccia. Ankerites in the Basal Pyrite Zone (BPZ) at the base of the orebody and silicified rocks ("cherty breccia, CBX) above the orebody, however, display a range of C-O values, but with typically low $\delta^{13}\text{C}$ indicating fluctuating conditions and imply an organic source for the carbonate carbon. The BPZ zone is overprinted by Fluid O which is distinctly different. Dolomite in the ore zone show variable isotopic compositions, some in equilibrium with a fluid with an organic source and others with higher carbon (closer to Fluid O). This supports field and petrographic observations showing consistent paragenetic sequences of ore carbonates replacing earlier dolomite of the LCM (Plate 5-1).

The $\delta^{13}\text{C}$ trend with time progressed from a high value at -7 per mil through deposition of subsequent units down to -15 per mil with deposition of the Onwatin Formation. The Sudbury crater deepened with time, likely due to tectonic subsidence, such that ensuing stratification and stagnation permitted the development of anoxic sediment conditions in Onwatin time (Rousell, 1984a, b; Whitehead et al., 1990). In the Sudbury crater shallow, low temperature hydrothermal activity was active. Faulting and intrusion of magma at relatively shallow levels also allowed the expulsion of pore water along faults to the paleoseafloor forming hot/warm springs. This was likely a protracted event operable during Onwatin time also. Evidence for this are hydrothermally altered peperite at various stratigraphic levels within the middle and upper units as well as the very top of the Onaping Formation (Azilda peperite), gabbroic dyke with peperitic

margins at the base of the Onwatin Formation (Stoness, 1994) and metal enriched halos in the Onwatin sediments (Rogers, 1999).

At depth in the Sudbury basin a deeper hydrothermal system was sustained by a relatively deep heat source, the SIC. During Onwatin time, the basal silicification zone was likely forming and faulting focused deep seated late mineralizing fluids near the surface and formed the replacement Errington and Vermilion deposits in buried carbonate mounds.

6-6d. Comparison of Sudbury Structure carbonate alteration with VMS-related and impact-related carbonate alteration

Carbonate halos on VMS deposits and in alteration pipes have been identified in Kuroko-type deposits, sediment-hosted modern deposits, Mattabi-type deposits and other early Proterozoic VMS camps (Morton and Franklin, 1987; Shikazono et al., 1998; Peter and Scott, 1991; Peter and Shanks, 1992; Goodfellow and Franklin, 1993; de Groot, 1993). Fe-Mg carbonates are usually close to or within the orebody whereas calcite is distal (Franklin et al., 1975; Shikazono et al., 1998), as is that observed in the Sudbury Basin. In the Hokuroku district, Japan, carbonates commonly occur in the argillaceous tuffs and dacite above the Kuroko ore as magnesite, dolomite, siderite and calcite. Carbonates formed at higher temperatures than those in the Sudbury Basin, 200-300°C, and are interpreted to have formed from mixing between hydrothermal solutions and biogenic marine carbonates by dissolution of the fossils and during cooling precipitated in the hangingwall sediments (Shikazono et al., 1998). These carbonates are post-ore and a

mineralogical and isotopic study of post-ore carbonates in the hangingwall Onwatin Formation in the Sudbury Basin would be useful. Shikazono et al. (1998) also note a positive correlation in the $Mg/Mg + Fe$ between chlorite and coexisting carbonate, similar to that observed at the Limerick showing and Errington deposit.

Stable isotope studies of carbonate alteration in the early Proterozoic, Bergslagen belt, Sweden show that non-skarn related regional carbonate alteration is of contemporaneous seawater origin (de Groot, 1993 and papers therein). The origin of carbonate carbon in modern sedimented rifts, such as Guaymas basin, Escanaba Trough and Middle Valley is oxidation of methane during fluid flow either, thermogenically within the sediment or biogenically at lower temperatures close to the seafloor (Stout and Campbell, 1983; Wehlan and Lupton, 1987; Peter and Scott, 1991; Goodfellow and Franklin, 1993). Typically, carbonate in these sedimented seafloor settings exhibit much more interaction with the carbonaceous sediments than that observed in the Sudbury Basin. In Guaymas basin, calcite occurs in the chimney structures as a consequence of mixing of equal amounts of oxidized organic matter in hydrothermal fluid and seawater at relatively high temperatures (213-339°C; Peter and Scott, 1991). However, a magmatic contribution to hydrothermal vent fluids from the sedimented Escanaba Trough has been proposed (Taylor, 1992).

Isotopic data of alteration minerals in impact craters is relatively scarce (Komor and Valley, 1990; Sturkell et al., 1998). Hydrothermal calcite in cavities from the subaqueously formed, 13.5 km diameter, Lockne crater, Sweden, is estimated to have formed at 210°C with a mixed source of carbon from seawater and organics. The trend is

an increasing seawater component with shallower depths (Sturkell et al., 1998). Most impact craters contain alteration minerals as cavity, vein and vug fillings (Allen et al., 1982; Masaytis and Naumov, 1993; Schuraytz et al., 1994; Englehardt, 1972; Newsom, 1980; McCarville and Crossey, 1996; Komor et al., 1988; Reimold et al., 1994) and not as pervasive replacement like that observed in the Sudbury Structure.

Regional alteration zones

Calcite alteration	Least altered
Transition alteration	Discordant
Chloritization	Peperite-associated
Albitization, weak, moderate, intense	
Silicification	actinolite mineral separate

Figure 6-1: Histogram of oxygen isotope data for alteration zones in the Onaping Formation. Whole rock ¹⁸O analyses and samples in Table 6-1. Average analyses for norite (N) and granophyre (G) from Ding and Schwarcz, 1983.

Figure 6-2: Variation of $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ in carbonate with stratigraphic height in the Onaping Formation and increasing distance from the SIC, Morgan township, Sudbury.

Figure 6-3: Stable isotopic trends for hydrothermal carbonate, Onaping Formation, Sudbury Structure. Data in Table 6-2.

Figure 6-4: Stable isotope data for carbonates from the Vermilion Formation and Zn-Cu-Pb deposits. Lines join analyses from the same sample. Brackets denote colour of layers with fine mixtures of carbonate. The dominant carbonate species is marked as defined through SEM observations. Refer to Table 6-2 for data and Figure 5-7 for sample locations in Errington drillholes.

Figure 6-5: C-O isotope data for carbonates in the Sudbury Basin compared with the fluid composition in equilibrium with the regional calcite alteration zone calculated at 170°C. Isotopic trend of calcite in equilibrium with the regional calcite fluid calculated at temperatures between 100 and 300°C. Fractionation factors used are O'Neil et al., 1969 and Bottinga, 1969. Dashed line represents calcite in equilibrium with the carbonaceous matter in the Onwatin Formation calculated at 170°C. Refer to Figures 6-3 and 6-4 for symbol legend of data from this study. Carbon isotopic data for carbonaceous matter in the Whitewater Group from Davies et al., 1990. Basement dolomites, Kona Formation, Gordon Lake Formation Bruce member of the Espanola Formation, Trout Lake Formation, data from Bekker pers. comm. Gunflint Formation (Carrigan and Cameron, 1991).

Figure 6-6: Calculated fluid compositions of bicarbonate-bearing fluid in equilibrium with carbonate in the Sudbury basin. Thick rim around symbol is the average fluid composition or a particular dataset. Data summarized in Table 6-3. ¹=Data from Whitehead et. al., 1990, and Davies et al., 1990. O=Ore fluid, R=regional semiconformable calcite alteration zone, I=Intra-Onaping Zn-Cu-Pb occurrences, PV=proximal Vermilion Formation, DV=distal Vermilion Formation.

Table 6-1: Whole rock 18O analyses for alteration, Onaping Formation

SAMPLE	AREA	UNIT	ALT.	COMMENTS	MINERALOGY	¹⁸ O (smow)
AV-157	A&M	DMMU	PS	Intense mixing zone	Qtz-plag-carbon	10.10
AV-171	MORG	SMEQ	RA-wk		cc-rt-chl Plag-qtz-act-chl-tnt	7.00
AV-182	MORG	SM	RS		Plag-qtz-amph-tnt	7.20
AV-194	MORG	SM	RS		<<pyx-tr. cc--po-cpy-sph Plag-qtz-ep-chl-ser/amph	6.7, 7.0
AV-201	MORG	SM	RS		<<sph-cc po-cpy qtz-amph-plag-chl-tnt-cc	6.70
AV-214A	MORG	DMMU	DS		** Qtz tr. carbon	12, 10
AV-230	MORG	DMCT	Chl-RA mod		Act-plag-qtz-tnt	6.30
AV-233	MORG	SMFL	Least		Plag-qtz-cz	7.00
AV-243	MORG	DMCT	Chl	Mid	tr. chl, tnt, sulphides Plag-act-qtz-chl-tnt	7.00
AV-252	MORG	DMMU	Tr	Base	** no surprises, trace carbon	7.60
AV-257	MORG	DMCT	DS	Limerick	qtz-plag-chl-tnt	8.30
AV-259	MORG	DMCT	CHL	Vapour phase	Qtz-fsp-chl-ep	8.70
AV-274	MORG	DMMU	CC	Mid	chl-cc	8.4, 7.8
AV-280	MORG	DMMU-U	CC	Top	Chl-qtz-plag	7.90
AV-485A	CAPR	VEIN	ACT		actinolite-only	5.8, 6.0
AV-488A	CAPR	SMEQ	DA-I		Qtz-fsp-act	7.30
AV-488B	CAPR	SMEQ	DA-Wk		qtz-fsp-chl-tnt	6.80
AV-502	JOE	BI	DA-I	Type 2	** plag-qtz-act	7.90
AV-503	JOE	BI	DA-Wk	Type 2-less	Plag-act-qtz	7.70
AV-507	JOE	SMFL	RA-I	Type 1	** Plag-qtz-amph-tnt	7.70
AV-532A	JOE	SMEQ	DA-mod	Type 2	Plag-act-qtz-chl-tnt	6.30
AV-533	JOE	SMEQ	DA-I	Type 2	Plag-qtz-ep-tnt	7.70
			(1848 Ma)		tr. hmnt-chl-sph-act	7.70
AV-565A	JOE	SMFL	RA-I	Type 1	Plag-qtz-act-tnt	7.70

Silicification- Regional (RS), Discordant (DS), Peperite-associated (PS)
Albitization -Regional (RA), Discordant (DA), Type 1 and 2 (Ames and Gibson, 1995).
Calcite-CC, Chlorite-Chl
Actinolite-ACT; Least altered, Transitional alteration (TR); I-intense, Wk-weak
SM-Sandcherry member, DM-Dowling member I-Intense, Weak-Wk

Table 6-2: Carbon and oxygen isotope data of carbonate,
a) Onaping Formation, b) Vermilion Formation and c) carbon
isotope data of organic carbon.

SAMPLE	Loc.	Host	Min.	$\delta^{13}\text{C}$ pdb	$\delta^{18}\text{O}$ sm	$^{87}\text{Sr}/^{86}\text{Sr}$
A) ONAPING FORMATION:						
SM- Basal silicification						
184	MORG	SMSR-BS	CC	-4.33	9.65	
208*	MORG	BI	CC	-20.15	7.51	
Albitization						
535	JOE	ALB	CC	-3.47	8.83	
534	JOE	SMSR	CC	-3.63	8.53	
527	JOE	SMFL	CC	-11.46	7.28	
DM- Chloritization, carbonate						
417*	COW	CT-carbon	CC	-7.42	8.89	
211*	MORG	CT	WR-CC	-8.83	10.43	
268*	MORG	CT	WR-CC	-8	8.36	0.71067
Regional semiconformable carbonate alteration						
296	MORG	DMMU	CC	-9.31	10.18	
307	MORG	DMMU	CC	-5.9	9.64	
212	MORG	MU	WR-CC	-7.8	11.18	
254	MORG	MU	CC	-6.67	9.93	0.71352
274	MORG	MU	CC	-3.69	12.76	0.71379
272	MORG	DMMU	CC	-7.33	10.19	
273	MORG	DMMU	CC	-6.56	10.39	
442	COW	DMMU	CC	-6.28	10.3	
440	COW	DMMU	CC	-6.68	11.49	
435*	COW	MU-MX	CC	-7.28	8.92	0.7145
576	GLRD	UMUU	CC	-13.91	10.59	
577	GLRD	UMUU	CC	-11.99	12.63	
318	MORG	DMUU	CC	-8.21	10.21	
451*	COW	NECK	CC	-8.77	8.66	0.70968
Peperite occurrences						
160B	A&M	LOBE	DLMT	-8.89	9.39	
153	AM	DMUU-SI	CC	-6.81	10.49	
149*	GLRD	PEP	CC	-7.64	9.06	
151*	GLRD	PEP	CC	-6.08	9.12	0.71324
683*	AZILDA	PEP	CC	-11.74	21.97	
Zn-Pb-Cu showings						
490A	CAP	VEIN	CC	-10.31	9.07	
433*	COW	CVN	CC	-7.46	10.01	0.71193
443*	COW	CVN	CC	-12.85	9.04	
429*	COW	CVN	CC	-7.32	11.02	

Table 6-2: (cont'd)

SAMPLE	Loc.	Host	Min.	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$^{87}\text{Sr}/^{86}\text{Sr}$
				pdv	sm	
425*	COW	CVN	CC	-4.94	10.39	
447*	COW	CVN	CC	-7.92	9.9	
265*	MORG	LVN	CC	-8.84	11.27	0.70759
672*	RYAN	RVN	CC	-7.12	10.97	
677	RYAN		CC	-3.65	12.4	
678	RYAN		CC	-6.5	10.87	
650	SIM	CT-MX	CC	-8.15	9.23	0.71777
635*	SIM	LU-MX	WR-CC	-14.21	9	
646	SIM	DMLU	CC	-14.53	9.94	
Ore deposit						
E79-7-44	Err	DMUU	DLMT	-11.66	16.57	
E79-1-30	Err	BPZ	ANK	-10.88	9.76	
E79-1-33.1	Err	DMUU	ANK	-7.49	21.84	
B) VERMILION FORMATION						
Errington mine						
EMDa	Err	LCM	DLMT	-4.37	14.49	
EMDb	Err	LCM	DLMT	-4.2	14.43	
EMDc	Err	LCM	CC	-6.52	15.89	
EMDd	Err	LCM	CC	-1.56	10.67	
E79-7-6	Err	UCM	CC	-6.78	10.04	
E79-7-12	Err	CHBX	DLMT	-7.63	12.83	
E79-7-14	Err	CHBX	CC	-12.81	10.71	
E79-7-17	Err	CHBX	CC	-23.24	14.64	
E79-7-19C	Err	ORE	CC	-3.92	9.67	
E79-7-19S	Err	ORE	SID	-3.82	11.13	
E79-7-22	Err	ORE	DLMT	-3.03	20.76	
E79-7-25	Err	ORE	CC	-4.58	9.6	
E79-7-29	Err	ORE	DLMT	-14.96	22.46	
E79-1-6	Err	CHBX	CC	-15.7	10.78	
Vermilion mine						
V1A	V.dump		DLMT	-7.66	20.34	
V1B*	V.dump		DLMT	-8.54	14.62	
V2*	V.dump		CC	-8.57	21.28	
JA*	V. mine	LCMP	DLMT	-3.48	12.97	
JB*	V. mine	LCMP	DLMT	-1.9	15.87	
JC*	V. mine	LCMP	CC	-7.07	8.54	
Distal LCM						
581A*	VRD	LCM	DLMT	-12.38	14.66	0.71657
581B	VRD	LCM	SD	-12.15	18.87	0.71657
581C*	VRD	LCM	DLMT	-17.29	18.99	

Table 6-2: (cont'd)

SAMPLE	Loc.	Host	Min.	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$^{87}\text{Sr}/^{86}\text{Sr}$
				pdv	sm	

C) Organic carbon

V-3	VERM	Ore	C-ORG	-30.19		
AV-ANTH	ANTHRAX	Onwatin	C-ORG	-31.38		

* duplicate (149 triplicate) analyses.

Table 6-3: Summary of fluid compositions calculated from carbonates
(Fluid temperatures based on fluid inclusion data in Davies et al., 1990).

	Calcite (T=170oC)		Dolomite (T=125oC)	
	O (smow)	C(pdb)	O (smow)	C(pdb)
Regional semiconformable calcite alteration				
	-0.5	-7		
Errington deposit				
UCM	-1.2	-6.8		
CBX	3.36	-23	-3.3	-7.6
	-0.6	-13		
	-0.5	-16		
ORE	-1.7	-4.3	5.53	-3, -15
BPZ			-6.3 to 5.8	-11 to -7.5
DMUU			0.49	-12
Dump samples-Errington and Vermilion mines				
Mine proximal LCM				
Group 1	4.61	-6.5	4.26	-7.7
Group 2	-0.6	-1.6	-0.2 to -3.1	-1.9 to -4.4
Distal LCM				
	-0.6		-1.4 to 2.9	-12 to -17
Vein carbonates-showings				
	-0.6	-4.9 to -10		
		avg. -8.3		
Peperite-associated				
Azilda-TOF			5.89	-12
GLRD-UU	-1.7	-6.85		
A&M-MU	-0.3	-6.8	-6.7	-8.9
Discordant associated with cpy-po				
Ct units	-1.6	-8.1		
Basal Silic.	-1.1	-4.3		
Discordant				
Joe Lk.	-2.2	-3.6		
SMFL-Morgan	-3.5	-11		

Chapter 7

SUMMARY AND CONCLUSIONS

Little has been written about water-rock interaction in the Sudbury Structure, except for the controversy between the role of magmatic versus hydrothermal processes of the world renowned Cu-Ni-PGE footwall deposits (Naldrett, 1986; Watkinson, 1990; 1994; Farrow and Watkinson, 1992; Farrow, 1994), despite the recognition of impact into water (Peredery and Morrison, 1984). In this chapter an empirical model is presented that explains the observations from this work in the Onaping Formation with implications for the evolution of the Sudbury Structure.

Three main points are emphasized 1) the emplacement of the Onaping Formation; 2) the timing and character of alteration zones in the upper hydrothermal system and 3) the relationship between regional alteration and impact-generated hydrothermal Zn-Cu-Pb mineralization. Figures 7-1 to 7-4 illustrate the sequence of events in the context of an impact crater in which a productive, major hydrothermal system in the highly permeable crater-fill deposits was initiated.

7-1. Model for the emplacement of the Onaping Formation

The evolution of the crater environment is revealed by the character and distribution of distinct depositional units that comprise the lower and upper parts of the Onaping Formation. The Onaping Formation formed first from debris fallback and crater collapse as a result of the initial meteorite impact on the Paleoproterozoic seafloor

(French, 1967; Peredery and Morrison, 1984). This was followed by a series of magmatic, seismic, erosional and hydrothermal events that shaped the late character of the formation.

7-1a. Stage 1: Emplacement of the lower Onaping Formation

The Sandcherry and Garson members that compose the lower Onaping Formation were deposited in an unstable tectonic environment. The Garson member formed during slumping immediately after meteorite impact, possibly from a quartzite-dominated (Huronian) peak ring or central peak structure. This was followed by the deposition of the Sandcherry member equant shard units. The origin of these laterally continuous, block and bomb-rich, non-bedded and vitric-rich strata is highly interpretive. Gibbins (1994) invokes an emplacement mechanism in which the equant shard units are lateral hyaloclastite facies to discrete, submarine andesitic vent (fluidal breccia) complexes. Equant shard units are deposited as a series of voluminous, subaqueous “pyroclastic” falls of slurry-like hyaloclastic flows (Gibbins, 1994; Gibson et al., 1994; Gibbins et al., 1997) equivalent to hyaloclastic mass flows on seamount summits described by Batiza et al. (1994). Meteorite impact fallback breccias are not present in the Onaping Formation according to this scenario (Gibbins, 1994). They were either eliminated by the intrusion of the Basal Intrusion or SIC, or for some reason were not deposited in the Sudbury basin (Gibbins, 1994).

Much of the field evidence suggests that the equant shard units were largely in place prior to intrusion of the fluidal breccia complexes. In an alternative model, the equant shard units represent a fallback-type impact breccia deposited into a subaqueous

impact crater. Melt in the ejecta curtain is predominantly quenched in the plume (Melosh, 1989) or fragmented upon deposition in water (Selivanovskaya, 1991). Liquid water in the plume environment (Schultz and Gault, 1979; Melosh, 1989) may play an important role in the development of small <1 cm equant shards observed in most impact craters. The blocky shard morphology so typical of subaqueous hyaloclastite deposits also forms from rapid fragmentation of the glassy melt rock generated by impact-induced crustal fusion and quenching and interaction with water in the plume (Kieffer and Simonds, 1980; Peredery and Morrison, 1984; Melosh, 1989). In a volcanic setting, the characteristic blocky, equant morphology of the vitric fragments (shards) in the laterally extensive equant shard units would be interpreted as the function of passive fragmentation (Gibbins, 1994; Wohletz, 1983; Kokelaar, 1986). However lapilli-sized equant shards are found as a component of suevite in many impact crater-fill sequences regardless of whether they are subaerial or subaqueous (Kara and Ust'-Kara craters, Mashchak, 1991; Selivanovskaya et al., 1991; and the Popigai crater, personal observations) (Figure 2-15). Water from the target (Peredery and Morrison, 1984) and that in the plume likely caused rapid alteration and fragmentation of the glass and lithification similar to the subaqueous Kara-Ust craters (Selivanovskaya et al., 1991).

The equant shard units would subsequently be injected by melt from below to form the intrusive/extrusive fluidal-breccia complexes. Facies distribution of fluidal fragment units and the relationship of dykes indicate that the fluidal breccia complexes were eruptive centres (Gibbins, 1994) but for only part of the Sandcherry member. Emplacement of the fluidal breccias and associated andesitic feeder dykes was controlled

by a set of NNW and NNE fractures (Figure 7-2), that when rotated relative to a paleohorizontal (Appendix 2-5) the paleofractures are north and northwest trending on the floor of the crater in “Sandcherry member” time. The floor-fractured Sudbury crater bears similarities to lunar craters and these extraterrestrial craters are better analogues for Sudbury than those reported on Earth. Hyaloclastite margins to dykes and lobate protrusions from dykes suggest that the fault set contained fluid during the extrusion of melt. The importance of these faults in localizing contemporaneous subseafloor hydrothermal activity is supported by the presence of altered bleached white bombs in proximal fluidal fragment units and dyke proximal alteration (Plate 4-4e).

7-1b. Stage 2: Emplacement of the upper Onaping Formation.

The Contact and Lower units that define the base of the Dowling member record a major period of crater wall instability that triggered the formation of mass flows. Dowling member units may be explained by seismically triggered phreatoplinian type eruptions outside of the Sudbury Basin (Figure 7-3). This was followed by subaqueous reworking of the upper parts of the Middle units (Figure 2-9) that ultimately formed the thinly bedded tuffaceous Upper units of the Dowling member.

The Dowling member records multiple faulting events that took place around the crater margins. The basal Contact units were emplaced as thin, laterally extensive pyroclastic-like flow and fall deposits that were almost immediately faulted and intruded by andesitic dykes (Figure 7-1, 7-3). Slumping of paleotopographic highs resulted in the deposition of channelized debris flows and thin laterally continuous mass flow deposits of

the Lower units. Strombolian-type fissure eruptions producing the fluidal breccia complexes of the underlying Sandcherry member continued during emplacement of the Contact and Lower units (Figure 7-3).

The large volume ($>3600 \text{ km}^3$) ash flow-like deposits of the Middle units formed from a major phreatoplinian event controlled by catastrophic faulting along the impact crater margin. This explosive eruption was similar in scale to those that resulted in cauldron collapse in such places as Taupo and Toba (Williams and McBirney, 1979). The rapid depressurization of a magma chamber can take place due to violent seismic activity and the resultant creation of large, single-slip listric faults (Williams and McBirney, 1979). The 45 km long concentric zone of pseudotachylite referred to as the Froid breccia belt in the southern Sudbury Structure is interpreted to be a superfault defined by large ($>100 \text{ m}$), high velocity displacement during a single slip event (Spray, 1997).

Wood and Spray (1998) propose emplacement of offset dykes due to a collapsing wedge of footwall rocks into the SIC melt sheet that caused back-injection of melt into the fault zone. Pattison (1979), Grant and Bite (1984) recognized the association of offset dykes with zones of brecciation and their formation during the crater modification stage. Pattison (1979) noted unusual leucocratic breccia phases along the Whistle offset that were indistinguishable from "green Onaping Formation glassy breccia", and suggested a genetic relationship. These may well represent eruptive centres to the Dowling member of the crater-fill sequence along faults occupied by multiple pulses of dykes similar to rapid cauldron collapse in volcanic environments (Setterfield, 1987; Reedman et al., 1987; Sparks, 1988; Setterfield et al., 1995).

The Dowling member is proposed to have originated from the phreatomagmatic eruption of “offset” melt upon interaction with downwelling water along the offset “superfaults”, produced during the crater modification stage and deposited as voluminous tuffaceous units in the Sudbury Basin (Figure 7-3). The geochemical similarities between the felsic norite/quartz diorite of the SIC and the Onaping Formation (Chapter 3) is consistent with this interpretation. The explosivity of the eruptions along the faults is controlled by the water to melt mass ratio, the amount of superheating, (boiling of water and its explosive expansion) and constraints on confining pressure. Evidence for water in the vent area is recorded by change in the shard morphology from blocky bases to lenticular tops in individual units in the Dowling member, Onaping Formation (Plates 2-4 and 2-5). This is similar to pulses of water interacting with hot magma that progress to more magmatic fragmentation as the vent area temporarily dries up (Kokelaar and Durant, 1983; Kokelaar, 1986). The Dowling member units record the effects of water: melt interaction and fragmentation.

The validity of this model partially rests on knowledge of the age relationship between the SIC and offset dykes. However, this relationship is still considered controversial, with the offset dyke emplacement proposed to have occurred: a) early, prior to differentiation of the main mass of the SIC (Lightfoot et al., 1997); b) related to the norite (Grant and Bite, 1984); or c) to have taken place 100-300 Ka after impact (Wood and Spray, 1998; Ivanov and Deutsch, 1997). However, the model proposed in this dissertation, based on the similarity in composition of the least altered melt with the norite and offset dykes coupled with the field characteristics of the Dowling member units

supports Lightfoot et al. (1997) with an early emplacement of the offset dykes, at least contemporaneous with emplacement of the Dowling member of the Onaping Formation.

The end of circum-crater eruptive activity is marked by the reworking of the upper units of the Dowling member tuffaceous units into thinly bedded units (Figure 7-1). Intra-crater magmatism in the form of andesitic dykes and peperite bodies continued after emplacement of the Upper units of the Dowling Member. The continuation of NW and N fault-controlled magmatism within the crater played an important role in localizing fluid upflow during subsequent hydrothermal activity.

The architecture of the subaqueous Sudbury Structure is conducive not only to the development of a major hydrothermal system within the Sudbury Basin owing to obvious heat sources, permeable rocks and faults, but also to the penetration of seawater along faults in the footwall to the SIC.

7-2. Character and timing of the Upper Hydrothermal System, Sudbury Structure.

The widespread distribution of various metamorphosed alteration mineral assemblages within the Sudbury Structure infill sequence is evidence that crater-scale hydrothermal activity took place during and after, emplacement of the Onaping Formation. Hydrothermal circulation of fluids in the Sudbury crater allowed for the effective dissipation of impact generated heat at $1848 \pm 3.4 - 1.8$ Ma, by convection (Ames et al., 1998). The deposition of the crater infill succession in a submarine environment, a heat source, the permeable nature of the Onaping strata, presence of syn-depositional faulting, and persistence of intra-crater magmatic activity, are conditions that would have promoted

the initiation of broad-scale hydrothermal convection (Galley, 1993). Similar conditions prevailed during the formation of regional-scale alteration systems in volcanoclastic dominated, VMS-rich environments such as the Archean Sturgeon Lake camp, Ontario (Morton et al., 1990), the Paleoproterozoic Snow Lake, Manitoba (Bailes and Galley, 1996) and Bergslagen camps, Sweden (Lundström et al., 1996), the Cambrian Mount Read, Tasmania (Eastoe et al, 1987), and the Carboniferous Iberian Pyrite Belt, Spain (Munha et al. 1986).

Alteration studies in terrestrial impact craters (McCarville and Crossey, 1996; Masaytis and Naumov, 1995) show the intensity of alteration (although minor volumetrically) increased around and was controlled by the central uplift. In contrast, extensive, pervasive alteration resulting from the upper hydrothermal system in the Sudbury Structure is controlled by syndepositional faults and the injection of dykes of melt which perturb the generally lower temperature broad alteration zones in permeable vitric rocks.

The spatial relationships of the various alteration assemblages also supports the presence of a large-scale paleohydrothermal convection system, circa 1848 Ma (Figure 7-4). The progression of alteration assemblages with depth records the thermal profile of the upper hydrothermal system in the Sudbury basin as well as the progressive changes in hydrothermal fluid compositions by fluid-rock interaction. The Dowling member of the upper part of the Onaping Formation is characterized by lower temperature calcite and metamorphosed clay-rich alteration assemblages that typically form at temperatures less than 180°C (Chapter 4-2g). The distribution of regional carbon in the Onaping Formation

(Figure 3-4b), although its origin is controversial, may represent a lower temperature isotherm ($<150^{\circ}\text{C}$; Chapter 4-2h). Higher temperature albite and actinolite-rich assemblages are restricted below 1000 m near the base of the Onaping Formation or about the fault-controlled fluidal breccia and andesitic dyke locations. These alteration assemblages are typical of seafloor depths with higher temperature ($250\text{--}300^{\circ}\text{C}$) seawater-rock interaction (Alt, 1996; Schiffman and Fredleifsson, 1988)(Chapter 4-2c). Petrographic and mineralogical data indicate that the lower silicification zone adjacent to the SIC at the exposed base of the pile formed at temperatures greater than 340°C (Chapter 4-2b). Between the high and low temperature alteration assemblages is a zone at the base of the Dowling of chlorite alteration accompanied by sporadic sulfide precipitation.

In a broad sense, this layering of distinct hydrothermal alteration assemblages reflects changing water/rock reactions within a steep thermal gradient (approximately $200^{\circ}\text{C}/\text{km}$) and has similarities to hydrothermal convection systems modeled in ancient and modern seafloor-spreading environments (Alt, 1996; Nehlig, 1991). A lower, high temperature fluid/rock reaction zone is maintained at temperatures resembling greenschist facies metamorphism by the presence of a sheeted dyke swarm in mid-ocean ridge systems. Fluid/rock ratios are minimized by structurally-controlled permeability and high temperatures are maintained in the presence of the cooling dykes and underlying magma chamber. The overlying pillowed basalt succession is much more permeable, allowing open convection of seawater and resultant higher fluid/rock ratios and lower reaction temperatures. Where the higher temperature fluids from below and lower temperature

fluids from above meet at the dyke/basalt interface there is a zone in which the latter cool and precipitate sulfides.

As appealing as this convection model is for the Onaping Formation, there are several factors that suggest a more complex hydrothermal history. The transition zone alteration which affects the lower units and the base of the middle units is laterally extensive. The discontinuous, underlying zones of chlorite alteration in downfaulted segments of the contact units in Morgan Township implies that chlorite alteration occurred early either synchronous with or prior to faulting. The transition zone is less altered than either of the surrounding alteration zones. The underlying chlorite alteration marks an early alteration with marked chemical gains of Mg possibly due to seawater incursion into a hot permeable pile upon downfaulting into an aqueous medium. The transition zone marks a period of reworking including, deposition of topographically controlled debris flows and mass flows of the lower units combined with enrichment in Fe, Mn, Zn, Pb and S. This may mark a temporary hiatus in the evolution of the Onaping Formation similar to the two-stage depositional process recognized by Peredery (1972) and Muir (1984).

Thus a multi-stage model is proposed for both deposition and hydrothermal alteration in the Sudbury basin (Figures 7-1 to 7-4). The emplacement of the Sandcherry member vitric units was in the presence of a fluid, likely early Proterozoic seawater (Peredery and Morrison, 1984). This water-saturated vitric fragmental pile was instantaneously altered upon deposition and likely in the impact plume. Contemporaneous faulting and deposition of the contact units at the base of the Dowling member essentially

capped this slurry. Evidence suggests that the contact units were emplaced subaerially and subaqueously (Figure 7-3) and were preferentially altered. Subsequent faulting and irregular topographic highs resulted in slumping and deposition of the lower units as debris flows in paleotopographic lows and thin extensive mass flow deposits. The rapid emplacement of the middle units likely sheltered the lower units from intense alteration and fluid-rock interaction. The transition zone alteration dominated by devitrification textures essentially separates an earlier hydrothermal cycle that involved the lower part of the Onaping Formation from the chlorite-calcite alteration in the uppermost Onaping Formation.

The stratiform calcite-rich alteration assemblages that overprint the middle and upper units of the Dowling member have a complex origin. The stratiform nature of this alteration type, its restriction to the upper section of the Onaping Formation, and its association with lower temperature clay (now metamorphosed to chlorite) alteration intuitively make it a product of shallow subseafloor seawater/rock interaction. This is the case in a similar situation in the Archean Sturgeon Lake camp, where pervasive carbonate alteration in the volcanoclastic strata of the Sturgeon Lake VMS camp has a dominantly seawater isotopic signature (Hudak, 1997; G. Holk, pers comm.). The isotopic signature of the Onaping carbonates is dominantly "magmatic", which suggests a deeper source for the CO_2 (possibly SIC, basal intrusion- remelted hydrothermally altered Onaping Formation). The presence of carbonate-rich, sulphide alteration along some of the syndepositional faults transecting the lower Onaping Formation may well be evidence that

“magmatic” CO₂ leaked upsection from degassing of the underlying SIC(?) due to decompression during crater modification.

Rapid deposition of voluminous tuffaceous units of the Dowling member was accompanied by (or immediately followed by) degassing of a deep magma/melt from below and infiltration of seawater from the top. Evidence for degassing from below includes patchy carbonate and carbonate filled amygdales proximal to discordant “syndepositional” faults through the Sandcherry member, rare calcite impregnation of the matrix near the base of the regional calcite zone only, miarolitic cavities (Jun Cowan pers. comm., University of Western Australia), skeletal and granophyric textures in the SIC and the compositions of apatite throughout the SIC and Onaping Formation (Warner et al., 1998).

7-3. Relationship of regional semi-conformable alteration zone to Zn-Cu-Pb mineralization.

Regional seawater convection and resultant seafloor fluid/rock interaction throughout the 1400 m thick Onaping Formation indicates the potential for mobilizing base metals from the devitrified andesitic pile and redepositing these metals as massive sulfide deposits. The variation in alteration mineral assemblages down section shows evidence for thermal gradients in excess of 100°C/km, which is adequate for generating a VMS-producing convective hydrothermal system (Cathles, 1993). The albite-rich alteration zones in the lower Onaping formation are depleted in Cu, Zn and S, indicating conditions in the lower part of the hydrothermal system were favourable for stripping and

removing metals. The presence of disseminated sulfides and small sulfide stockwork zones in the lower Dowling member above paleotopographic highs and/or syndepositional faults indicates that hydrothermal fluid remobilized metals upsection. The sulfides were precipitated near the base of the regional calcite alteration zone largely due changes in pH and possibly cooling of the hydrothermal fluids by downwelling seawater.

Basin deepening and deposition of the fine carbonaceous upper units of the Dowling member was interrupted by local minor faulting and dyke injection into the water saturated sediments. Peperites indicate magma injection into a wet medium and their proximity to ore deposits on the South Range may not only be a function of faulting. The occurrence of fault-controlled peperite bodies below the Errington and Vermilion Zn-Pb-Cu deposits indicates the presence of a thermal and structural anomaly along which focused ascending hydrothermal fluids could reach the seafloor. Research on modern ocean-spreading centres has recognized high level magma injection as a critical factor in both initiating and reactivating rigorous hydrothermal venting events such as the “megaplumes” along the southern Juan de Fuca Ridge (Fornari and Embley, 1995). Silica alteration of upper Onaping strata about these peperite bodies, and the early silicification of the mounds at the Errington “vent site” (Figure 5-5) are the likely result of similar processes that operated in the Sudbury crater (Chapters 5 and 6), (Figure 7-4).

The presence of carbonate as a major hydrothermal precipitate in both the crater- and deposit-scale hydrothermal systems is an important link, and an essential component in the development of the two massive sulfide deposits. It was the early precipitation of carbonate as early stage seafloor “sinters” that allowed the later trapping of hotter, metal-

rich hydrothermal fluids before their metals could be dispersed as vent plumes during Vermilion Formation time and precipitation in metalliferous haloes in the Onwatin Formation (Figure 5-4).

Although it has been stated that the entire Onaping Formation contains abundant sulphide, in general the albitized Sandcherry member shows depletion in Cu, Zn and S at a depth of 1100 to 1400 m below the Onaping/Onwatin contact. Bulk compositions of modern seafloor deposits are the product of the rock types in the subsurface and similarly the Pb-Ba-Zn and Cu in the Errington and Vermilion deposits are the result of leaching from the andesitic glass in the Onaping Formation and deposition due changes in pH upon interaction and replacement of carbonate mounds of the Vermilion Formation. The small size of the Errington and Vermilion deposits is likely due to a combination of, the relatively short-lived and low temperature impact-generated hydrothermal system (phases of prospective heat source; SIC all 1850 Ma), and the evidence for diffuse flow of fluids through the permeable Dowling member and subsequent precipitation of disseminated sulphides.

Basin deepening and the development of anoxic sediment conditions in late Onaping into Onwatin time (Rousell, 198) was likely triggered by widespread diffuse hydrothermal input of Fe^{2+} , H_2S , SO_2 and CH_4 due to degassing of melt, methane generation from organic carbon in the Onaping Formation and subsequent bacterial bloom in a restricted Sudbury crater. This diffuse low temperature seepage was produced by the extensive hydrothermal system in the Onaping Formation.

7-4. Conclusions

1) An early impact melt composition in the Sudbury Structure is represented by the least altered Onaping Formation andesitic glass. The Onaping Formation andesite has rare earth elemental abundances and patterns similar to that of the felsic norite of the SIC and is most similar in composition to the offset dykes that occupy fault structures in the footwall of the SIC. Thus a comagmatic derivation is evident and a parental melt composition defined. Both the quartz dioritic offset dykes and andesitic melt of the Onaping Formation occupy the compositional gap between norite and granophyre of the SIC.

2) Previously unrecognized regional alteration obscured the primary features so this study is the first documentation of the geochemistry of the least altered glass in the Onaping Formation with major implications for current models proposed for the Sudbury Structure. The new comprehensive interpretation for the emplacement of the Onaping Formation is intermediate between endogenic and impact theories, but within the framework of a meteorite impact crater.

3) The depositional and hydrothermal history of the Onaping Formation are multi-staged, multicomponent processes and intimately linked. Two main stages are evident in the field, petrographic and geochemical data and are related to the complex magmatic/melt and structural events in the Sudbury Structure during crater modification.

4) New field observations, petrological and geochemical data constrain the nature of fluid-rock interaction in the productive Onaping-hosted hydrothermal system in

impacted crust at $1848 \pm 3.4/-1.8$ Ma. Alteration assemblages record the initiation and cooling of an impact-induced hydrothermal system that, when combined with the structural, stratigraphic and magmatic history of the impact crater, allow a glimpse of the subsurface plumbing system in the Sudbury basin.

5) Syndepositional structures are recognized as playing an important role in the emplacement of melt and focusing hydrothermal fluids in the crater-fill sequence. The structures focused magma/melt into a seawater saturated crater-fill sequence subsequent to deposition of the fragmental pile. Seismic activity and melt intrusion into the Onaping Formation throughout its deposition and into Onwatin "time", focused fluid flow to discordant structures and produced local higher temperature perturbations in the broad scale hydrothermal system (Figure 7-1). This set of syndepositional faults should be considered primary mining camp scale targets for Zn-Cu-Pb mineralization in the Sudbury crater. These faults likely represent floor-fractures that have been reported in extraterrestrial craters.

6) Mineralogical, geochemical and mapping data suggests a much more complex hydrothermal history than a single fluid pass involving seawater, modified seawater and magmatic contributions to the hydrothermal precipitates in the crater. The regional calcite alteration zone in the Sudbury Basin is the result of relatively low temperature (100-180°C) precipitation from a bicarbonate fluid derived by mixing from two sources: 1) possibly degassed melt deeper in the system and 2) seawater dominant fluids in the upper 1 km of the Onaping Formation.

Figure 7-1: Relative time-space chart for events in the Sudbury Basin. See Chapter 7 text for discussion.

Figure 7-2: Model illustrating the interpreted reconstruction for emplacement of the Sandcherry and Garson members, lower Onaping Formation, Sudbury Structure.

Figure 7-3: Model illustrating the interpreted reconstruction for emplacement of the Dowlings member, upper Onaping Formation, Sudbury Structure.

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SUMMARY OF MAP AREAS

AREA	SIGNIFICANCE	MAP SCALE	REF.
Morgan township NR	<p>complete strat. section through Onaping Formation</p> <p>control stratigraphic/alteration sequence for other areas</p> <p>Stratigraphic: dominance of fluidal breccias in SM</p> <p>abundant syn-depositional fault control of units</p> <p>block faulting, unstable SM depositional environment and DMct and DMLU</p> <p>stable geotectonics during DMMU and DMUU deposition</p> <p>syndepositional dyke emplacement into DMCT</p> <p>Alteration: basal zone of silicification, early silicification</p> <p>rebrecciated, feldspar alteration localized around fluidal breccia-dyke-sill complexes.</p> <p>carbon transgresses DM-SM stratigraphic contact</p> <p>carbonate (calcite alteration) in upper 2/3rd of OF, with local discordant calcite-absent zones with fracture-controlled silicification and mineralization</p> <p>Mineralization: Limerick Cu-Zn showing</p>	<p>1:2000</p> <p>1:5000</p> <p>(Ames and Gibson, 1999)</p>	<p>Map 1 (pocket)</p> <p>2 sheets OF#3717</p>
Cow Lake (north of Dowling) NR	<p>Stratigraphic: Section through Dowling member</p> <p>discontinuous scoreaceous beds</p> <p>Alteration: regional carbonate, carbon and disseminated sulphide.</p> <p>Mineralization: McNunes and Cow Lake Cu-Zn showings</p> <p>cpy-po in amygdales in basal intrusion near top of MU</p>	1:2000	<p>unpub.</p> <p>Map 4 (pocket)</p>
Simmons N-WR	<p>Stratigraphic: section through DMCT and DMLU</p> <p>thin N/S magnetite-rich mafic dyke</p> <p>abundant intrusions (Basal intrusion)</p> <p>Alteration: Epidote-pyrite-BaKsp zone at DMCT/LU interface, strong carbonate alteration.</p> <p>Mineralization: Abundant disseminated po-cpy-sph</p> <p>Simmons Pb-Zn-Cu veins.</p>	1:2000	<p>unpub.</p> <p>Map 5 (pocket)</p>
Joe Lake NR-eastern	<p>Stratigraphic: section from granophyre SIC to DMLU</p> <p>complete section through SM, intrusive fluidal-breccia sill/dyke complex,</p> <p>possible transported, slumped fluidal vent complex and proximal facies.</p> <p>discordant intrusive basal intrusion-former Basal Mbr.</p> <p>Alteration: three types of feldspar alteration</p> <p>regional syn-depositional albitization controlled by fluidal breccia complex, fracture-controlled albitization (1848 Ma).</p> <p>Kfeldspar-quartz hydrothermal breccia-local alteration.</p> <p>"pocket" of carbon-bearing SM 10 m from granophyre contact</p>	<p>1:2000</p> <p>(Ames et al., 1997)</p> <p>(Ames et al., 1998)</p>	<p>pub. page size</p> <p>Map 2 (pocket)</p> <p>Geochron.</p>

Appendix 1-1: continued.

AREA	SIGNIFICANCE	MAP SCALE	REF.
Hanmer powerline NR	<i>Stratigraphic:</i> SM to top of DMCT Basal intrusion-discordant near base of exposed O. Fm. SM- numerous bombs, near DMCT abundant aphanitic dykes, excellent transect through DMCT units <i>Alteration:</i> Regional basal silicification zone in SM and BI Increased albitization spatially associated with dykes Fracture-controlled silicification xcuts SM/DM contact	1:2000	
Nelson W NR	<i>Stratigraphy :</i> SM to DM two orientations of aphanitic dykes proximal fluidal breccia <i>Alteration:</i> Intense albitization amphibole alteration of matrix at dyke terminations.	1:5000	Fig. A2-4.1e
Nelson E NR	<i>Stratigraphy:</i> SM near granophyre <i>Alteration:</i> Basal silicification zone <i>Mineralization:</i> Unnamed base metal -py gossan	1:5000	
Rockcut Lake NR (Capreol)	<i>Stratigraphic:</i> near base of O.Fm. in SM Multiple textural phases of the basal intrusion discordant xcuts fluidal complex excellent 3D view of dyke-sill complex <i>Alteration:</i> regional albitization, east side of lake carbon -bearing SM near the base of O.Fm. discordant zone of actinolite fractures and albite-quartz alteration haloes	1:2000	Map 3 (pocket)
Gordon Lake rd. (GLR)	<i>Stratigraphic:</i> Dowling member below Vermilion mine DMUU and local setting for detailed mapping of peperite peperite is quite extensive <i>Alteration:</i> carbonate-epidote	1:5000 1:2000	Fig. 2-12
GLR peperite SR	<i>Stratigraphic:</i> dyke intrusive into DMUU formation of blocky peperite <i>Alteration:</i> peperite-associated silicification, phengitization, carbonatization <i>Mineralization :</i> cpy-sph	1:250	Fig. A2-5.1 Fig. 4-13
A&M peperite SR	<i>Stratigraphic:</i> dyke intrusive into DMMU early dykes and associated peperite formation, later intrusive andesite lobes formation of globular peperite <i>Alteration:</i> peperite associated, silicification, chloritization, carbonatization and Fe-Mn oxides.	1:200	page size (Ames and Gibson, 1995). Fig. 4-14 A2-5. 2 A2-5.3

Appendix 1-1: continued.

AREA	SIGNIFICANCE	MAP SCALE	REF.
Azilda peperite NR	<i>Stratigraphic</i> : upper 50 m of O. Fm. dykes with blocky peperite <i>Alteration</i> : peperite associated chloritization, phengitization, carbonatization.	Drill hole BA 51-01 (Falconbridge Ltd.)	
Detailed maps/sketches			
	Cow Lake base metal showing	1:200	Map 4
	McNunes base metal showing	1:100	" "
	Simmons base metal showing	sketch	Map 5
	Ryan base metal showing	1:200 to 1:25	Fig. 5-2
	Errington deposit-Tournigy Pit Trench	1:100	-
Sampling and observations only			
	Errington deposit		
	Irwin trench		
	#1 Shaft		
	Mine dump		
	Vermilion deposit		
	Mine dump		
	LW base metal showing		
	Vermilion Fm.-Midzone area, Gordon Lk Rd.		
	Davey road anthraxolite showing		

Appendix 2-1

MAPPING METHODOLOGY AND TERMINOLOGY

2-1a. Methodology and classification used for mapping.

The controversial Onaping Formation, whether volcanic or impact derived continues to be debated after 50 years of study (Table 2-1; Muir, 1984; Peredery, 1984; Gibbins, 1994; Avermann, 1994). Commonly, classification systems use a rock chemistry designation derived from a major-element chemical analysis (SiO_2 content) and a textural analysis. Mapping criteria for fragmental rocks of volcanic derivation are well documented (Fisher, 1966), however a systematic method for mapping impact breccias is lacking. It is useful however to examine and describe the fragmental rocks of the Onaping Formation in a system that is non-genetic. Muir and Peredery (1984) modified Fishers (1966) classification by substituting Type 1 to Type 5 into the classification scheme (Figure A2-1). Gibbins (1994) also used Fishers (1966) classification scheme for volcaniclastic rocks and emphasized that the classification terms were used only for descriptive purposes and do not reflect the origin. Similarly, Fishers (1966) direct classification scheme for mapping was adopted in this study as readers can relate readily to the terms which are based on the percentage of vitric fragment sizes (Figure A2-1).

2-1b. Glossary of Sudbury Geology terms and nomenclature used.

The literature on impact craters and Sudbury geology contains a number of terms that are not readily recognized by many geologists. Many of the Sudbury terms used are

those defined in the 1984 Volume on Sudbury Geology (Pye et al., 1984) with modifications by Corfu and Lightfoot (1996); Lightfoot et al., (1997a and b) and Wodicka (1997) and definitions of terms used in mapping the Onaping Formation are listed below:

Andesite: refers only to the major element chemical composition of the rocks. It is the most general basis for classification and contains , 56-62 % SiO₂.

Autobreccia: non-explosive fragmentation of flowing lava.

Block: angular, lithic, vitric or composite fragment larger than 64 mm

Bomb: Aerodynamically shaped glass or vitric fragment larger than 64 mm ejected in a molten or fluid state.

Composite fragment: Fragments of Onaping lithology, that comprise breccia within breccia, glass within glass and breccia within glass

Cored bomb: A bomb with a solid core of an older lithology. Rims of typically flow banded glass. A simple cored bomb contains a core of country rock. Complex cored bombs have composite or Onaping Formation lithologies as a core.

East Range: part of the Sudbury Igneous Complex and Onaping Formation, commonly considered to be part of the North Range. It extends from the pronounced flexure of the SIC and OF in Norman Township southward to the faulted flexure in Falconbridge Township.

Felsic norite: the major unit of the Lower Zone of the SIC in the North Range.

Fluidal fragment: A glass shard, generally ribbon-like to tabular in shape and commonly displays contorted to parallel flow banding.

Footwall Breccia: a collective term for various breccias found in the Footwall of the SIC, particularly on the North Range. The breccia is compositionally and texturally variable and is characterized by abundant Footwall rock fragments, local sulphide inclusions in a contact-metamorphic matrix consisting mainly of variable proportions of plagioclase, quartz, pyroxene, amphibole, biotite and granophyric intergrowth of feldspar and quartz. The breccia hosts a major portion of the ore deposits on the North Range.

Glass: the juvenile component, no discrete crystalline units and are wholly without crystalline structure. In the Onaping Formation there is no glass remaining as it has been devitrified or recrystallized and altered (Muir and Peredery, 1984).

Granophyre: the major unit of the Upper Zone of the Sudbury Igneous Complex.

Juvenile: Material derived directly from a melt, magma or lava.

Levack Gneiss Complex: a belt of upper amphibolite to granulite facies Archean gneiss adjacent to parts of the North Range of the SIC.

Lithic fragment: Fragments or mineral grains of rocks in the footwall of the SIC or rocks that pre-date the main Sudbury Event.

Melt: The terms melt and magma are used interchangeably. It is a molten rock with no emphasis placed on its derivation whether melted crust or mantle.

Mafic norite: the basal unit of the Main Mass of the SIC in the North Range.

Main Mass: the major part of the SIC, consisting of the felsic and mafic norites of the Lower Zone, quartz gabbro of the Middle Zone and granophyre of the Upper Zone. It is exclusive of the Sublayer and the offset dykes are considered part of the Main Mass.

North Range: the northern part of the SIC and Onaping Formation. The boundary with the South Range is a fault zone extending from the Chicago Fault to the Cameron Creek Fault in the west. The eastern boundary is the pronounced flexure in Falconbridge Township.

Offset; offset dyke: a radial or concentric dyke of the SIC consisting predominantly of quartz diorite but may include significant Footwall Breccia material.

Palagonite: a low temperature, hydrous alteration product of basaltic glass. It is not a mineral nor a mineral family.

Peperite: a rock generated by mixing of coherent lava or magma with unconsolidated wet sediment and is characterized by a clastic texture in which either component may dominate.

Shard: Angular and/or curved glass fragment formed by fragmentation and quenching of molten material. All shards are altered from their original glassy state. Evidence to support shards in the Sandcherry member are vesicles inside the blocky shapes. The contact units (previous Green member) contains arcuate shards broken across bubble walls and contain vesicles within them. Similarly the shards in the Dowling member are lenticular with vesicles.

South Range: the southern part of the SIC and Onaping Formation whose boundary with the North Range is defined in the North Range definition.

Suevite: a polymictic breccia containing fragments with highly variable shock metamorphic features, glass and rock fragments.

Sublayer: the lowermost unit of the SIC; generally inclusion-rich norite. It is characterized by its discontinuous and inhomogeneous nature. It consists of a) fine- to medium-grained norite which hosts mafic, ultramafic and sulphide xenoliths, b) felsic footwall breccia and c) inclusion-bearing massive sulphide facies.

Sudbury Basin: the area enclosed by the SIC and occupied by rocks of the Whitewater Group.

Sudbury Igneous Complex (SIC): a large layered intrusion with which the nickel-copper-precious metal deposits of the Sudbury district are associated. The main igneous units of the SIC are 1) concentric and radial dykes of quartz diorite or offset dykes 2) the sublayer and 3) noritic, gabbroic and granophyric rocks of the Main Mass of the SIC.

Sudbury Structure: a collective term of a feature consisting of 1) the Sudbury Igneous Complex 2) the Sudbury Basin and 3) the brecciated country rocks of the Archean Superior and Proterozoic Southern Provinces of the Canadian Shield which surround the Complex.

Transient crater: Produced after contact and compression of the target rocks by excavation which produces a “bowl-shaped” crater larger than the diameter of the projectile (meteorite). This transient crater subsequently collapses due to gravity during the modification stage.

Figure A2-1: Classification of the fragmental rocks of the Onaping Formation.
A) This study (Fisher, 1966), B) Muir and Perederys (1984) modification.

Appendix 2- 2

DETAILS OF ONAPING FORMATION ROCK DESCRIPTIONS

2-2a. Actinolite-chlorite fragments and clots, Sandcherry member

The distribution of lithic fragment types is chaotic, although “actinolite-chlorite” clots are more common in fluidal fragment lapilli-tuff units. Muir and Peredery (1984) described both mafic lithic fragments and minor irregularly shaped patches of calcite-chlorite, chlorite-actinolite or actinolite that were interpreted as vug fillings. Gibbins (1994) suggested that the vugs were recrystallized mafic-ultramafic rock fragments. In fact, actinolite occurs as altered mafic rock fragments, possible pyroxene pseudomorphs, amygdale fillings, vein fillings and hydrothermal actinolite occurs as open space fillings and replacement of matrix. Partially amphibolitized mafic fragments have been observed in the field. Both altered fragments and amygdale-fillings may have bleached alteration haloes. The latter alteration types will be discussed in Chapter 3. Field, petrographic and polished slab observations revealed angular to subangular mafic fragments composed of amphibole $\pm$ titanite-leucoxene, amphibole-chlorite $\pm$ plagioclase/quartz $\pm$ calcite $\pm$ chalcopyrite, pyrrhotite and pyrite and amphibole-chlorite-pyroxene-titanite. Locally mafic fragments are weakly altered or only partially altered to actinolite.

2-2b. Fluidal fragment units, Sandcherry member

Contact relationships and syn-depositional fault control (Plate A2-3.1)

Contacts with equant shard units are dominantly knife sharp (e.g. Joe lake Map 2, Nelson lake Figure A2-4.1E, Morgan Twp. Map 1), locally diffuse over 1 m (e.g. Morgan, Map 1) and rarely gradational (e.g. Morgan, Map 1) (Appendix 2-3, Plate A2-3.1). All of the contacts are sharp between the Sandcherry member fluidal fragment units and the Dowling member units (Appendix 2-3, Plate A2-3.1). On the western part of the Morgan map area (Figure 2-5), fluidal breccia and massive flow banded andesite is in contact with Sandcherry member equant shard unit and Dowling member contact units. The contact with equant shard units is generally sharp but 100 m along strike the massive andesite forms *in situ* brecciated angular blocky fragments indicating autobrecciation. This massive to autobrecciated unit transects strata as it is in sharp contact and includes fragments of Dowling member contact tuff. Bedding ($055/0-30^\circ$) in the Dowling member contact unit, defined in this locality by block-rich/-poor subunits and a consistent flattening of chloritic shards, is oblique to the contact with the fluidal breccia. Therefore, part of the fluidal breccia was emplaced after deposition of the Dowling member contact units and whose distribution is controlled by syn-depositional faults. The central north-south elongate sequence of Dowling member contact tuff is also in sharp fault contact with fluidal fragment units along the western and southern margins. This sharp contact is discernible over 50 cm and yet undulates over the 50 m outcrop exposure. Massive fluidal amoeboid apophyses intrude the contact unit which contains a weak foliation for 30 cm adjacent to the contact. Isolated outcrops of proximal fluidal breccia are located at the intersection of perpendicular offsets of the contact member. This is interpreted as proximal fluidal breccias emplaced at syndepositional fault intersections. This relationship is found also at

Sandcherry Creek (Figure 2-6). Fluidal lapilli-tuff and massive to autobrecciated andesite have knife sharp, locally lobate subvertical contacts with north-south trending Dowling member contact tuff and an east-west subvertical contact with Sandcherry member equant shard unit. Flow banding in an andesite dyke is subparallel to the north-south trending contact unit. These subvertical orthogonal contacts represent faults which control the deposition of fluidal fragment units. Dyke and fluidal breccia emplacement locally postdates the contact and lower units, synchronous with faulting and locally “jacks up” the middle units similar to cryptodome-sill complexes (McPhie et al., 1993).

2-2c. Transitional units, Sandcherry member

Lithology

Transitional units contain 15-30% chloritic, brown recessive weathering blocky shards, 50-60% lapilli-sized flow banded vitric fragments, 10-20% aphanitic matrix and the remainder vitric blocks and lithic blocks, finer lithic fragments and chlorite/actinolite clots. Generally two size populations of lapilli vitric fragments are evident in one outcrop (outcrop 1, 2 mm to 1.5 cm - 25% and 2 cm - 40%; outcrop 2, 0.5 cm - 30% and 2 cm - 25%; outcrop 3, 4 mm, - 40% and 1 cm -10% etc.). The percentage of blocks varies from <2-30 % with the proportion of lithic fragments usually greater than vitric blocks (vitric 2-5%; lithic 2-15%). Bombs are most abundant in transitional units (Table 2-2) and range from 10 cm to 1 m, typically 20 cm. The cores of complex and simple bombs are angular, fluidal-fragment and granitoid fragments, respectively (Plate 2-2). Complex bombs are present in 30 % of the transitional unit outcrops in the Morgan map area (Table 2-2).

Block size is variable within an outcrop generally with 6 cm to 4 m angular to subrounded felsic granitoid, quartzite and rare mafic lithologies. Small lithic fragments (<6 cm) are ubiquitous with 3-10% averaging 6%. 25% of the transitional unit contains 1-3%, typically 1-3 cm, angular and subrounded, radiating chlorite and/or actinolite bearing mafic fragments.

2-2d. Contact units, Dowling member

Distribution

The following descriptions are based on mapping in Morgan township, Joe lake, Hanmer powerline, Diabase fault lake (Dowling Twp.) on the North Range and Garson powerline on the South Range. Detailed mapping shows that the distribution of contact units is unlike that previously documented as either a continuous unit around the entire structure (hence Green member, Dressler et al., 1987; Avermann, 1997) or as a single sheet like unit subparallel to the SIC contact (Gibbins, 1994), (Figure 2-5). In these areas the true thickness of the contact units is 35-300 m. In five of seven unit occurrences the contact units abruptly stop laterally along northerly “structures”, oblique to stratigraphy.

Contact relationships

The lower contact is conformable, sharp and erosive with fluidal lapilli tuff fragments within the base of the contact units (Plate 2-3). Bedding is defined by variations in size and abundance of vitric fragments, block distribution and flattening of chloritic shards. A bedding contact (060/39) between a 2 m thick, lapilli-rich bed and lapilli-poor contact unit is sharp and yet wavy with undulations on the dip surface of 23-65 degrees in

detail. There is no difference in the shard morphology, size or abundance between subunits that are block-rich versus block-poor within an outcrop. Therefore the distinction is only the distribution of blocks.

The bedding contacts are oblique to the western and eastern contacts with Sandcherry member strata. These northerly trending contacts are knife sharp and may or may not host a flow banded aphanitic dyke. Observations from a number of localities show that contact unit shards are not flattened parallel to the sharp contacts with Sandcherry member equant shard units nor is there flow banding in fluidal fragments that parallels the contact. This coupled with the obliquity of the “structure” relative to internal bedding contacts within the contact unit suggests that these structures are faults and the contact units were deposited prior these faults and were not controlled by these topographic features. The strike of the contact is consistent although over ~50 m the dip is irregular. This will be discussed further in section 2-4.

Lithology

A minimum of four depositional units have been observed comprising the contact units. Individual units are generally thinner near the base (~5-10 m true width) with 100-130 m units progressing upsection. These are characterized by 1) a block or lapilli-rich base with subequant blocky shards 2) a change in the morphology of shards from blocky to lenticular and wispy upsection (Plate 2-6) 3) the percentage and size of shards decreases (fining upwards) and 4) the abundance of matrix increases. Accretionary lapilli were observed at the top of the lowermost, “basal” block-rich subunit in Morgan township. Although they are common within carbon-bearing equant shard units on

Highway 144 (Peredery, 1972) these have not been reported in this unit or higher in the sequence.

Section at Joe Lake (Map 2): Block or lapilli-rich zones are present throughout the contact units marking the base of a new depositional unit. At Joe Lake, the upper and lower contacts of the contact unit are subparallel to bedding in the overlying middle units and therefore conformable. This sequence is ~35 m thick (assuming 30° dip) with two units 10-15 m wide. Unit 1 contains a block- and bomb-bearing base (2%) composed of subequal proportions (0.75%) of lithic versus vitric blocks/bombs and minor (0.5%) 20 x 15 cm blocks of underlying SM equant shard unit fragments (25%). The blocks are less than a metre (Lithic max=80x30 cm, Vitric max=70x30m) averaging 20x10 cm generally subangular with some rounded lithic fragments. A breadcrust bomb suggests subaerial eruption. Upsection there is a decrease in the abundance (1%) and size of blocks. Unit 2 is marked by an increase in bombs and blocks (3%). Cored bombs and vitric blocks are more abundant and on average larger than those in unit 1 and blocks (rip-ups) of underlying Sandcherry member strata are absent. The top of the sequence in contact with the lower units of the Dowling member are difficult to discern.

Section at Morgan (Map 1): At Morgan township, in the western and central exposures of contact units, the basal block-rich zone also contains angular blocks of underlying Sandcherry member strata and marks the first appearance of large ~ 1 m basaltic lithic blocks, observed. The basal block-rich zone contains 15-20% blocks dominated by vitric (17%) blocks and bombs with lesser lithic blocks (8%), 40-55% 2-4 mm blocky shards, 15% 1 cm, flow banded andesite lapilli in a bluish, greenish gray

matrix. Overlying tuffaceous units contain fewer blocks and lapilli tuff units contain 20-40% 0.5 cm feldspathic altered shards, 25 % 2 mm chloritic shards, 5-10%, <1 cm lithic fragments in a fine matrix. Contact units may also contain 10-25% lapilli-sized (<6.4 cm) flow banded andesite fragments and rare angular flow banded blocks containing fragments of contact unit tuff. Locally, elongate 30 x 5 cm wispy devitrified irregular flow banded andesite fragments are present and represent spatter. Flow banded andesite blocks and bombs are amygdaloidal and locally scoriaceous. Welding was not found in any of the contact unit sequences studied although Gibbins (1994) documented incipiently welded contact tuff.

Interpretation

Contact units comprise a series of subaerial to shallow water, fall and flow deposits that may contain a block- and bomb-rich base, accretionary lapilli and welded and non-welded tuff. The basal units are erosive and contains blocks of underlying Sandcherry strata, breadcrust bombs and granitic and basaltic fragments. The linear control on the distribution of the Contact units is a consequence of a series of north-northwest and minor east-west block faults (Figure 2-5; note Sandcherry Creek area).

2-2e. Detailed sections of the lower units, Dowling member

Lower units are heterogeneous and contain typically 20-30% blocky to lenticular, chloritic shards, 5-20% partially devitrified, lapilli-sized, flow banded andesite, 5-45% blocks (vitric>lithic), 2% fine (2 mm) black quartz and 30-50% carbonaceous matrix ±

calcite, pyrite, pyrrhotite and base metals. Fine lithic fragments are dominated by grey to black chert with lesser granitoid and quartzite fragments.

Sections across individual units identifies a number of different channelized and blanket-like units. One channel-shaped deposit cutting into a Sandcherry member transitional unit shows a normal grading of lithic and vitric fragments and the abundance of lithic increases upsection. The block-rich base contains greater vitric than lithic blocks, complex cored bombs (Dowling member core) and fragments of underlying Sandcherry member tuff and grades up into lapilli-sized lithic dominated units. Another channel shaped deposit scours both Dowling member lower unit lapilli-tuff and proximal Sandcherry member fluidal fragment unit and is also injected by a flow banded andesitic sill/dyke complex (Figure 2- 7). Reverse grading of lithic fragments is evident with 35-40% rounded, 20 cm blocks at the 6 m wide base and fewer and larger (1m) blocks are at the top. The unit is anomalous in blocks with 30% subangular to angular, bleached (altered) and unaltered vitric fragments, (max.= 50x40 cm, min. 10x3 cm, avg. 30x15 cm) and fewer 15% subangular lithic fragments (max. 2x3 m, min. 6x6 cm, avg. 25x15 cm) and 2-3% rounded cored bombs. The host sequence, angularity of the blocks, dominance of cored bombs and vitric blocks both altered and less altered suggests that this mass flow deposit is proximal to a fluidal vent complex. Elongate pods of very amygdaloidal, contorted flow banded andesite in the adjacent lower units also suggests proximity to a vent. A number of different mass flow units in close proximity to this vent may support a growth fault-like scenario.

2-2f. Detailed sections across the Middle units, Dowling member

Three stratigraphic sections across the middle units shows minor variations at the base of the sequence and defines a change in the depositional style mid-way up the section (Figure 2-8). At ~300 m, there is a pronounced increase in the proportion of lensoid fine tuff and lapillistone blocks and thus marks the initiation of reworking. The middle units are subdivided into lower middle units (0-300 m) and upper middle units (~300-780 m). Due to poorly defined bedding and moderate outcrop exposure it is difficult to define exact thickness' of individual units. Some units are as much as 140 m thick and thin with increasing stratigraphic height.

Units at the base of the lower middle units are heterogeneous and in detail the middle units are composed of similar yet discontinuous units. The base at section A-A' consists of a series of poorly but thinly bedded (1-5 m locally) coarse and fine tuff with minor fine tuff beds with abundant lapilli-sized flow-banded andesite fragments, small 5-17 cm simple cored bombs and minor lithic blocks. The basal unit at B-B' is poorly- non bedded fine tuff to lapilli-tuff and at section C-C' is 80-160 m wide consisting of a very fine tuff base grading up into a block-rich, welded tuffaceous zone and lapilli-tuff, and a thick zone of massive, homogeneous, featureless tuff (Figure 2-7, Plate A2-3.4). The cm-scale zone with reverse grading of vitric fragments at the base is the result of traction (McPhie et al., 1994). Five metres above the basal contact the unit shows normal grading of lithic and vitric fragments.

In general, the majority of the lower middle units contain minor fine tuff and lapillistone blocks except in minor amounts. Trace small 10-50 cm blocks and pods of fine

tuff, lapillistone and coarse tuff are common (Plate A2-3.4). 50 m up from the base. Upsection, the size and abundance of chloritic shards increases, the amount of lapilli-sized vitric and lithic fragments decrease and bombs and blocks are absent after 50-100 m. Discontinuous pumiceous beds and scoriaceous fragments are rare (Plate A2-3.4).

The upper middle units have similar concentrations of fine chloritic shards but, more coarse 0.5 - 2 cm chloritic shards than the lower middle units (Figure 2-8). In detail, the tuffaceous units are texturally inhomogeneous with irregular zones of increased coarse, < 2 cm chloritic shards. These zones have no distinct boundaries and occur as 5-10-20-40 cm clumps throughout the upper section (Plate A2-3.4). The frequency and abundance of large (avg. 20 x 100 cm) fine tuff and lapillistone blocks, lenses, irregular amoeboid pods and rare beds increases. Near the top lenses rich in fine tuff and lapillistone blocks attain true thickness' of 10-12 m and extend for 20-80 m.

Lapillistone blocks typically consist of coarse blocky chloritic shards (4 mm, 40%), fine chloritic shards (2 mm, 10-20%), lapilli-sized lithic (3 mm-1 cm, 20%) and blocky flow-banded andesite (1-2 cm, 10-15%) fragments in a fine aphanitic matrix. Fine tuff blocks and irregular pods may be lithic-rich or lithic-poor (0-20%, <3 cm fragments) and contain 1-2 mm lenticular chloritic shards (5-25%) and minor (5-10%) coarse blocky shards in a fine matrix. Some contain 40% coarse 0.5-1 cm angular blocky chloritic shards and rare angular 4 cm tuff fragments. Coarse chloritic shards are delicate, broken across vesicle boundaries are locally vesicular to scoriaceous or contain spherulites along fine fractures. Lithic fragments are gray, black and white chert, quartz, minor granitoid fragments and trace carbonaceous fragments. The middle units are carbon-bearing and

may contain minor to trace amounts of alteration minerals ($\pm$ pyrrhotite, pyrite, calcite, epidote, chalcopyrite, sphalerite and sericite). The distribution and characteristics of this alteration are discussed in chapter 4.

2-2g. Upper units

A section whose true thickness is 65 m shows the characteristics of this unit with only weak deformation as mapped in Morgan Township (Map 1). The proportion of fine tuff-sized particles increases up-section within the upper units, which are characterized by $>70\%$, <2 mm fragments to thinly bedded normally- to non- graded beds and mark the first definitive appearance of water-lain epiclastic strata (Plate A2-3.5). The proportion of vitric fragments is low ($<15\%$) and fine, <2 mm lithic fragments high (60-70%). In a pyroclastic terminology these would be lithic ashes (Cas and Wright, 1988) but since they are reworked and redeposited “pyroclastic-like” middle units a sedimentary terminology is more suitable.

Bedding is shallow (average 21° S) and the strike of the units is consistent at 070° with that in the underlying Dowling member units (Figure 2-5, inset). Near the base of the upper units the segregation of tuffaceous sandstone and coarse tuff is poorly developed and inhomogeneous (Plate A2-3.5). The contact between middle units and upper units is gradational over two metres and shows an increase in fines and decrease in cm-sized lithic fragments. Whereas fine tuff occurred as pods, blocks and beds in the middle units, fine tuff (sandstone) is the dominant component of the upper units with subordinate tuff, minor coarse tuff and trace lapillistone pods. Thinly bedded units contain 10-35 cm coarse beds

interbedded with 5-12 cm wide, well sorted sandstone beds and locally normally graded beds. Pods of middle unit tuff ranging from 10 x 40 cm to 4-5 m anhedral bodies contain 1) 5-7% coarse 4 mm to 1 cm chloritic shards and fine, <5% 5 mm lithic fragments or 2) 35% blocky equant chlorite shards with dark black chert lithic fragments in a fine aphanitic black carbon-bearing matrix. Discontinuous fine tuff pods, 40 x 20 cm, are imbricated with an acute angle of 48-55° to bedding.

The abundance of chloritic shards decreases with stratigraphic height. Fine tuff near the base of the upper units contains <15% 1-6 mm shards while 50 m upsection fine tuff beds contain trace to 3% shards. Delicate shards broken across vesicle boundaries retain their morphology and do not show evidence of rounding due to abrasion (Plate A2-3.5). Beige weathering fine tuff at the top of the sequence is carbon-bearing consisting of 30-40%, 1 mm, subangular monocrystalline quartz, 5-10% subrounded 2-4 mm monocrystalline quartz, 20% polycrystalline quartz fragments, 5-15% chlorite-titanite-epidote shards, minor Kfeldspar, albite and trace felsic fragments and 1-5% subrounded carbonaceous fragments in a carbon-bearing aphanitic matrix. Pyrrhotite laths and minor chalcopyrite occurs within chloritic shards, intergranular fillings and within fragments dominated by anhedral polygonal quartz. Carbonate is absent proximal to mineralization as described above. Carbonate in the upper units occurs as amygdale fillings and polygonal, angular grains that may represent either carbonate fragments or replacement of fragments. In carbonate-poor versus carbonate-bearing upper units, the proportion of monocrystalline quartz and feldspar is consistent but the abundance of shards decreases. Minor replacement of shards and partial replacement of polygonal quartz fragments is

evident although some may be carbonate fragments. Carbonate is absent in the matrix. Observations of the upper units on the south range were made in areas of mineralization and thus were affected by alteration minerals with pyrite the dominant sulphide (documentation in Chapters 4 and 5).

Appendix 2-3

PHOTOGRAPHS AND MICROPHOTOGRAPHS

PLATE CAPTIONS

Plate A2-3.1. Contact relationships.

- a) Autobrecciated contact between massive andesite (msv) and proximal fluidal-fragment lapilli-tuff (lt), Sandcherry member. Note fragment spalled off above rapidograph lid. Morgan township, station 022, photo 1-31.
- b) Knife sharp contact between massive to autobrecciated fluidal-fragment unit (bottom), Sandcherry member and contact unit tuff (t), Dowling member. Morgan township, station 022, photo 1-28.
- c) Sharp east-west contact between fluidal-fragment unit (bottom) and equant-shard unit (top), Sandcherry member. Morgan township, station 023, photo 4-24.
- d) Subvertical dip between massive to autobrecciated fluidal-fragment unit (right) and equant-shard unit (left). Plan view shown above in plate A2-3.1c. Morgan township, station 023, photo 35.
- e) Subvertical, sharp contact between equant shard unit and fluidal fragment unit, Sandcherry member. Joe lake, station 417, photo 7-14.
- f) Hammer head at the shallowly dipping (034°S) contact between lower unit debris flow, Dowling member (top) and fluidal-fragment lapilli tuff, Sandcherry member (bottom). Morgan township, photo 33-9.

PLATE CAPTIONS

Plate A2-3.2: Characteristics of fluidal-fragment units, Sandcherry member.

- a). Cuspate and lobe-like apophyses of massive dyke into autobrecciated pile, fluidal fragment unit. Morgan township, station 023, photo 1-25.
- b) Sharp contact between block-rich proximal fluidal fragment unit (Fl) and equant shard units (Eq) of the Sandcherry member.
- c) Concentrically flow-banded andesite in massive to autobrecciated proximal facies, fluidal-fragment units. Morgan township, station 085, photo 39.
- d) Irregular sharp contact between massive andesite and fluidal-fragment lapilli tuff. Morgan township, station 017, photo 1-22.
- e) Sharp contact between equant shard unit tuff (top) and fluidal fragment lapilli-tuff (bottom). Joe lake, station 413, photo 7-15.
- f) Wispy, torn andesite fragment in proximal fluidal lapilli-tuff, interpreted as spatter. Note the subangular lithic fragment to left. Joe lake, station 442, photo 34-15.
- g) Corroded contacts of felsic lithic fragments in fluidal-fragment unit. Partial assimilation. Morgan township, station 041, photo 3-2.
- h) Autobrecciated margin (hyaloclastite) of aphanitic flow banded dyke (top) with proximal fluidal fragment unit, Joe Lake area. Note the change in shape of amygdales from elongate at the edge of the dyke to circular towards the dyke core. Arrow marks fragment spalled off dyke. Joe Lake, station 416, photo 28-20.

PLATE CAPTIONS

Plate A2-3.3: Characteristics of the lower units, Dowling member.

- a) Small, subrounded lithic and cored bombs at the base of the lower units in contact with fluidal-fragment units (below the hammer handle). Morgan township, debris flow hill, photo 33-4.
- b) Hammer head at south dipping (34°) contact between lower unit debris flow(DMLU) and fluidal-lapilli tuff (SMFL). Morgan township, debris flow hill. photo 33-9.
- c) Angular fragment of fluidal-fragment lapilli-tuff in the lower units, Dowling member. Morgan township, station, photo 32-10.
- d) Elongate, wispy and tabular flow-banded andesite fragments in lower units. Note the discontinuous blebs of flow banded andesite bottom left, interpreted as spatter. Morgan township, station 323, photo 33-11.
- e) Massive andesite (Adyke) intrudes and cuts the contact between fluidal-fragment lapilli-tuff (SMFL) and debris flow unit of the lower units(DMLU) marked in yellow. Same outcrop as plate A2-3.3b but contact is dipping shallowly (34°) north. Channelized debris-flow unit. Morgan township, photo 33-10.
- f) Lapilli-rich unit of blanket-like continuous lower units. Morgan township, station 323, photo -7.

PLATE CAPTIONS

Plate A2-3.4: Characteristics of the middle units, Dowling member.

- a) Contact between lower units and ash base of middle units at hammer . Note stratigraphic section figure 2-8, sub unit A. Morgan township, station debris flow hill. photo 24- 33.
- b) Base of the middle units with a block-rich tuffaceous zone with linear fluidal andesite fragments interpreted as spatter. Fragment orientation parallel to basal contact. Subunit B, Figure 2-8. Morgan township, photo 33-1.
- c) The block-rich tuffaceous zone in A2-3.4b grades into a lapilli-rich ash with armoured lapilli (arrow). Subunit C, Morgan township, Figure 2-8, photo 33-15.
- d) Basal middle unit. Devitrified bomb in lapilli-rich ash zone. Morgan township, debris flow hill area.
- e) Close-up of typical middle unit tuff, Morgan township. Station 186, photo 15-4.
- f) Ash block within coarse middle unit tuff. Cow lake, station Cow lake trench, Photo 19-2.
- g) Coarse lapillistone block within middle unit tuff. Morgan township, hangingwall to Limerick Cu occurrence. Photo 16-17.
- h). Lithic-rich ash pod within middle units. Morgan township, station 224, photo 15-22

A

B

C

Plate A2-3.5: Characteristics of the upper units, Dowling member.

A. Discontinuous irregular zones of coarse tuffaceous sandstone and fine tuffaceous mudstone. Morgan township, station 314, photo 32-2.

B. Well bedded coarse tuff and fine tuffaceous mudstone dipping shallowly (24oS) toward the interior of the basin. Morgan township, station 314, photo 32-1, looking east.

C. Sketch of upper unit shards. Note the increased vesicularity and the preservation of delicate shard shapes. Shards are broken across vesicle walls marked at arrows. Thin section AV-318.

Appendix 2- 4

APHANITIC DYKES AND STRUCTURAL ANALYSIS

2-4a. Distribution, morphology and mineralogy of aphanitic dykes

Over sixty, strike and dip, measurements of 'glassy' mafic dykes were collected from the North Range, Onaping Formation. They are more common within the Sandcherry member up into the Contact units of the Dowling member but extend to the top of the Onaping Formation (Figure 2-3, Plates 2-6, A2-4.1). The dykes of andesitic composition throughout the section are commonly flow banded at the base of the Onaping Formation and are more spherulitic and amygdaloidal toward the top and may have massive cores. They are spatially associated with fluidal breccia complexes and are morphologically and texturally similar to the flow banded fluidal fragments that comprise fluidal fragment units. Locally, fluidal fragment units form at the intersection of orthogonal faults along which an aphanitic dyke was injected producing sharp contacts with the pre-existing contact unit. Aphanitic dykes are also locally injected into their own autobrecciated pile to form fluidal breccia complexes, (insectuous emplacement, similar to cryptodomes) (Figure 2-6). In the contact units of the Dowling member, the dykes are commonly irregularly shaped, amoeboid and spherulitic in texture, and in the Morgan area are dominant in this unit with fewer near the base of the middle units. In the South Range, peperite units are formed in both the middle units and upper units in the vicinity of the Errington and Vermilion Zn-Cu-Pb deposits (Ames and Gibson 1995; Ames *et al.* 1996). Peperite is defined as a rock

generated by mixing of coherent magma with unconsolidated wet sediment (McPhie *et al.* 1993). The first detailed documentation of peperite occurrences in the Sudbury Structure is in the following Appendix 2-5.

Dyke contacts are either sharp or autobrecciated, or have zones of mixing between the host fragmental rocks and the melt (Table A2-4.1, Plate 2-6, Plate A2-4.1d). Dyke contacts that are arrested in various stages of autobrecciation in the Sandcherry member have intensely altered host rocks adjacent to the dyke/sill complexes although it is not ubiquitous.

Many dykes have a complex form (Figure A2-4.1) with autobrecciated margins both in the Sandcherry member and in Dowling member. The morphology of aphanitic dykes that intrude the Onaping Formation can be classified as (1) irregular, (2) blade-shaped or planar or (3) 3-d penny-shaped crack (Plate 2-6). Morphology types 1 and 2 are more common while type 3 was observed in the Nelson Lake area only. This is perhaps due to the lack of extensive three dimensional outcrop exposures. Planar dykes emplaced at a high angle to bedding have bedding parallel apophyses traced for over 100 m. Dyke thicknesses range up to 15 m but are on average less than 30 cm. Thicker dykes have a massive core with flow-banded margins $\pm$ spherulites and amygdales. Thinner dykes and irregular pods are either aphanitic and flow banded or spherulitic.

Aphanitic dykes are xenolithic with host rocks and/or basement fragments but they are typically xenolith-rich at the microscopic scale. Massive dykes and massive interiors to amygdaloidal and/or spherulitic dykes are equigranular and composed of amphibole (30-35%), plagioclase and quartz (50-60%), titanite (5-10%) $\pm$ chlorite, with pyrrhotite and

chalcopyrite the principal accessories (Table A2-4.2). Massive parts of dykes are typically free of xenoliths. Spherulitic dykes may have irregularly disseminated plagioclase microlites. Quench textures in massive dykes are evident in radiating amphibole, plagioclase, chlorite and titanite as well as “bow-tie” and “feathery-textured” plagioclase. Stellate amphibole cuts the radiating, spherulitic feldspar.

2-4b. Structural Analysis

The orientations of aphanitic dykes, sills and linear fluidal complexes were measured in the North Range principally within the Sandcherry member (Table A2-4.3). This qualitative study is based on the dykes measured routinely in the field. The purpose was not a rigorous, statistically valid, structural analyses focused on dykes but a qualitative analyses of the field data collected during routine mapping to determine the mechanical significance of the dykes. Are they situated in fracture sets, in radial or concentric arrays around the basin or are they controlled by pre-existing fractures?

The apparent strike of the dykes forms three populations at 345° , 020° and 065° (Figure 2-13). The 065° trend, subparallel to bedding, forms basin parallel apophyses off the main 330° trend at Crystal lake and the northerly trend at Nelson lake (Figure A2-4.1). The northwest and northerly trending dykes are present in the same host rock without crosscutting relationships to determine relative age. They occur in both the Dowling and Sandcherry member rocks suggesting that differences in host rheology is not the cause of different orientations. The poles to dykes were classified according to the credibility of the field measurement due to the small number of measurements (a subjective rating in field

whether the measurement was poor, good or excellent) and more weight was given to those with excellent to good ratings (Table A2-4.3). The dykes form two populations (1) 310/70 and (2) 015/65 whose intersection is 082/65 (Figure 2-13).

These dykes were also reoriented in their possible 'pre-tilted' position relative to the regional bedding from Cow Lake, north of the town of Dowling to Capreol (Figure A2-4.2). Regional bedding was determined by the general trend of the Sandcherry and Dowling members contact at the site specific to the dyke. The overall dip was estimated to be 030° based on measurements through the Onaping Formation at Morgan Township (Figures 2-5, 2-9) and based on measurements of the SIC/ Onaping Formation contact on the lithoprobe transect (Card and Jackson, 1997). The bedding was rotated back to the horizontal and the dykes rotated in the process (Figure A2-4.2). The poles to the transformed dykes form two populations: a NW set 305/70 (from the pre-tilted 310 set) and a northerly set 000/60 (from the pre-tilted 015 set), (Figure A2-4.3).

Mechanical significance of dykes

The NW dykes and N/NE dykes do not form radial or concentric arrays relative to the Onaping Formation contacts or Sudbury Structure. The NW dykes are present in both the western and eastern North Range (Figure A2-4.3). The two populations may form a set of fractures oriented relative to the least compressive stress in the regional stress field during emplacement of the dykes or be controlled by pre-existing fractures or a combination of these factors.

The question of what the fracture sets represent is crucial to the correct structural analysis of the dykes. In relation to the regional stress field there are three possibilities or modes of formation for the structures that the dykes occupy: (1) dilatant extensional cracks (2) brittle shear fractures and (3) extensional-shear fractures (Irwin, 1958; Pollard, 1987).

Dilatant extension crack scenario: Dykes occupying mode 1 fractures develop in response to the maximum compressive stress and are oriented perpendicular to the least compressive stress (Pollard, 1987). This provides limits in that only one fracture could be extensional and the moderately steeply dipping dykes define a subhorizontal σ_3 . Ideally markers transected by the dyke would help define whether the dykes formed by pure extension but small scale markers are not present in the Onaping Formation. Assuming one dyke set formed by extension, the orientation of σ_3 would be basin subparallel at 75° or 115° depending on the dyke set. In general, east-west extension can be inferred. The orientation of the maximum compressive stress is not constrained. An extensional or strike-slip regime is consistent with a subhorizontal σ_3 .

Brittle shear fracture scenario: Conjugate fracture systems typically form at angles less than 45° to the principal stress direction, typically 30° (σ_1 ; Hobbs et al., 1976). The two main populations at 345° and 020° form an angle of 35° (Figure 2-13, inset B). Evidence is present at Morgan township with sinistral offset along the more northerly trend and dextral offset along the NW trend at Crystal lake (Figure A2-4.1d). This is compatible with a fracture origin of brittle shear although there is no evidence of the slip

direction. This lack of kinematic indicators negates any estimation of the regional stress field by either shear fractures or extensional-shear fractures.

A combination of one shear and one extensional fracture is possible and may be present at Crystal lake with the more northerly fractures extensional and dextral offset evident along a northwesterly dyke (Figure A2-4.1d). The lack of marker beds hinders the interpretation. A northwesterly planar dyke with very sharp contacts in the Cow lake area (Plate 2-6c) is subparallel to the apparent sinistral offset along Gibson fault (Map 4) and may occupy a shear fracture.

The possibility also exists that the orientation of some of the dykes is controlled by pre-existing fractures. At Crystal lake the orientation of the dyke changes from 020° closer to the granophyre contact to 330° upsection and may be due to refraction as a result of differing host rock rheology or changes in the local stress field. Shear displacements along the trajectory of the dyke indicates that dilation was possibly accompanied by slip induced by the shear stress across the dyke (Figure A2-4.1). These dyke parallel shear fractures are of similar orientation to the Onaping Fault system (Fahrig and West, 1986).

Interpretation of dykes: The dykes are the result of intrusion of a pressurized melt. The propagation of dykes may be controlled by either the orientation of the regional stress field or by preexisting structures, joints or faults (Pollard, 1987). The aphanitic dykes are interpreted as cogenetic as they are glassy, compositionally similar (Chapter 3) dykes with no crosscutting field relationships. These dykes were emplaced syntectonically and syndepositionally (i.e. peperitic margins, peperite) with emplacement of the Onaping

Formation and the relative timing in terms of emplacement of Onaping Formation units is similar for all dyke orientations. The possibility that the dominant northerly trending dykes were emplaced in extensional fractures is compatible with the presence of fluidal fragment complexes parallel to this orientation. East-west extension is compatible with the down dropped right-stepping normal faults observed in Morgan township. The northwesterly dykes are subordinate and are subparallel to faults that offset contacts in numerous localities in Morgan Township, Cow Lake (Gibson fault) and subparallel the Fecunis and Sandcherry faults of the Onaping Fault system.

The fractures that the dykes occupy, at a high angle to bedding are early-syn depositional and are significant in that hydrothermal fluid flow is partially focused by these. Whether they formed by extension, shear fracture or rejuvenation of pre-existing fractures is irrelevant to use of these high-angle pathways as hydrothermal fluid conduits and ultimately the focussing of high temperature metal bearing solutions.

Figure 2-4.1: Morphology of aplanitic dykes, for legend see Map 1A. A) Aplanitic dyke associated with fluidal breccia complex at intersection of orthogonal fault set. Intrudes associated with fluidal breccia contact units. B) Aplanitic dyke associated with fluidal contact of faulted Dowling member contact units. C) Detailed sketch of intrusive andesite lobes into the contact units, Dowling member. A to C, Morgan township, Map 1A.

Figure 2-4.1 (cont'd): Morphology of aphanitic dykes, for legend see Map 1A.
 C) Fluidal breccia complex at Crystal lake, mapped by H.L. Gibson. Northwesternly trending fluidal breccia complex with associated aphanitic dykes along apparent sinistral offset of Sandcherry member/Dowling member contact.

Figure 2-4.1 (cont'd): Morphology of aphanitic dykes, for legend see Map 1A. E) Compositionally similar aphanitic andesite dykes form two coeval orientations. Localized fluidal breccia complex intrudes equant shard units which are intensely albitized. Actinolite alteration is associated with the dykes. Nelson Lake area, North Range. F) Deformed fluidal breccia and aphanitic dykes intrusive into Sandcherry member units on the South Range. Garson powerline. Dykes have hyaloclastite margins and associated albite alteration.

Figure A2-4.2: Equal area stereographic projections showing rotation of bedding to the horizontal in localities from west to east along the north range, Sudbury Structure. Dyke orientations rotate accordingly.

Figure A2-4.3: Location map of dykes reconstructed in a pre-tilted horizontal position, North Range, Onaping Formation. Inset is an equal area projection of the poles to rotated dykes.

Table A2-4.1: Dyke contact relationships

Host rock		Morphology	Area	Contacts and comments
stn 504	SMEQ-t	- flow banded dyke 185/45, < 1m planar, discontinuous - flow banded and spherulitic margins spherulites for 2-3 mm aligned wisps - 340/90 dyke also	Hanmer	- sharp contact, contains fragments of host rock. - little alteration adjacent to dyke
622 SMEQ swamp		- contorted flow banding irregular. 120/60; folded	Garson	-autobrecciated margins, autobreccia fragments intensely feldspathized, orangey-white weathering. - concentric alteration rings on fragments. - lobes cascade down SMEQ, hyaloclastite-like along strike of apophyses. - gossan along contacts
690 SMEQ- stn. 600 lt, lst, t		- 030/59 planar, exposed > 100 x 15 m	Nelson W	- very sharp contact btm. dyke and SM strata. - dominantly autobrecciated and flow-banded contacts - flow bands follow contacts - dyke contains blocks of SMSR. - intense feldspar alteration, bleaching at dyke margin within dyke - SR-lt immediately at contact is bleached, pink mottled
708		-planar, 016/32. pinches 10-20 cm to 8 cm in dip	Nelson W	- sharp
no sample stn 445	SMFL	-30 cm, pinches down, -irregular	Cow	-autobrecciated margin
564 SMFL-tr stn 447		- 2m spherical body with concentric flow banding.	Cow	-sharp
560 SMFL		-N trending apophyses, 25cm tapering dyke spherulitic	Cow	- increased feldspar alteration adjacent to dyke
565 SMFL		- irregular, flow-banded	Cow	- autobrecciated margin of dyke - intense feldspar alteration of vitric fragments in tuff up to ~ 1m from contact.

Table A2-4.1: (continued)

	Host rock	Morphology	Area	Contacts and comments
no sample	SMFL- SMFQ contact	planar, flow banded, variable thickness, 1-7 m in 3 m -108/90	Cow	-follows contact between smeq-t and smfl-lt -sharp et with smfl-lt, increase in feldspar alteration in ad acent lt. - 5 cm of dyke margin with actinolite-filled amygdaloes in a pink matrix -southern contact very sharp between smeq-tuff contact makes orthogonal jogs - locally brecciated dyke, 3% 25 cm leucocratic xenoliths.
408a	SMFL-tr		Cow	-extremely sharp, 20% amygdaloes elongate subparallel to contact (1mm x1-2 cm) -contains 5-10% irregular wisps and kspars-bearing felsic igneous xenoliths.
21/22	contact SMFL/DMCT	subvertical linear plane	Morgan mtn	sharp, subvertical with dmct autobreccia with smfl
260/271	DMCT	irregular pods- 2m	Lim	2 m amygdaloidal pod with 25 cm marginal zone with mixing with the DMCT
285	DMCT	series of 040 linear dykes 65% spherulites, 15% amygdaloes	N. of Lim	-irregular lobes, sharp and mixed zones sharp, vitric fragments feldspar altered intense for 30 cm adjacent to dyke.
336	XC SMFL, DMLU	dyke/sill complex fingers and main dyke	Hill	sharp contact see sketch.
251	DMMU- base	spherulitic, amygdaloidal irregular -locally wispy, 10 - 40 cm -oriented N/S, exposed for 4 m	Morgan	sharp contacts, Bleaching of host rock, white wea. 225 vitric fragments.
283	DMMU-mid	linear 2 m wide continuous for 15 m, 130/50		272 sharp contacts, no cc ad acent to dyke amygdaloidal, cc-qtz 1-100mm
	DMMU	-lensoidal "peperite"	A&M	- zones of DMMU tuff mixing and dyke (melt)
Stn 175	DMUJ	-planar, discontinuous 014/84	Morgan	- sharp contacts, cut by brittle sigmoidal fractures massive
	DMUJ	- folded dyke/sill complex - massive core, amygdaloidal vitric margins - blocky peperite	GLRD	- autobrecciated, zones of mixing with DMUJ tuff and dyke

Table A2-4.2: Dyke Petrography

Sample	Host	Station	Orientation	Major minerals	Minor	Trace	Comments
251	dmmu	225	000/irr	plag,qtz	chl	tnt	-spherulitic, amygdaloidal (>qtz, amph, tr. opaques) -brown felted mass of <0.2 mm spherulites, devitrified. -xenolith-free, host rock carbon-poor adj. to dyke -contact of dyke, insitu brecciation -interspherulitic chlorite radiating, tnt tr-10% intersph.
285	dmct	274	40	plag. amph	tnt		-spherulitic (3mm and impinging), 10-15% amygdaloidal quartz-filled. -xenolith-free -radiating amph and tnt, quench-textures.
690	smeq	600	330	amph, plag	qtz	tnt mt leuc.	-flow-banded at >0.04 mm scale -very fine-grained amph/mica and felsic minerals. -geochem poor (increase in SiO2-xenos)
698	smeq	603	nw	plag/qtz amph	tnt/leux		-margin to aphanitic dyke complex; quenched -massive aphanitic with 2cm amph-filled amygdales (10%) -amph, hexagonal pseudomorphous poss. after pyroxene, tr euhedral tnt associated with mafic pseudo. -majority of amph 0.05mm needles radiating -felsic spherulitic matrix. -cut by fine calcite veinlet.
708	smfl	NW	016/32	plag/qtz		amph	-spherulitic, no xenoliths, tr amygdales (qtz, po); quenched. -brown indiscernible mass of spherulites with microcrystalline stubby 0.03 mm plag crystals. -spherulites 2mm, impinging spherulites ~ 6mm.
408a	smfl	307	300/85	amph plag/felsic	tnt	po cpy	-massive, amygdaloidal, amygs. flattened qtz/po-cpy -1% qtz xenoliths - matrix radiating amph needles in felsic matrix
639	dmlu	562	100	tremolite/chl plag			-quartz xenoliths, massive, chlorite-minor qtz filled amyg. -3% chlorite hexagonal; likely pyx pseudomorphs -amph max. 0.3 mm blades, microcrystalline plag laths -anhedral tnt,
565b	smeq -fl	442	nw/irr.				

Table A2-4.3: Strike and dip of aphanitic dykes

<u>Area</u>	<u>Dyke</u>	<u>Comment</u>	<u>Bedding</u>	<u>Measured dyke</u>	<u>Transformed dyke</u>
Cow Lake	D1	(?) Falco. smfl	050/30	185/85	353/74
	D2	Good, xc smfl, Av-408		300/85	112/83
Morgan	D3	Good, hill, xc dmlu/sm	065/30	308/90	134/80
	D4	Good, mtn, smfl/dmct		135/90	140/82
	D5	Cross str're to D4, no dyke	014/84	050/65	042/34
M. Mtns	D6	(?) Falco.,sm	065/30	166/75	171/86
Nelson	D7	Excell., all in sm,xc	075/30	022/74	006/54
	D8	same dyke as D7	016/32	014/66	358/56
	D9	Ok.		000/37	316/40
	D10	Excell. dip, Av-690,xc fl		030/59	008/42
Joe Lake		Apophyses off N/S		070/60	
	D11	OK-good, 20 cm wide	090/30	360/90	360/90
	D12	Excell, sharp ct edge of smfl		108/90	112/60
	D13			360/90	360/90
	D14	sill ok poor dip		180/20	236/35
Capreol		stn 445		340/70	
	D15	Good	085/30	308/60	303/76
	D16	All sill/dyke complex		292/40	284/70
	D17	on hwy.		330/50	314/68
	D18			038/45	004/30
Hanmer powerline				185/45	
				344/90	

PLATE CAPTIONS

Plate A2-4.1: Polished slabs of dykes, Onaping Formation

- a) Spherulitic andesite dyke in the footwall to the Limerick Cu showing. Morgan township, station 242, sample AV-271.
- b) Spherulitic and amygdaloidal dyke. Intruded into contact unit near eastern, north/northeast trending contact. Morgan township, station 274, sample AV-285.
- c) Localized, peperitic margin between flow-banded aphanitic dyke and contact units, Dowling member footwall to Limerick Cu-showing. Morgan township, station 242, AV-269.
- d) Sharp contact between fluidal-lapilli tuff and flow-banded aphanitic dyke. Cow lake area, station 307, AV-408.
- e) Aphanitic, amygdaloidal neck with perlitic cracks. Intruded upper middle units, Cow lake, station 347, sample AV-451.
- f) Amygdaloidal aphanitic dyke intruded mid, lower middle units. Morgan township, station 272, sample AV-283.

Appendix 2-5

PEPERITE

2-5a. Introduction

Peperite, is an unusual, poorly recognized rock produced from magma emplaced into unconsolidated wet sediment (Jones, 1969), composed of a mixture of sediment and melt. The occurrence of peperite is important as it reveals that the timing of intrusions is late-syn-depositional with unconsolidated, wet host strata and that the depth of intrusion is shallow (McPhie et al., 1993). The proximity of peperite in the footwall to 8 million tonne deposits of Zn-Cu-Pb is not entirely fortuitous; it is hydrothermally altered and defines zones where magma/melt intruded close to the paleosurface in weakly consolidated wet sediments, possibly defining syn-'volcanic' structures. The hydrothermal alteration of peperite and the relationship to Zn-Cu-Pb base metal mineralization will be documented and discussed in Chapters 4, 5 and isotopic characteristics of alteration minerals defined in Chapter 6.

Textural and field relationships of peperite in the Onaping Formation are significant to our knowledge of the genesis and mode of formation of peperite in general and provides critical constraints on the timing and genesis of the Sudbury Structure crater-fill sequence, the 'enigmatic' Onaping Formation.

2-5b. Local setting and distribution

Peperite has been observed to date only in the Dowling member. In the North Range Onaping Formation, peperite is localized (<50 cm) at the margins of aphyric aphanitic dykes intruded into the contact units at the base of the Dowling member. In the South Range, the extent and abundance of peperite are greater. Laterally extensive zones of peperite occur only in the south-southwest part of the Sudbury Basin in the middle and upper units of the Onaping Formation.

In the footwall to the Vermilion deposit, northeast-trending zones (055°) slightly oblique to stratigraphy are anomalous in aphanitic, spherulitic and amygdaloidal 'andesitic' sills/dykes (Tims, 1990; Bell, 1990) (Figure 2-12). In present map position, these anomalous zones (2-3) of intrusions extend from the surface (Onaping/Vermilion formation contact) to 1500 m depth. Within this area the concentration of 'melt bodies' near the base of the Onaping Formation is also high, (Sudbury map, Dressler et al., 1984). The peperite localities studied are well exposed parts of these extensive zones (Gray, 1995; Bell, 1990, Tims, 1990) (Figure 2-12). Two zones outcrop in the middle and upper units, south of Vermilion lake (Figures 1-2, 2-12, A2-5.1-3) and one was intersected in Falconbridges drilling in 1994 at the top of the Onaping Formation near Azilda (Figure 2-2).

The association between peperite and anomalous intrusive activity is evident. A 600 m x <100 m intrusive zone contains the A&M peperite in carbonaceous tuff of the middle units, Dowling member (Figure 2-12). Aphanitic, spherulitic and amygdaloidal dykes range from 10 cm to 2 m wide and are less than 15 m long (Bell, 1990). Another major zone of peperite and dykes extends at 055-060° for over 6 km, and contains the

Gordon lake peperite showing (Figures 2-12, A2-5.1). The peperite zone mapped, 175 m by >1000 m is part of a 6 km long zone of intrusive activity which lies presently 300 m below the Vermilion deposit. This structure is slightly oblique to bedding and subparallel to the foliation. The Gordon lake road peperite is hosted in bedded to poorly bedded, carbonaceous tuff and ash of the upper units, Dowling member. Spherulitic and amygdaloidal intrusions occur as 1-2 m irregular pods, 5-10 m lobes, and a 060/70° dyke was traced for over 800 m (Tims, 1990).

The results are based on combined detailed mapping (1: 200, 1:250), drill core logging, thin-section studies and follow-up, rock geochemistry, alteration mineral chemistry and isotope geochemistry. Study of two peperite showings reveals the macroscopic and microscopic evidence for 1) interaction between hot magma and unconsolidated wet sediment 2) in-situ brecciation of host rocks and 3) fluidization of sediment (Plates A2-5.1-5).

These two peperite showings have differing host rocks and textural characteristics. The peperite exposures are characterized by a classic, blocky clastic texture hosted by the carbon-bearing (0.4 to 1.6 wt% C_{org}; Gray, 1995) upper units at the Gordon lake road and Azilda showings or a lensoidal texture in the coarser middle units exposed at the A&M showing (Figure A2-5.4, Plates 16g 2-14). Outcrop exposures at the Gordon lake road showing are oriented perpendicular to foliation and lineation, thus the effects of shortening and stretching on the textural features in outcrop are minimal.

Zones of mixing were classified based on the relative proportion of andesite (magma/melt) to tuff (sediment) and textural characteristics. The most intense mixing zone

comprises a greater percentage of andesite with lesser tuff than the moderate and weak mixing zones.

2-5c. Lensoidal peperite (A&M showing, Figures A2-5.2 and 3)

Host rock characteristics and *in situ*-brecciation:

The tuffaceous middle unit host rocks are altered in a zone at least 100 m wide. Alteration of the tuffs in the hangingwall and footwall of the peperite differ. Silicification and chloritization dominate in the footwall and Fe-Mn alteration in the hangingwall. Rusty recessive weathering concretions (1-5%, avg. 3% mm to cm scale) are disseminated in the hangingwall tuffs and vugs (50 x 100 cm) filled with comb quartz and black Mn-oxide (?). Distal to the peperite zone in the footwall (15-50 m) the middle unit tuff is silicified, carbon-poor and autobrecciated with numerous examples of *in situ* brecciation of the tuff (Plate A2-5.1c, A2-5.2a). Tabular, tuffaceous fragments average 10 cm with minor 1 m pods of massive tuff with *in situ* brecciated margins. The size of brecciated fragments increases away from the peperite.

A pseudo tuff-breccia outcrops within 15 m of the intense zone of mixing (Plate 2-13c). It consists of 55% light grey weathering, silicified tuff, 25% angular clots of green hyaloclastite and 20% fine spherulitic amoeboid dykes. Cuspate and arcuate pods of hyaloclastite are disseminated within the altered tuff and forms the matrix to the irregular spherulitic dykes. The abundance of andesitic dykes increases to 55% and forms the matrix

weathering with 60% amygdales and 10% fine spherules in a brown chloritic matrix of hyaloclastite.

Morphology of peperite

Intense Mixing Zone (IMZ): The zone of most intense mixing trends 095°, is 8 to 12 m wide by > 40 m long and is subparallel to bedding (Figure A2-5.2). The proportion of andesite (spherulitic or chloritic) to tuff remains constant (65:35) but there are textural and size variations of the various components laterally. Tuff fragments are hosted in a matrix of spherulitic to hyaloclastitic andesite. The contact between the intense zone of mixing and more homogeneous tuff is sharp with a 1 cm wide silicified band within the tuff. The tuff is weakly altered with 2% 1 cm arcuate, cusped brown weathering hyaloclastite clots containing <5% 1 mm, white spherules. Within the intense mixing zone along the contact, 10 cm blocks of tuff have less altered cores whereas in the core of the zone the tuff is pervasively altered. Contacts between the tuff fragments and dyke component to the peperite are irregular with *in situ* brecciation of the tuff.

Spherulitic and/or hyaloclastitic andesite forms amoeboid pods averaging 1 m but also forms the matrix to 10 cm blocks of silicified tuff (Plate A2-5.2e). The dykes are amygdaloidal and spherulitic with spherules nucleating on the edge of silicified tuff fragments. Generally the amygdales (15-25% of the dyke) are partially to totally filled with quartz but locally with pink Kfeldspar and range from mm to 1 cm. The hyaloclastite in spherulitic dykes forms linear bands 1-2 mm wide, separating 1 cm spherulites and also forms the matrix for spherulites (spherulites comprise 95-80% and hyaloclastite matrix 5-

20% in pods). Arcuate, angular patches of hyaloclastite may be dominated by chlorite 60% with lesser to no spherulites.

In general, to the east, the size of the tuff fragments decreases and the proportion of hyaloclastite to spherulitic andesite increases (Plate A2-5.2d, f, g). The eastern exposures consist of 50% spherulitic andesite, 35% bleached silicified tuff and 15% brown weathering tuff spherulitic andesite pods, 15-35 cm, form the matrix to 1 by 10 cm elongate, angular, tabular silicified tuff slabs. The andesite contains mm-sized spherules that form <1 cm aggregates in the core of cusped hyaloclastite. Sediment slabs are generally elongate along 060° but are locally randomly oriented. Many are not aligned but follow curvilinear flow lines around dykes (Plate A2-5.2). Sediment width is generally 1 cm with minor 6-10 cm blocks within larger peperite dykes. To the west the proportion of dykes increases to 60-80%.

Moderate Mixing Zone (MMZ): The MMZ is laterally equivalent to the IMZ on the eastern edge and is defined by a decrease in the amount of andesite dyke. The proportion of andesite to tuff is 35:65 and the pods of andesite are all aligned at 070° within a more cohesive tuff matrix (Plate A2-5.2). The contact between the MMZ and IMZ is undulose yet sharp (Plate A2-5.2b). The tuff is silicified in the main zone and chloritic at the eastern footwall contact with the pseudo breccia. Contacts with the tuff are sharp, marked by a decrease in dykes and the tuff is not visibly altered.

Andesite dykes occur as 1 m amoeboid bodies with a core of spherules and chlorite and 95% of the dykes contain xenoliths of silicified tuff. Fine 1 mm spherules dominate and may coalesce into 1 cm aggregates. The contacts of the amoeboid bodies

with the tuff matrix is defined by a <10 cm band of silicified tuff or fine rim of chlorite. To the south the andesite is less spherulitic and more chloritic with an sudden increase in chlorite and decrease in silicification of the tuff within the weak mixing zone (Figure A2-5.2). The pods are all <1m elongate pods averaging 25 x 15 x 20 cm and each contain ~ 15-20% silicified tuff xenoliths.

Chloritized tuff in the footwall to the peperite zone, contains 1 cm gas cavities filled with euhedral quartz. There are local zones with intense chloritic alteration of the tuff both within the MMZ and IMZ. One location at the edge of the MMZ is a zone of silicified light grey weathering tuff with 15 % andesitic xenolith-free dykes composed dominantly of hyaloclastite with minor spherules. The tuff contains, 5%, 2 cm discontinuous chloritic stringers.

Morphology of penetemporaneous andesitic intrusions

Lobes: Andesitic lobes, 2.5 to 5 m in diameter are concentrated in an area trending 028° (Figures A2-5.2 and 3, Plate A2-5.3). Many are nested or occur as isolated bodies that intrude least altered tuff and peperite. Contacts with the tuff are free of hyaloclastite and sharp. The lobe contact with the zone of intense mixing is sharp and orthogonal to the 060° fabric in the peperite produced by the elongation direction of discontinuous dykes and brecciated altered tuff (Plate A2-5.3).

These andesite lobes have leakage pods and may display annular, texturally variable, bands. These include massive cores, spherulitic bands with coarse <2 cm

spherulites, xenolith-rich zones and outer amygdale-rich margins (Figure A2-5.3 and Table A2-5.1).

Isolated Andesite Pods: Isolated andesite/tuff pods vary from 10 cm to 3 m, averaging 60 cm and have a 0.5 cm continuous silicified rims (Plate A2-5.2c). They are spatially associated with the andesitic lobes. The andesite consists of fine spherulites in a chloritic/hyaloclastite matrix. They are generally hosted by tuff containing 20%, 4 mm wispy chloritic shards, minor 2 cm arcuate andesite clots and 1%, 1cm amygdaloidal andesite angular lithic fragments.

Andesite Breccia: An isolated 7 x 4 m pod of andesite breccia with poorly exposed contacts, consists of 30% irregular 20 cm pods of massive amygdaloidal andesite within a matrix of spherulite- and hyaloclastite-rich andesite. The massive andesite contains 15-20% 2 mm amygdales and the chilled matrix material contains large 1 cm gas cavities partially filled with quartz. Andesite fragments are as large as 80 x 20 cm.

2-5d. Blocky peperite (Gordon lake road; Figure A2-5.1 and Azilda localities)

Host rock characteristics and *in situ* brecciation: The upper unit tuff of the Dowling member host of the blocky peperite showing, is locally thinly bedded with alternating 20 cm tuff and fine tuff beds ($S_o=087/69$). Discrete spherulitic, amygdaloidal and massive dykes and sills crosscut the tuff proximal to peperite (Plate A2-5.1a). Numerous examples of the transition from massive silicified tuff, to incipiently fractured, then progressive alteration along fractures into pseudo-breccias and lapilli peperites with tuff fragments in

an andesitic matrix, occur within the area mapped (Plate A2-5.1 b, d). *In situ* brecciation of the silicified tuff produces small local pods of peperite.

Morphology of zones of mixing

Most contacts show a progression from massive to *in situ* brecciation to peperite formation with an increasing component of andesite (i.e. Plate A2-5.1 and 4). Lateral textural variations in the peperites consist of a fining, (eastwards) and an increase in the andesitic component. The contact relationships are sharp and mappable, yet are gradational. The contact between a silicified tuff zone with the least amount of andesite and the blocky peperite with the most andesite is sharp with a marked, sudden increase in the amount of brecciation (Plate A2-5.1f). There is no transition or progression in the brecciation between a weak and strong mixing zone in this locality. This suggests local remobilization (local transport) of the blocky peperite. The contact between the same *in situ* brecciated zone and dispersed coarse peperite is marked by an increase in the amount of andesite with large pods of silicified tuff and andesite. Fragments of the delicate net-textured rocks are contained within an adjacent tuff-dominant zone. A chloritic amoeboid mixing zone occurs in the footwall on an isolated outcrop ~30 m south of the detailed map area.

Delicate net-textured tuff: A local area of fine delicate textured peperite in the footwall to the main blocky peperite zone is hosted by a relatively coarse lithic-rich (60-70%, 4-6 mm) carbonaceous tuff. The tuff contains 20 %, fine 5 x 2 mm, ragged, chloritic shards and 10-15%, carbonate with associated trace sphalerite (red), pyrite and

chalcopyrite. Coarse, 2-4 cm, spherulitic andesite pods are minor (10%), (Plate A2-5.1e).

The recessive weathering shards and carbonate and positive weathering quartzose 6 mm lithic fragments reveal the texture characteristic of this zone. Subrounded fine <1 cm, carbonaceous lithic fragments are common. Sediment-infilled vesicles attest to the fluidity in this zone although there is only minor addition of andesitic magma as rounded 3 cm pods.

Massive silicified tuff with irregular andesite dykelets (5%): The transition from more massive tuff to that with increased andesite is marked by the increase of *in situ* brecciation. In this zone, massive, light grey weathering silicified tuff dominates (85-90%) with 5 mm discontinuous andesite dykelets and <5% arcuate chloritic clots.

Tuff with minor andesite (10-15%): These orangey brown and pocketed weathering tuffaceous zones are in the footwall in contact with the delicate-textured and blocky peperite (Figure A2-5.1). The tuff is carbon-bearing and is host to 20% grey weathering elongate pods of silicified tuff and 5-10%, rounded clots of andesite and 5% carbonate bearing clots (Plate A2-5.1b). Amygdales and bubble-like protrusions in the angular andesite fragments are infilled with sediment attesting to the fluidity of the sediments during peperite formation. The andesite is composed of mm-sized feldspar spherulites, chlorite, biotite and calcite. Carbonate occurs as a replacement of chloritic shards and andesitic fragments and is associated with sphalerite, chlorite and chalcopyrite.

Dispersed coarse peperite (50% andesite): The zone of dispersed coarse peperite (B) is inhomogeneous and contains subequal amounts of andesite and tuff. The tuff varies

from massive to fragmental with irregular small blocks (5-10 cm) and irregular andesite clots are coarse 10-20 wide.

Dispersed fine peperite (40-60% andesite): This zone is characterized by abundant, 40-60%, fine 1-2 cm, recessive weathering, pale green, sericitized, blocky andesite clots in a silicified tuff host. This peperite has a variable matrix between andesite and tuff. The arcuate andesite fragments increase in abundance laterally (eastward). Silicified tuff fragments vary from 10 cm to 1 cm and fine laterally (eastward). Irregular light green weathering, amygdaloidal pods and dykes of altered andesite are also present comprising ~10%. The <30 cm dykes are more abundant in this zone than in the adjacent zone to the west. Within the silicified tuff are 2% quartz vugs with pink feldspar. Locally pink weathering feldspar also rims the andesitic pods.

Silicified tuff with discrete pods of andesite(50% andesite): This zone is coarse with 50% silicified tuff containing minor (10-15%) arcuate chloritic melt fragments and 40% discrete <1 m irregular andesite pods. These pillow-like light green weathering pods are described below.

Chloritic Amoeboid Mixing Zone(60% andesite): This mixing zone contains 60%, 5-40 cm amoeboid “globular” andesite pods within carbonaceous tuff. The isolated andesite pods are spherulitic with 3-5% quartz filled amygdales and <4 cm partially filled vugs. Spherulites nucleate on the outer rim of the amygdales and on the edge of the globular andesite pods. The host tuff is weakly chloritized and contains <1% 1cm, rounded quartzite clasts.

Blocky peperite (60-80% andesite): Blocky peperite consists of abundant (60-80%), fine (1cm), angular cusped fragments of greenish brown to grey weathering altered andesite (glass) in a silicified tuff matrix (Plate A2-5.1). On average the blocky peperite contains 65% 1-2 cm spherulites and associated chloritic, biotitic or sericitic arcuate clots in a matrix of silicified tuff and locally contains <<5%, discontinuous chloritic ribbons. Irregular, globular spherulitic andesite dykes including 6 cm silicified tuff fragments are present in minor amounts at the western extremity. These are similar to those in the intense mixing zone at the A&M showing except that the host rock differs. Textural variations in the altered and devitrified andesite are the result of devitrification and alteration features. Spherulite content ranges from 70% to 30%. Carbon is present in the tuff in minor amounts but is concentrated within the devitrified and altered andesite fragments in interspherulitic spaces, discontinuous pods and blebs and along fine fractures centred on vugs.

Lithic fragment types include, amygdaloidal andesite lapilli, blocks of carbon-bearing lapilli tuff and quartzite lapilli (2cm). The 1-1.5 cm white weathering, amygdaloidal fragments (possibly andesite) are fractured along bubble walls and situated in the most intense zone of mixing. They comprise 5% of the tuff and are concentrated in this zone only. Rusty weathering, carbon bearing lapilli tuff fragments ranging from 10 cm to 40 cm coated with brown weathering tuff are hosted within the blocky peperite (Plate A2-5.1). Carbonaceous fragments are tear drop shape with the wider end consistently oriented northeast (060°).

Morphology of penetemporaneous andesitic intrusions

Lobes: Massive white weathering amygdaloidal andesite is poorly exposed in this locality and is hosted within the blocky peperite. The morphology is that of linear 20 cm wide discontinuous pods, possibly a boudinaged dyke, and a partially exposed white weathering lobe. The lobe is partially massive, contains ovoid cm sized quartz-filled gas cavities and a 30 cm wide, autobrecciated outer carapace with 20-60 cm white massive andesite fragments in a green weathering matrix.

Isolated Andesite Pods: Amoeboid and pillow-like andesite pods (100 x 45 cm; 40 x 5 cm) are sericite altered, pale green, and amygdaloidal. They occur as coherent bodies within both cohesive and brecciated tuff but generally do not contain tuff xenoliths (Plate A2-5.2). The contacts with the tuff are locally chilled with a fine grained 1-2 cm wide amygdale-poor zone. The pods typically consist of a core with 65-70%, 4 mm quartz filled amygdales with amygdale size increasing towards the margin and a thin (5-10 cm) outer zone with finer, 2 mm amygdales. Amygdale size and abundance increases to the north and south in adjacent pillow-like pods and thus are not paleotop indicators. Amoeboid pods occur within the blocky peperite zone with an irregular globular morphology similar to that in the intense mixing zone at the A&M showing.

2-5e. Discussion and interpretation

The depositional setting of the Onaping Formation with rapidly deposited fragmental rocks favours the development of intrusions rather than flows. The rise of magma through a thick sequence of less dense, wet, poorly consolidated fragmental rocks

is impeded due to buoyancy constraints and aqueous quenching (McBirney, 1963). The melt, instead of being extruded spreads laterally at shallow levels into the weak sediments and may cause explosive and/or passive interaction upon interaction with the cool wet host rocks. Peperites are produced as a consequence of combined quench and explosive hydrovolcanic processes. At the contact of hot melt and wet sediments temperatures can reach 1000°C. At this point water vaporizes and expands explosively. The sediment then becomes fluidized by the vapour with the volume of fluidized sediment constrained by the PT conditions of the critical point of the sea- or pore-water (Kokelaar, 1982). Theoretically the depth constraint of peperite formation is 1.6 km of wet sediment (assuming a density of 2 g/cm³) (Kokelaar, 1982).

Fragmentation occurs due to steam explosions (Kokelaar, 1982, 1986; Wohletz, 1986; Sheridan and Wohletz, 1983) or quenching to form hyaloclastite (Carlisle, 1963; Hanson, 1991; Hanson and Wilson, 1993; Brooks et al., 1982). The expansion of heated pore water and flashing to steam causes explosive mixing, disruption of the sediment and allows rapid, irregular penetration by melt. Space for the melt is created by lifting the rock/water and expulsion of pore water. Variable textures in peperite bodies have been explained due to differences in host rock rheology (Busby-Spera and White, 1987), the amount of pore water (Brooks et al., 1982) and/or the melt:water mass ratio (Sheridan and Wohletz, 1993). The optimal ratio of water:melt is 0.3 for maximum transfer of thermal energy to mechanical work in a basaltic melt and results in the production of fine (<50 µm) blocky shards (Wohletz and Sheridan, 1983). Busby-Spera and White (1987) noted that different lithofacies of peperite formed in differing host sediments. Blocky

peperite as opposed to globular peperite formed in a poorly sorted, coarser grained sandstone whose greater permeability interferes with the development of a vapour film, thereby suppressing the amount of sediment that is fluidized where the water to melt ratio is relatively high. Blocky peperite is therefore inferred to occur dominantly by passive fragmentation and quenching. Blocky angular shard outlines are controlled by fracture surfaces rather than broken vesicle walls and are characteristic distinguishing features of hydroclastic fragmentation (Heiken, 1972). Globular peperite forms lensoidal, bulbous and lobate bodies in fine-grained, well sorted sediments which are permissive to fluidization and fluid flow. The insulating vapour film insulates the magma from the wet sediments and suppresses steam explosions. The host characteristics of the two peperite bodies in different stratigraphic levels and host rocks in the Onaping Formation reveal the opposite textural features. Fine-grained well sorted tuff of the upper units hosts the blocky peperite and more poorly sorted coarser-grained middle units host the lensoidal peperite. The differences in grain size and sorting are not pronounced, thus other factors may be more important in controlling the textural lithofacies in the Onaping Formation. Other factors influencing the fragmentation may include different; melt/water mass ratios, rate of supply of melt, the rate at which the water and melt are brought in contact, relative confining pressures and lithification of the sedimentary pile.

Lensoidal peperite textures with very fluidal, amoeboid, smooth boundaries to the melt fragments are exposed deeper in the pile than the blocky peperite although the relative proximity to the paleoseafloor at time of peperite formation is unknown. The occurrence of blocky peperite near the Onaping Formation/Vermilion Formation contact

(Azilda showing; Figure 1-2) and peperitic margins on a mafic dyke near the base of the Onwatin Formation (Stoness, 1994) suggest that batches of melt were injected as the Onaping Formation was being buried. The larger size and shape of melt fragments in lensoidal peperite relative to that in the blocky peperite suggests a more passive mode of fragmentation.

The lensoidal peperite showing displays an evolution in peperite formation. Two structural features are outlined by the E-W orientation of the intense mixing zone and the NNE trending zone of intrusive andesite lobes. The semi-conformable nature of the intense mixing zone may represent a boiling front above a sill, out of section or may represent a fluidized mixture moving laterally away from a structure along a permeable aquifer. Fluidization of sediment is evident by sediment-filled vesicles in the melt and vesicles in the tuffaceous sediments. Ovoid lobes intrude tuff without a marginal zone of hyaloclastite or peperite, intrude peperite and themselves. The discordant nature of the andesite lobes and intrusive contacts with the intense mixing zone or lensoidal peperite suggests that the sediment was lithified and dewatered prior to this phase of melt injection. The interstitial water was driven out by earlier melt that interacted with and fluidized the sediments (first boiling). Initial rapid boiling of pore water caused silica dumping, rapid dewatering and lithification of the sediments during formation of the lensoidal peperite. The lithified altered sediments behaved by "pulling apart" and allowed the penetration of the magma passively. Silicification and vesiculation of the sediment is common within the zones of mixing reflecting hydrothermal alteration during peperite formation. The sequence of events suggests that the magma was emplaced in pulses or small batches.

Lateral facies changes in the mixing zones have an east-west trend, sub-parallel to bedding. The western part of the intense mixing zone is dominated by spherulitic andesitic magma which forms the matrix to sediment fragments whereas to the east the spherulitic andesite is subdominant forming amoeboid lenses within the sediment. This may reflect proximity to magma source implying magma injection along the NNE intrusive zone and dispersal of melt fragments through a steam/sediment slurry along bedding planes or zones of weakness. Isolated andesite pods are globular and proximal to within 1-2 m of andesitic lobes. These may represent tongues of peperite close to the intrusive contact as typically documented in the literature.

A peculiar feature of the Onaping Formation blocky peperite is the large scale of the peperite formation in the absence of large dykes. Many studies document narrow, < 3 m peperitic margins on thick sills (Busby-Spera and White, 1987; Kokelaar, 1982; 1986). It is possible that a large dyke is not at the present erosional surface and the surface only intersected the peperitic margin. In the Onaping Formation, there is an association with anomalous dyking but the transition from dyke through peperite to cohesive sediment is observed only on a small scale.

The blocky peperite showing is stratigraphically higher than the lensoidal peperite and is many orders of magnitude larger. The relative timing of dyke injection is unknown but different textural features likely reflect that the confining pressure was less at the blocky peperite showing. Blocky angular shapes are distinguishing characteristics of hydroclastic fragmentation (Heiken, 1972). The blocky yet irregular shapes of melt fragments suggests that passive fragmentation (i.e. during quenching) or dynamic stress

fragmentation (i.e. hyaloclastite margins on a flowing dyke) are not the only processes responsible for the Onaping Formation peperites.

Common on the fringe of the two peperite zones are arrested, *in situ* brecciated silicified sediment with the fractures infilled by melt (Plates A2-5.1c, A2-5.2a). These fractures may have formed by 1) magma overpressuring, 2) volume loss in the sediment due to expulsion of pore fluid along the intrusion front, 3) hydraulic fracturing due to thermal expansion of heated groundwater/shallow aquifers during magma rise, or 4) least likely, melt injected along pre-existing joints or fractures. Fractures may propagate due to thermal expansion of heated liquid or pore water (Germanovich and Lowell, 1995). The heated water expands, fractures the rock causing a pressure drop which may induce boiling until all of the pore fluid is converted to steam causing rapid fracturing. Melt then enters the cracks. An open system would not allow pressure build up under purely hydrostatic pressure in shallow unconsolidated sediments and the heated water could escape upward resulting in fumarolic and hot spring activity. An impermeable layer could allow pressure increase.

Angular, cusplate melt shapes or blocky textures in the lensoidal peperite showing are present in minor amounts near the margins of the intense mixing zone (Plate A2-5.2d). These andesite “clots” may represent either quench or explosively formed fragments or an infilling of open spaces. These blocky andesite textures appear to be due to the infilling of void spaces in the silicified andesite possibly due to volume loss and not fragments due to quench fragmentation as proposed in the literature (Brooks et al., 1982; Kokelaar, 1982; Hanson and Schwieckert, 1983; Busby-Spera and White, 1987; Heiken, 1972). In the

blocky peperite showing, blocky melt fragments comprise >50% of the rock and in this case it is unlikely that the shapes could all be due to contraction and infilling with magma but that quenching and explosive dispersal of melt clasts also occurs. A number of processes are likely involved in forming the complicated, spectacular peperite textures.

The chaotic aspect of the blocky angular andesite fragments suggests that steam explosions played an important role in dispersal of the fragments. Methods to disperse melt fragments during peperite formation consist of gas (Kano, 1989; Kokelaar, 1982) and/or continued movement of disintegrating sills (Brooks et al., 1989). If the rate of melt injection was fast enough to induce boiling of pore water violent phreatomagmatic activity would ensue. The sharp contact relationships (Plate A2-5.1) suggest that the tuff fragments were not derived from the locality adjacent to the intense blocky peperite and the material probably moved as a fluidized mass. There were multiple events such as fragmentation due to volatile expansion to produce rare bubble wall andesite fragments, fragmentation to produce the main blocky peperite zone and rapid dispersal and inclusion of delicate peperite fragments and carbon-bearing middle units Onaping Formation into the blocky peperite.

Peperite has not been observed in the North Range, perhaps as a consequence of the absence of structures to bring volumes of melt near the top of the fragmental pile. Dykes associated with peperite formation in the Onaping Formation are demonstrably contemporaneous with the epiclastic strata. The linear distribution of peperite zones and anomalous zones of intrusive activity thus define linear structures that are syn-depositional and were possibly reactivated during deformation. These syn-depositional structures that

focused hypabyssal melt close to the surface are also loci for hydrothermal fluids which altered the melt-derived clasts in peperite and silicified the surrounding sediment. This bedding-parallel silicification zone produced an impermeable layer possibly impeding hydrothermal circulation on a large scale. The importance of these structures for syn-depositional hydrothermal alteration and base metal deposition is discussed in chapter 4.

Appendix 2-5f. Geochronology of peperite

Introduction

The age of these intrusions that are contemporaneous with deposition Onaping Formation is of utmost interest since they would define the age of the top of the complex fragmental pile. Sample AV-162 was selected for geochronology from the upper 400 m of the Onaping Formation, southwest of the Vermilion deposit at the A&M peperite (Figure A2-5.3). Zircon from the chloritic interstices between 1-2 cm spherulites within a 7 m diameter, glassy intrusive pod in peperite was analyzed. Magmatic zircons from this sample should date deposition of the upper part of the Onaping Formation and xenocrystic zircons should give an indication of the source basement rocks below the South Range of the Sudbury Structure.

Methodology and results

Zircon was dated by conventional U-Pb methods (Krogh, 1982; Parrish et al., 1987; Roddick, 1987; Roddick et al., 1987). Zircon was abraded and analyzed as single

grains because, from their morphological characteristics (angular, broken grains), they were suspected to be xenocrystic. Pb and U blanks were about 5 and 0.2 picograms, respectively. Isotopic results are documented in Table 4-6 and reported in Ames et al., 1998. Four zircons from sample AV-162 were analyzed as single grains; two are concordant to nearly concordant, and analysis A was strongly discordant with substantial Pb loss (Ames et al., 1998, Figure 4). The $^{207}\text{Pb}/^{206}\text{Pb}$ ages in Ma and discordance in percent, of xenocrysts A, B, C, and D are: 2296.9 ± 5.8 , 9.1; 2602.8 ± 3.3 , -1.3; 2616 ± 5.7 , -0.3; and 2628.6 ± 3.2 , 3.7, respectively. The nearly concordant zircons indicate sources of these ages.

Discussion of peperite geochronology

The peperitic nature of the andesitic intrusions emplaced into the top of the Onaping Formation implies that the intrusions were part of the same depositional cycle or event as that of the Onaping Formation. The ultimate goal of geochronology on these intrusions was to determine the age of their host rock, the Onaping Formation by obtaining crystallization ages of the intrusions. Recent geochronologic work on fluidal glass dykes and pods within the lower Onaping Formation on the North Range yielded concordant Archean zircons ranging from 2719 to 2686 Ma (Krogh et al., 1996) and it was suggested that the zircons were derived from a sedimentary target rock. Xenocrystic zircon from a fluidal glassy pod in our study near the top of the Onaping Formation, South Range yielded much younger ages between 2600 and 2632 Ma. These are significant in that Archean Superior Province rocks within a 2600-2632 Ma age range are rare and

volumetrically insignificant (Corfu and Davis, 1992). They are restricted to mid- to lower-crustal Archean rocks such as the Kapuskasing Structural Zone (Krogh, 1993) and in kimberlite-borne granulite-facies xenoliths (Moser and Heaman, 1995). Granulite facies rocks of the Levack gneiss complex reveal part of the lower crust below the Sudbury Structure. Until recently, the only available protolith age for the Levack gneiss complex was 2711 ± 7 Ma (Krogh et al., 1984). Younger ages such as 2669-2668 Ma granodiorite and a 2657 ± 3 Ma monzodiorite (Wodicka, 1997) are compatible with a local Levack gneiss origin for some xenocrysts in glass bodies previously dated (Krogh et al., 1996). Late pegmatite in the Levack gneiss complex yielded a U/Pb date of 2631 ± 2 Ma on zircon (Wodicka, pers. comm.). Thus pegmatite from the Levack gneiss complex could be the source of xenocrystic zircon D dated in this study although the sources of the 2600 to 2622 Ma xenocrysts are not evident.

Percival and Krogh (1983) recognized that the highest grade and deepest rocks in granulite terranes yielded the youngest ages. Therefore, part of the melt in the Onaping Formation may have had in part a deep crustal source. This could have been achieved during impact by 1) melting of the lower crust, which is compatible with mathematical models of the depth of shock wave penetration (Grieve, 1994) or 2) higher level melting of partially exhumed Levack gneiss complex.

Figure 2-5.1: Geology map of the Gordon Lake road, blocky peperite showing. Peperite developed in the Upper units of the Dowling member. The showing is intensely altered and a simplified alteration map is shown in Figure 4-13.

Figure A2-5.2: Geology map of the A&M, lensoidal peperite showing. East-west trending mixing zones transected by NNE trending zone of intrusive lobes. Textural features of lobes are noted in Table A2-5.1 and Figure A2-5.3.

LEGEND

- outer rim, hyaloclastite rich with fine spherulites
- Andesite**
 - Andesite lobes
 - Massive andesite
 - Andesite breccia
- amygdales
- * • spherulites, unimodal/bimodal size population
- △ spherulites, unimodal/bimodal size population
- ① Lobe number
- block-rich zone

Figure 2-5.3: Detailed map of textural features of andesitic lobes intrusive into the lensoidal peperite and middle unit tuff, Dowling member. See Table A2-5.1 for descriptions of individual lobes.

Figure A2-5.4: Characteristic melt morphologies in intense mixing zones of peperite showings, Onaping Formation, Sudbury Structure. Sketches of photographs of A) Blocky peperite, intense mixing zone, Gordon Lake road B) Lensoidal peperite, intense mixing zone, A&M showing. m=andesitic melt, spherulitic in B, t=Dowling member tuff.

Table A2-5.1: Textural characteristics of intrusive lobes (see Figure A2-5.3)

	Textural features (core to rim)	Size (m)	Host	Morphology
Lobe 1	A: 85%, core with 1.5 to 2 cm spherulites within a chloritic matrix local spherulites impinge to form massive zones B: 3 cm wide: zone of amygdaloidal andesite with an increase in chlorite (30%) C: 1-2 cm wide: fine coalesced spherulites with 5% amygdales D: 3 cm wide amygdale-rich (70%) band with 20%, 4 mm spherulites in a chloritic matrix. e: 1-2 cm chloritic outer carapace brown weathering with fine spherulites	>3.6 x 2	FW to main peperite MU with large irreg. isolated peperite pods	? not exposed fully
Lobe 2	A: 70%, 1.5-2 cm joined and isolated spherulites in chloritic matrix (AV-162) B: 60 cm wide band with 30%, 1 cm spherulite, 50% 4 mm spherulites within a greenish brown chloritic matrix. Bimodal spherulites (AV-161) C: 2.5 to 3 cm wide. 7 mm coalesced spherulites with 35% 2-3 mm quartz-filled amygdales. D: 2 cm wide. 65-70% 3 mm spherulites in a chloritic matrix E: 0-2 m discontinuous block-rich zone. quartzite blocks in amygdaloidal andesite Rounded blocks 10-20 cm. F: Discontinuous lense of closely packed 5 mm spherulites and quartz-filled amygdales in a chloritic matrix (25%) D,E,F= AV-160	>7 x 2	HW to main peperite	irregular
Lobe 3	massive core surrounded by a 20 cm annular block-rich band and a 10 cm spherulitic outer rim. (Plate 2- x)	3 D view 2.3x0.6x2.5	crosscuts peperite tuff contact.	annular with leakage tube
Lobe 4	A: < 2m, spherulite-rich core with chlorite-altered groundmass. Spherulites fine from 1.5 cm in the core to 5 mm near margin. B: < 20 cm. rim of altered tuff with 30-40% feldspar-filled amygdales and carbonate leached cavities.	~ 2	Hw of main peperite Fe-Mn altered MU	annular
Lobe 5	annular zones apparently thicker on west side likely due to dip of lobe. A: ~ 2m wide, densely packed coarse grained spherulites and ~5% large gas cavities. B, D: < 40 cm. amygdale-rich andesite with 10-15% amygdales rimmed by feldspar with euhedral quartz infillings and Fe-Mn carbonates C: <40 cm. 60%, 5-15 mm spherulites within a chloritic groundmass. Lobe 5 xcut by abundant tensional veins with comb quartz, pink feldspar and Fe-Mn carbonate.	3.5 x 3.5	HW of main peperite Fe-Mn altered MU	annular
Lobe 6	A: core irregular shaped zone 5.6 x 2 m of coarse grained spherulites B: 60-140 cm wide annular zone, bimodal spherulite population with abundant quartz-feldspar filled amygdales. Larger spherulites rimmed by Fe-Mn carbonates. C: outer <1 m zone. Chlorite-rich (possibly hyaloclastite) with fine grained closely packed spherulites.	8.4 x 3.4	HW, Fe-Mn altered tuffs with small local pods of peperite	elliptical
Lobe 7	core local massive zone coarse spherulitic with amygdaloidal margins 3-20 mm. flow banded contact with layers of impinging spherulites	2.5-6 x >6	crosscuts IMZ and MMZ of peperite.	elongate

PLATE CAPTIONS

Plate A2-5.1: Host rock characteristics, brecciation and dyke injection.

- a) Down plunge view of folded spherulitic, amygdaloidal dyke intruded into upper units, Dowling member (t). Gordon lake road, photo 7-34.
- b) Transition from massive homogeneous upper unit tuff (t) to blocky peperite (pep) to xenolithic dyke (left). Gordon lake showing, photo 9-17.
- c) Insitu brecciation of middle unit tuff displaying 'jigsaw-fit of altered silicified duff. Recessive weathering andesitic 'magma'. A&M showing, photo 10-14.
- d) Contact between massive to autobrecciated tuff with blocky peperite. Initiation of insitu fracturing along chloritized fractures. Gordon lake showing, photo 8-29.
- e) Sediment within moderate mixing zone with quartz-filled gas cavities, vesicles. A&M showing, photo 11-32.
- f) Typical upper unit tuff, host to the blocky peperite showing, Gordon lake road powerline, photo 13-33.

PLATE CAPTIONS

Plate A2-5.2: Textural features of mixing zones associated with lensoidal peperite, &M showing.

(t=tuff; m=melt, andesite; pep=peperite)

Weak mixing zone with grey silicified tuff fragments in brown recessive weathering melt matrix. Photo 10-17.

Sharp, undulose contact between moderate (top) and intense (bottom) zones of mixing. Note silicification of tuff in intense mixing zone. Photo 11-15.

Isolated peperite pods in middle unit tuff, typically 10-50 cm. Note strong silicification, leaching of sediments within peperite. Photo 11-14.

Close-up of arcuate andesite fragments within bleached silicified tuff. Plate 10-19. Eastern part of intense mixing zone.

Peperitic breccia with 10 cm silicified tuff fragments in a matrix of spherulitic andesite. Photo 10-29.

Peperitic breccia. Note slabby nature of silicified fragments of tuff in spherulitic andesite matrix. Photo 10-32. Western part of intense mixing zone.

) Typical lensoidal peperite with 65% lensoidal spherulitic andesite. Photo 33-22.

PLATE CAPTIONS

Plate A2-5.3. Morphology of andesitic intrusions in lensoidal peperite.

- a) Sharp intrusive contact between spherulitic andesite lobe 7 and intense zone of mixing (IMZ). Photo 33-16.
- b) Orientation of consistent lensoidal fabric in intense zone of mixing orthogonal to andesite lobe 7 margin. Intrusive contact, photo 10-26.
- c) Andesitic lobe (0.8 m by 1 m) with massive core progressing outwards into large 2 cm impinging spherulites that fine with an outer amygdaloidal rim. Photo 13-17.
- d) Xenolith rich zone near outer margin of andesitic lobe 3. Photo 13-11.
- e) Xenolith rich zone in lobe 2. Rounded quartzite xenoliths in vesicular, spherulitic andesite. Photo 13-9.
- f) Brown weathering hyaloclastitic margin to spherulitic lobe 7 in contact with middle unit tuff. Photo 11-38.
- g) Lobe 2: Gradational contact between zone A; coarse (1.5-2 cm) spherulitic core (right) and zone B; 60% 1 cm spherulites in a matrix with 4 mm spherulites. Photo 13-2.
- h) Coarse grained spherulites in a chloritic matrix within the core of an andesitic lobe. Site of geochronology sample, AV- 162, Lobe 2.

PLATE CAPTIONS

Plate A2-5.4: Textural features of mixing zones associated with blocky peperite.

- a) Transitional contact from massive tuff to autobrecciated tuff to blocky peperite. Photo 8-27.
- b) Close-up of isolated spherulitic andesite with fine silicified contact with tuff. Photo 9-27.
- c) Peperitic lapillistone with green weathering spherulitic andesite (m) containing angular fragments of silicified tuff. Photo 9-1.
- d) Contact between delicate carbonate altered peperite (c-pep) and hyaloclastite dominant peperite (h-pep). Photo 9-31.
- e) Close-up of delicate textured peperite. Photo 9-30.
- f) Sharp contact between moderate zone of mixing (MMZ) and intense zone of mixing (IMZ) with blocky peperite. Photo 9-24
- g) Classic blocky peperite texture with angular dark recessive weathering andesite fragments in a matrix of light silicified tuff. Photo 9-11.
- h) Teardrop shaped fragment of carbonaceous lapillistone (lst) typical of middle unit lapillistone blocks. Photo 9-34.

Plate A2-5.5: Morphology of andesitic intrusions in blocky peperite (Gordon Lake road showing).

A) Zone with pillow-like green weathering andesitic lobes. Photo 9-7. Lobes contain barian phengite.

B) Molar tooth, spherulitic andesite lobe. Photo 9-5.

Table A3-1: Geochemistry of least altered units, Onaping Formation

SANDCHERRY MEMBER											
EQUANT SHARD UNITS				FLUIDAL FRAGMENT UNITS				CARBON-BEARING SM			
AVG.	S. D.	MIN	MAX	AVG.	S. D.	MIN	MAX	AVG.	MIN	MAX	
n=12				n=10				n=4			
SiO2	64.97	2.71	62.00	69.70	64.03	2.83	61.20	69.60	65.75	63.90	68.40
TiO2	0.51	0.05	0.43	0.59	0.54	0.04	0.47	0.58	0.49	0.45	0.52
Al2O3	12.15	0.75	10.90	13.40	12.75	0.72	11.20	13.50	12.03	11.20	12.60
Fe2O3T	6.67	1.63	4.30	9.10	6.94	1.13	5.30	8.40	6.68	4.90	7.90
Fe2O3	1.03	0.44	0.50	2.00	1.00	0.21	0.70	1.20	0.95	0.60	1.50
FEO	5.07	1.27	3.30	7.10	5.34	0.94	4.00	6.50	5.15	3.90	6.10
MNO	0.12	0.03	0.07	0.16	0.13	0.03	0.07	0.18	0.14	0.08	0.18
MGO	4.55	0.75	3.33	6.08	3.87	0.83	2.38	5.57	3.91	3.37	4.42
CAO	3.61	1.23	1.67	5.38	3.68	1.62	1.21	7.58	3.67	2.71	4.44
Na2O	4.76	1.04	2.60	6.10	4.60	0.73	3.50	5.60	4.65	2.70	5.90
K2O	1.16	0.84	0.14	2.11	2.02	0.57	0.65	2.57	1.70	0.24	2.84
H2OT	1.78	0.41	1.30	2.90	1.65	0.25	1.10	2.00	1.38	1.10	1.70
CO2	0.08	0.07	0.05	0.30	0.19	0.43	0.05	1.40	0.06	0.05	0.10
C	0.15	0.10	0.10	0.40	0.10	0.00	0.10	0.10	0.30	0.10	0.80
P2O5	0.13	0.03	0.09	0.21	0.14	0.04	0.09	0.24	0.11	0.08	0.13
SU	0.12	0.15	0.01	0.43	0.22	0.17	0.07	0.63	0.19	0.01	0.41
S	1148.00	1543.34	76.00	4300.00	2150.70	1708.21	679.00	6300.00	1900.00	100.00	4100.00
BA	377.50	294.00	70.00	810.00	654.00	233.39	210.00	1000.00	435.00	120.00	620.00
BE	1.79	1.00	1.20	4.90	2.10	1.40	1.20	4.80	1.45	1.40	1.50
CO	14.58	4.32	7.00	20.00	20.30	5.98	14.00	33.00	15.50	10.00	20.00
CR	93.42	9.62	80.00	110.00	103.70	12.21	77.00	120.00	78.25	51.00	110.00
CU	55.08	107.11	5.00	390.00	154.00	334.16	5.00	1100.00	23.50	5.00	52.00
NI	51.17	13.10	27.00	70.00	70.20	22.89	39.00	110.00	54.25	44.00	66.00
PB	3.92	1.93	1.00	7.00	12.90	28.89	1.00	95.00	3.00	2.00	4.00
RB	39.38	28.73	3.40	74.00	65.80	21.73	17.00	95.00	55.30	7.20	90.00
SC	11.67	1.15	10.00	14.00	12.80	0.92	11.00	14.00	11.25	10.00	12.00
SR	156.42	144.84	52.00	480.00	180.10	113.96	64.00	360.00	168.50	54.00	420.00
V	108.83	13.68	87.00	120.00	104.90	17.40	63.00	120.00	102.60	100.00	110.00
Y	17.33	1.78	14.00	20.00	17.50	1.65	14.00	20.00	16.25	15.00	18.00
YB	1.68	0.15	1.30	1.90	1.46	0.51	0.05	1.80	1.48	1.40	1.60
ZN	23.50	8.49	8.00	36.00	28.40	14.55	3.00	43.00	27.25	11.00	47.00
ZR	140.00	24.49	110.00	210.00	144.00	13.50	120.00	160.00	125.00	110.00	140.00
AG	0.10	0.10	0.05	0.40	0.10	0.07	0.05	0.30	0.09	0.05	0.10
CE	50.00	9.23	29.00	62.00	59.40	6.43	47.00	66.00	44.25	12.00	59.00
CS	0.18	0.07	0.08	0.32	0.35	0.22	0.05	0.72	0.20	0.08	0.28
DY	2.98	0.26	2.60	3.30	3.04	0.30	2.50	3.40	2.88	2.70	3.00
ER	1.63	0.14	1.40	1.80	1.67	0.12	1.40	1.70	1.63	1.40	1.60
EU	0.81	0.23	0.38	1.10	0.96	0.16	0.73	1.20	0.94	0.67	1.30
GA	15.33	1.72	12.00	18.00	15.80	2.04	13.00	19.00	14.25	12.00	16.00
GD	3.69	0.41	2.90	4.30	3.83	0.43	3.10	4.40	3.78	3.60	4.00
HF	3.66	0.50	3.20	5.10	3.60	0.18	3.30	3.90	3.15	2.90	3.40
HO	0.59	0.06	0.51	0.70	0.60	0.06	0.47	0.68	0.57	0.51	0.62
IN	0.03	0.09	-0.05	0.19	0.04	0.07	-0.05	0.14	0.03	-0.05	0.12
LA	25.33	5.52	14.00	30.00	30.20	3.46	24.00	34.00	21.78	3.10	30.00
LU	0.25	0.02	0.23	0.31	0.25	0.02	0.21	0.28	0.23	0.22	0.24
MO	9.68	14.96	0.30	52.00	17.38	43.10	1.60	140.00	3.78	0.50	6.00
NB	9.23	1.01	7.80	11.00	8.44	1.06	6.40	10.00	8.33	7.70	9.10
ND	23.50	3.87	15.00	28.00	25.90	3.48	20.00	31.00	20.75	12.00	24.00
PR	6.18	1.03	3.60	7.30	6.95	0.85	5.30	7.90	5.38	2.00	6.80
SM	4.42	0.67	3.30	5.70	4.68	0.62	3.60	5.40	4.28	3.70	4.70
TA	0.63	0.18	0.40	1.10	0.52	0.11	0.30	0.70	0.63	0.50	0.70
TB	0.52	0.04	0.42	0.59	0.54	0.05	0.45	0.59	0.51	0.50	0.54
TH	7.76	0.78	6.80	9.80	7.52	0.75	5.60	8.20	7.10	6.30	7.60
TL	0.18	0.13	-0.02	0.32	0.33	0.11	0.10	0.44	0.27	0.07	0.39
TM	0.26	0.02	0.23	0.28	0.25	0.02	0.20	0.28	0.25	0.23	0.27
U	4.05	2.27	2.40	11.00	2.81	0.53	2.00	3.80	2.80	2.20	3.20
F	551.42	215.19	1.00	865.00	511.80	215.39	1.00	793.00	364.25	1.00	501.00
CL	265.25	176.74	1.00	741.00	352.70	249.96	1.00	695.00	285.25	1.00	456.00
BI	0.51	0.19	0.10	1.00	0.56	0.26	0.10	1.00	0.40	0.10	0.50

Table A3-1: (cont'd)

DOWLING MEMBER											
CONTACT UNITS				LOWER UNITS				MIDDLE UNITS			
AVG.	S. D.	MIN	MAX	AVG.	S. D.	MIN	MAX	AVG.	S. D.	MIN	MAX
n=21				n=7				n=23			
62.38	1.64	59.50	67.30	61.83	0.40	61.10	62.20	60.98	1.70	58.70	66.00
0.56	0.05	0.44	0.69	0.51	0.03	0.46	0.55	0.49	0.04	0.44	0.60
12.21	0.57	11.40	13.40	11.81	0.49	11.30	12.80	10.87	0.61	10.20	13.30
8.46	1.44	5.00	11.00	8.89	1.05	6.60	9.70	9.78	1.63	7.60	16.40
1.44	0.53	0.60	2.70	1.99	0.67	1.30	2.90	2.23	0.86	0.10	4.40
6.32	1.09	3.70	8.20	6.21	0.72	4.80	6.80	6.17	1.46	0.10	7.90
0.19	0.05	0.12	0.29	0.30	0.10	0.18	0.45	0.39	0.07	0.13	0.52
4.70	0.50	3.59	5.79	4.59	0.32	4.29	5.11	4.38	0.41	3.94	5.46
3.82	0.71	2.55	5.43	4.15	0.58	3.52	5.19	4.41	1.76	0.80	8.86
4.40	0.86	2.70	6.10	3.56	0.80	2.30	4.30	2.23	0.84	0.80	4.90
1.43	0.88	0.19	3.51	2.08	0.41	1.59	2.72	1.68	0.65	0.28	2.63
2.03	0.54	0.90	3.20	2.03	0.10	1.90	2.20	2.78	0.79	0.10	4.00
0.17	0.18	0.05	0.80	0.22	0.33	0.05	0.90	1.71	1.62	0.05	4.10
0.14	0.12	0.10	0.60	0.41	0.16	0.10	0.60	0.47	0.14	0.10	0.70
0.15	0.01	0.13	0.18	0.14	0.01	0.14	0.15	0.14	0.01	0.12	0.16
0.19	0.21	0.01	0.65	0.36	0.17	0.19	0.55	0.61	0.56	0.21	2.97
1885.71	2091.00	100.00	6500.00	3585.71	1742.06	1900.00	5500.00	6069.57	5550.30	2100.00	29700.00
429.05	260.73	70.00	1000.00	695.71	201.40	520.00	1100.00	657.39	316.45	110.00	1400.00
1.41	0.28	0.70	1.90	1.36	0.24	0.90	1.70	1.51	0.14	1.30	1.80
18.90	4.71	7.00	26.00	16.43	1.99	13.00	19.00	17.78	1.78	15.00	22.00
96.33	14.89	62.00	130.00	79.71	19.35	59.00	110.00	78.96	19.17	52.00	130.00
61.57	85.41	5.00	370.00	32.57	15.37	13.00	51.00	66.22	42.29	23.00	220.00
62.76	10.79	38.00	80.00	63.57	4.54	58.00	70.00	68.87	7.43	57.00	93.00
3.71	2.83	1.00	11.00	4.94	1.30	3.00	7.00	22.04	53.03	2.00	260.00
43.65	28.33	6.30	120.00	60.57	8.30	49.00	74.00	40.43	15.84	8.40	71.00
12.38	1.16	10.00	15.00	11.86	0.69	11.00	13.00	11.00	0.85	10.00	14.00
91.95	40.05	35.00	180.00	122.29	65.40	58.00	220.00	118.52	62.68	33.00	280.00
121.14	8.80	94.00	140.00	118.57	9.00	110.00	130.00	115.22	10.39	100.00	140.00
18.52	1.54	16.00	23.00	17.43	0.98	16.00	19.00	17.83	1.50	15.00	22.00
1.70	0.14	1.40	2.00	1.59	0.16	1.40	1.80	1.56	0.12	1.40	1.90
57.52	110.85	21.00	540.00	96.43	108.23	28.00	330.00	196.30	568.05	31.00	2800.00
137.14	9.02	120.00	160.00	132.86	7.56	120.00	140.00	131.74	13.02	110.00	160.00
0.10	0.06	0.05	0.30	0.08	0.04	0.05	0.14	0.15	0.11	0.05	0.50
62.43	18.50	43.00	140.00	58.14	8.93	45.00	73.00	56.22	3.81	51.00	65.00
0.24	0.10	0.07	0.51	0.32	0.11	0.19	0.52	0.41	0.14	0.20	0.78
3.21	0.33	2.70	4.10	2.97	0.25	2.50	3.20	2.97	0.30	2.60	3.80
1.75	0.19	1.40	2.10	1.66	0.10	1.50	1.80	1.58	0.13	1.40	1.90
1.05	0.15	0.68	1.30	0.97	0.08	0.84	1.10	0.98	0.13	0.78	1.30
15.43	1.40	13.00	18.00	15.14	1.07	14.00	17.00	14.91	1.68	13.00	20.00
4.00	0.44	3.20	5.40	3.80	0.37	3.20	4.10	3.65	0.32	3.20	4.30
3.59	0.38	3.00	4.60	3.37	0.37	2.80	3.90	3.33	0.24	2.90	3.80
0.64	0.07	0.52	0.86	0.61	0.06	0.54	0.69	0.59	0.05	0.52	0.72
0.03	0.07	-0.05	0.14	-0.03	0.05	-0.05	0.08	0.01	0.07	-0.05	0.12
32.10	12.75	19.00	86.00	29.86	5.67	22.00	41.00	28.83	1.61	25.00	32.00
0.26	0.02	0.20	0.31	0.25	0.02	0.23	0.27	0.24	0.02	0.21	0.29
4.48	3.21	0.05	8.80	5.61	2.50	0.05	7.20	5.91	1.68	3.50	13.00
9.21	0.65	7.90	10.00	9.36	0.44	8.60	9.80	9.79	0.93	8.30	12.00
25.86	4.98	21.00	46.00	24.29	3.30	20.00	30.00	23.48	2.25	20.00	29.00
7.01	1.49	5.40	13.00	6.46	0.99	4.80	7.80	6.38	0.55	5.60	7.60
4.64	0.64	3.60	7.10	4.33	0.46	3.60	4.80	4.22	0.41	3.70	5.10
0.82	0.10	0.49	0.80	0.58	0.25	0.30	1.10	0.64	0.11	0.50	0.90
0.57	0.06	0.48	0.73	0.53	0.03	0.48	0.57	0.53	0.04	0.46	0.60
7.67	0.51	6.70	8.50	7.46	0.40	6.80	8.00	7.06	0.49	6.10	8.10
0.24	0.14	0.02	0.59	0.38	0.07	0.30	0.49	0.28	0.10	0.07	0.47
0.27	0.02	0.22	0.33	0.25	0.02	0.23	0.27	0.25	0.02	0.22	0.29
3.58	1.04	2.50	7.80	3.40	0.26	3.00	3.80	3.56	0.73	2.60	6.40
389.19	290.50	1.00	780.00	516.57	229.98	1.00	658.00	511.17	177.10	1.00	698.00
177.05	147.74	1.00	462.00	193.14	111.30	1.00	382.00	201.35	78.85	1.00	344.00
0.41	0.23	0.10	1.00	0.44	0.15	0.10	0.50	0.60	0.54	0.10	2.90

Table A3-1: (cont'd)

UPPER UNITS				BLOCKS AND BOMBS			APHANITIC DYKES				
AVG.	S. D.	MIN	MAX	AVG.	MIN.	MAX	AVG	S.D.	MIN.	MAX	AVG
n=8				n=6			n=12				n=5
62.80	3.14	58.10	69.10	62.87	60.20	69.10	62.66	1.75	60.60	66.40	64.62
0.45	0.03	0.41	0.49	0.57	0.44	0.62	0.61	0.04	0.52	0.66	0.57
9.64	0.50	8.80	10.20	13.48	13.00	14.60	13.58	0.49	12.70	14.40	13.56
11.94	1.40	10.20	14.50	7.27	5.00	8.30	7.46	1.18	6.20	9.30	5.86
2.03	1.25	0.10	3.20	1.30	0.80	1.70	1.36	0.25	0.90	1.70	1.18
6.24	3.91	0.10	10.20	5.37	3.80	6.10	5.49	1.00	4.40	7.20	4.20
0.53	0.15	0.27	0.74	0.13	0.07	0.17	0.19	0.09	0.09	0.34	0.09
4.69	0.65	3.90	5.74	3.94	2.66	4.77	3.94	0.46	3.29	4.76	3.61
3.05	1.84	0.16	5.14	2.57	0.91	3.47	2.26	0.73	0.93	3.47	3.72
1.15	0.53	0.40	1.90	3.80	2.90	5.30	3.69	1.25	1.30	4.80	3.78
1.64	0.98	0.58	3.35	3.53	1.02	4.91	3.23	1.48	1.70	6.34	2.34
2.90	1.87	0.10	5.20	2.08	1.80	2.50	2.38	0.58	1.50	3.50	2.06
1.06	1.29	0.05	3.30	0.10	0.10	0.10	0.39	0.58	0.05	1.60	0.07
0.40	0.21	0.30	0.90	0.10	0.10	0.10	0.11	0.03	0.10	0.20	0.10
0.16	0.01	0.14	0.17	0.14	0.12	0.15	0.15	0.01	0.12	0.16	0.13
0.71	0.74	0.02	2.11	0.14	0.02	0.31	0.10	0.11	0.01	0.41	0.03
7062.50	7354.29	200.00	21100.00	1416.67	200.00	3100.00	1033.33	1145.21	100.00	4100.00	338.20
875.00	624.75	250.00	2100.00	1330.00	460.00	1900.00	1511.67	997.45	550.00	3700.00	602.00
1.48	0.74	0.30	2.80	1.13	0.80	1.50	1.19	0.30	0.70	1.60	5.02
16.50	2.07	14.00	20.00	20.17	13.00	26.00	20.58	3.23	15.00	26.00	14.60
70.88	10.92	51.00	87.00	103.00	78.00	120.00	108.00	15.95	71.00	130.00	107.40
64.50	57.13	18.00	200.00	69.00	5.00	160.00	120.08	171.87	5.00	600.00	13.00
63.38	5.78	56.00	74.00	59.67	55.00	64.00	61.58	8.89	47.00	84.00	55.00
39.09	85.49	3.00	250.00	4.30	1.00	7.40	22.58	62.25	1.00	220.00	5.80
34.50	21.39	12.00	74.00	135.83	34.00	200.00	86.33	28.75	42.00	140.00	68.40
9.79	0.40	9.00	10.00	13.83	11.00	15.00	14.25	1.14	12.00	16.00	13.80
77.00	53.71	10.00	180.00	215.00	140.00	500.00	157.17	82.01	69.00	340.00	292.00
121.25	9.91	110.00	140.00	108.33	70.00	120.00	108.75	7.33	98.00	120.00	87.40
17.50	2.67	12.00	21.00	17.83	16.00	20.00	18.92	2.07	17.00	24.00	18.00
1.55	0.09	1.40	1.70	1.72	1.60	1.90	1.84	0.18	1.60	2.30	1.64
125.50	96.86	37.00	350.00	26.17	22.00	32.00	106.42	167.15	20.00	610.00	15.20
138.75	9.91	130.00	150.00	145.00	140.00	170.00	148.33	5.77	140.00	160.00	152.00
0.18	0.13	0.05	0.40	0.37	0.05	1.80	0.21	0.21	0.05	0.78	0.08
49.00	13.69	16.00	59.00	64.17	58.00	74.00	65.67	7.58	53.00	78.00	57.20
0.51	0.23	0.24	0.78	0.54	0.17	1.30	0.45	0.21	0.10	0.74	0.26
2.85	0.28	2.30	3.30	3.32	2.90	3.70	3.52	0.40	2.80	4.40	3.04
1.63	0.09	1.50	1.80	1.82	1.60	2.00	1.88	0.25	1.60	2.50	1.62
0.81	0.19	0.40	0.99	0.96	0.60	1.40	0.95	0.17	0.70	1.20	0.92
12.25	0.71	11.00	13.00	14.83	12.00	17.00	15.67	1.23	14.00	18.00	16.20
3.18	0.72	1.50	3.90	3.98	3.40	4.50	4.08	0.48	3.50	5.20	3.70
3.60	0.26	3.30	3.90	4.05	3.70	4.20	4.08	0.26	3.50	4.40	3.88
0.92	0.92	0.49	3.20	0.64	0.58	0.71	0.68	0.08	0.59	0.88	0.60
0.03	0.09	-0.05	0.13	-0.01	-0.05	0.09	0.02	0.07	-0.05	0.11	-0.02
23.13	7.38	5.00	27.00	31.33	27.00	37.00	33.83	4.53	27.00	43.00	27.60
0.25	0.02	0.21	0.27	0.27	0.25	0.29	0.28	0.03	0.24	0.34	0.26
3.63	2.62	0.05	7.50	0.41	0.05	2.20	1.10	1.56	0.05	4.20	2.80
10.96	1.10	9.30	12.00	7.90	7.50	8.40	8.51	0.59	7.70	9.60	8.00
20.50	6.02	6.00	25.00	28.17	24.00	32.00	29.42	4.98	23.00	39.00	24.40
5.55	1.72	1.40	6.70	7.50	6.70	8.50	7.56	0.88	6.20	9.10	6.34
3.84	1.07	1.30	4.60	4.97	4.40	5.50	4.90	0.61	3.90	6.00	4.36
0.68	0.13	0.49	0.90	0.52	0.26	0.77	0.52	0.11	0.35	0.70	0.76
0.47	0.07	0.31	0.54	0.57	0.50	0.63	0.60	0.07	0.52	0.77	0.55
6.71	0.33	6.30	7.30	8.38	7.30	11.00	8.13	0.30	7.70	8.80	7.96
0.33	0.18	0.16	0.66	0.77	0.24	1.10	0.57	0.22	0.33	1.00	0.37
0.25	0.02	0.23	0.28	0.27	0.25	0.29	0.29	0.03	0.26	0.36	0.27
3.90	0.34	3.50	4.50	2.57	2.20	4.20	2.43	0.31	2.00	3.00	2.44
348.63	380.52	1.00	865.00	1.00	1.00	1.00	181.42	268.64	1.00	598.00	553.60
105.63	112.38	1.00	230.00	1.00	1.00	1.00	94.92	163.54	1.00	520.00	283.40
0.49	0.64	0.10	2.00	0.10	0.10	0.10	0.23	0.20	0.10	0.50	0.90

Table A3-1: (cont'd)

BASAL INTRUSION-"SHEET"			BASAL INTRUSION-NECK	
MIN	MAX	AVG	MIN	MAX
		n=5		
61.10	68.70	64.54	61.90	69.50
0.46	0.67	0.57	0.47	0.60
12.50	14.90	13.20	12.30	13.70
3.80	7.30	6.32	3.40	7.50
0.70	1.60	0.88	0.30	1.40
2.80	5.50	4.90	2.80	6.00
0.06	0.11	0.15	0.08	0.27
3.01	4.36	3.70	3.20	4.00
2.05	5.67	2.38	1.76	2.98
3.00	4.90	3.88	2.50	5.30
1.50	2.72	3.48	1.48	5.38
1.30	2.50	1.90	1.30	2.20
0.05	0.10	0.07	0.05	0.10
0.10	0.10	0.10	0.10	0.10
0.10	0.16	0.14	0.11	0.15
0.01	0.12	0.08	0.01	0.23
50.00	1200.00	800.00	100.00	2300.00
440.00	720.00	1660.00	800.00	2900.00
1.60	7.20	1.42	0.70	1.70
10.00	18.00	16.40	6.00	21.00
86.00	120.00	104.80	84.00	110.00
5.00	45.00	34.80	5.00	100.00
41.00	80.00	58.20	47.00	66.00
2.00	11.00	8.30	2.70	24.00
50.00	98.00	116.00	48.00	180.00
11.00	17.00	13.60	11.00	15.00
120.00	510.00	164.00	110.00	200.00
58.00	110.00	101.60	78.00	110.00
15.00	21.00	17.40	14.00	19.00
1.30	1.90	1.70	1.50	1.90
3.00	43.00	39.20	23.00	57.00
140.00	170.00	146.00	130.00	150.00
0.05	0.10	0.09	0.05	0.15
40.00	73.00	57.80	40.00	65.00
0.14	0.37	0.40	0.25	0.55
2.50	3.60	3.16	2.70	3.50
1.30	1.90	1.76	1.40	2.00
0.55	1.20	0.67	0.09	1.10
14.00	18.00	14.60	12.00	16.00
2.70	4.40	4.00	3.20	4.70
3.50	4.30	3.76	3.30	4.20
0.50	0.70	0.63	0.50	0.72
-0.05	0.09	0.03	-0.05	0.10
15.00	36.00	28.20	18.00	33.00
0.21	0.30	0.27	0.23	0.29
0.80	7.00	1.54	0.05	3.70
7.00	8.80	8.04	7.20	8.90
15.00	31.00	25.60	17.00	29.00
3.90	8.10	6.70	4.60	7.60
3.00	5.60	4.54	3.20	5.30
0.50	1.00	0.52	0.30	0.70
0.44	0.65	0.57	0.46	0.66
7.60	9.10	7.96	6.70	9.10
0.28	0.47	0.67	0.28	1.10
0.22	0.33	0.27	0.21	0.30
2.20	2.60	2.32	2.20	2.50
398.00	821.00	379.60	1.00	820.00
159.00	441.00	173.20	1.00	292.00
0.50	1.00	0.34	0.10	0.50

Appendix 6-1

Sample preparation and isotope methods.

Whole rock powders were used for the oxygen isotope study of the silicate minerals as the alteration minerals are fine grained, complexly intergrown and difficult to separate for mineral-pair analyses. Samples were coarsely crushed and hand picked to avoid lithic fragments. Identical powders for isotope analyses were also analyzed for whole rock, trace element and REE analyses. Oxygen isotope analyses were performed on the 1) regional and discordant silicification zones, 2) weak and intense albitization and discordant 1848 Ma albitization, 3) amphibole mineral separate from veins at Capreol 4) chloritized contact units and 5) the regional calcite alteration zone (Table 6-1). Whole rock oxygen isotope analyses were completed through Dr. K. Ansdell, at the stable isotope laboratory, University of Saskatchewan, Saskatoon, Canada in 1996.

Samples selected for the stable isotope study of carbonates included 23 whole rock powders with 1.1 to 7 wt% CO₂ and 42 carbonate mineral separates (Table 6-2). Identification of calcite, dolomite, ankerite and siderite were identified by a combination of methods including XRD, SEM-EDS, carbonate staining (Evamy, 1963) and microprobe analyses. Minerals were hand-picked where coarse or hand-drilled using a Dremel Moto-flex (dentist-like) drill which provides a powder or coarser pieces depending on the bit. Carbon and oxygen isotope analyses of carbonates and C analyses of carbonaceous matter were completed by the Ottawa-Carleton Geoscience Centre Stable Isotope Facility, Ottawa, Canada in 1995 and 1996. Conventional methods of conversion to CO₂ and measurements using a mass spectrometer were used.

Radiogenic isotope analyses of carbonate were determined on the same mineral separate as the stable isotope data. Isotope measurements and initial ratios were determined by Dr. Brian Cousens at Carleton University, Ottawa, Canada (1996); (Table A6-1). Mineral separates (50-400 mg) were dissolved in 2-3 ml of 0.25N HCl to preferentially remove the carbonate from mixed carbonate/silicate samples. The leachate residue was redissolved in 2.5N HCl for Rb-Sr processing. Rb and Sr were spiked, separated and processed for measurements. Samples were run on Carleton's Finnigan MAT261 thermal ionization mass spectrometer, running in the static mode.

Table A6-1: Sr isotope study of regional carbonate alteration, Sudbury Basin

Location	sample	% CaCO3	% dissolved	87/86 meas.	2-sigma	Age Ma	Sr(ppm)	2-sigma
GLrd	AV151	60	32	0.714423	0.000023	1850	162.8	0.013245
Morg MU	AV254	3	1.4	0.715442	0.000012	1850	115	0.027414
Limerick	AV265	80	31	0.708715	0.000031	1850	41.36	0.003877
Morg CT	AV268	70	44	0.711766	0.000022	1850	65.92	0.010542
Morg MU	AV274	2	1.4	0.715226	0.000013	1850	120.9	0.029647
Cow vein	AV433	90	45	0.711962	0.000019	1850	24.67	0.002293
Cow MU	AV435	5	2.7	0.715011	0.000015	1850	118.3	0.024712
Cow BI	AV451	80	76	0.710093	0.000002	1850	45.66	0.004381
VFM.	AV581A	7	17	0.733192	0.000017	1850	123.5	0.007805
Sim CT	AV650	5	1.5	0.726441	0.000016	1850	70.6	0.00797

Sample	Error MagFac	Rb(ppm)	2-sigma	Error MagFac	87Rb/86Sr	2-sig	87Sr/86Sr
AV151	1.46	2.5	0	1.82	0.0444	0	0.71324
AV254	1.39	2.87	0	2.12	0.0724	0	0.71352
AV265	1.19	0.61	0.07	1.33	0.0424	0.01	0.70759
AV268	1.27	0.94	0	1.45	0.0413	0	0.71067
AV274	1.45	2.26	0	1.98	0.054	0	0.71379
AV433	1.15	0.01	0	2.47	0.0011	0	0.71193
AV435	1.44	0.79	0.02	1.37	0.0193	0	0.7145
AV451	1.16	0.24	0	1.19	0.0154	0	0.70968
AV581A	1.12	26.59	0.02	3.23	0.6243	0	0.71657
AV650	1.26	7.94	0.01	4.14	0.3258	0	0.71777

sample	mineral
AV151	calcite separate
AV254	whole rock-calcite
AV265	calcite separate
AV268	calcite separate
AV274	calcite separate
AV433	calcite separate
AV435	calcite separate
AV451	calcite separate
AV581A	dolomite separate
AV650	whole rock-calcite

control on the member and the small in has been affected by ts. Note the orthogonal faults that control the distribution of small clures and the northwesterly and Dowling member.

APING FORMATION
Flow-banded and/or oolitic
DOWLING MEMBER
Contact unit
SANDCHERRY MEMBER
Fusil fragment unit
Massive, flow banded dykes and autoclasts
Fusil fragment unit
Transitional unit
Equant - shaly units
Block - rich
Tuff
Lapilli tuff
Subvolcanic contacts
Approximate location of the Onaping Formation

ing member, Onaping Formation.
nts of the underlying Sandcherry
ff and the numerous shallowly
The western fault contact is
ke.

ugh the lower and middle units,

Figure 3

Figure 4

Figure 5

Figure 6

- LEGEND
- Note: areas of outcrop are shown in darker colour
- 13 Dist-covered area
- LITHOLOGY
- 12 Feldspar-phryic dyke
- SUDBURY IGNEOUS COMPLEX
- 11 Aplitic dyke
- 10 Granophyre
- ONAPING FORMATION
- INTRUSIVE ROCKS
- 8a Basal intrusion "barni-concordant" xenolith-rich with fragments predominantly of Anorthite rocks in a fine grained sugary-textured igneous matrix
- 8b Basal intrusion discordant xenolith-rich pools with a fine-grained igneous textured matrix
- 8 Aphelitic dykes and sills - flow-banded and/or massive with autobrecciated or intact conatite
- DOWLING MEMBER (lenticular, altered vitric fragments, ~60% matrix)
- 7 Upper units
- Thinly bedded, normal to non-graded beds of reworked ash-sized debris and fine tuff
- Middle units
- 5a Block and bomb-poor tuffaceous units
- 5b Tuffaceous units with increased ash and lapillstone blocks and rare beds
- Lower units
- 5a Conformable, normally graded lapillstone to tuff units containing rounded lithic and vitric blocks and bombs
- 5b Channelized deposits of short strike length, unconformable lower contact, block and bomb rich, reversely graded with respect to lithic blocks
- Contact units
- 4a Normally graded tuff and lapilli-tuff units with predominantly chertic shales with blocky shawl morphology ± highly vesicular vitric blocks and bombs, broad-based bombs, blocks of Sandcherry member units
- 4b Tuff to lapilli-tuff units with lenticular shawl morphology ± accretionary lapilli, fluidal fragments, vitric and lithic blocks
- SANDCHERRY MEMBER (blocky, altered vitric fragments, <35% matrix)
- 3a Massive to autobrecciated facies
- 3b Intermediate facies, lapilli-tuff with tabular fragments, 25-40% matrix
- 3c Distal facies: lapilli-tuff with < 15% chertic shales, 30-40% matrix
- Transitional units
- 2 15-30% equant, plate-like altered vitric fragments, 50-60% flow-banded vitric fragments
- Equant shaly units
- 1 Predominantly lapilli-tuff characterized by equant, plate-like, altered vitric fragments
- Note: non-genetic lithic classification used (Fisher, 1988)
- Geological boundary (defined, approximate)
- Area of outcrop
- Carbon boundary (arrow indicates carbon-bearing)
- Shear zone
- Tuff
- Lapilli-tuff
- Lapillstone
- Fine Tuff
- Blocks, model estimate
- Bedding (inclined, vertical, dip unknown, tops unknown)
- Strike-slip ash or lapillstone blocks
- Strike-slip of flattened shales
- Foliation (inclined, vertical, dip unknown)
- Shear foliation (inclined, dip unknown)
- Joint
- Trench pit
- Powerline
- Road
- Trail

Geology by D.E. Ames, Geological Survey of Canada

Digital cartography by E. Hilary and the Geoscience Information Division

Any revisions or additional geological information known to the user would be welcomed by the Geological Survey of Canada

Base map from the Ontario Provincial topographical sheets, scale of 1:20,000, updated by the Geological Survey of Canada from aerial photograph enlargements

Some geographical names subject to revision

Magnetic declination 1989, 10°09' E, increasing 2.5' annually

MAP 1A: GEOLOGY OF THE ONAPING FORMATION, MORGAN TOWNSHIP, SUDBURY STRUCTURE, ONTARIO

Scale 1:5000 - Échelle 1/5000

Mètres 0 100 200 300 400 Mètres

Universal Transverse Mercator Projection
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3717
GEOLOGICAL SURVEY OF CANADA
COMMISSION GÉOLOGIQUE DU CANADA
OTTAWA
11/1999

SHEET 1 OF 2
FEUILLET 1 DE 2

Recommended citation:
Ames D.E. and Gibson H.L.
1989. Geology of the Onaping Formation, Morgan Township,
Sudbury structure, Ontario. Geological Survey
of Canada, CP3717, sheet 1, scale 1:5000.

Figure 1: Simplified stratigraphic and alteration section for the Onaping Formation, Sudbury Structure showing the distribution and vertical stacking of regional basinwide hydrothermal alteration zones. Brackets denote alteration types with poorly constrained regional distribution patterns (modified from Ames et al., 1998).

Figure 2: Simplified alteration map showing the distribution of regional synsedimentary alteration in the Onaping Formation, Sudbury Structure. Alteration zones are extrapolated (light shades) between defined mapped zones of alteration (dark shades). s=Sandcherry member, d=Dowling member. Note the transgressive nature of the carbon contact across the Sandcherry/Dowling member contact. Data compiled from this study, unpublished Falconbridge Ltd. data, Gibbins et al., 1994, Gray et al., 1995.

Geology by D.E. Ames, Geological Survey of Canada, 1983, 1994

Digital cartography by E. Hilary and the Geoscience Information Division

Any revisions or additional geological information known to the user would be welcomed by the Geological Survey of Canada

Base map from the Ontario Provincial topographical sheets, scale of 1:20,000, updated by the Geological Survey of Canada from aerial photograph enlargements

Some geographical names subject to revision

Magnetic declination 1990, 10°00' E, increasing 2.5° annually

LEGEND

ALTERATION ZONES (outcrop shown in darker colour)

- Silicification
- Albite-quartz-Kfeldspar alteration, weak
- Albite-quartz-Kfeldspar alteration, moderate
- Albite-quartz alteration, strong
- Chlorite
- Carbonate-calcite + chlorite
- Carbonate-absent, chlorite + epidote

- Carbon boundary (arrow indicates carbon-bearing)
- Quartz-albite, pervasive silicification
- Bleached sand rim
- Pervasive replacement of sand
- Epidote alteration
- Vein
- Vegetation
- Modal estimate
- Trace amounts
- Weak
- Fragments
- Silicification
- Altered mafic fragments and clots
- Chlorite
- Chlorite with bleached rim
- Trench, pit

- MINERALS
Actinolite	act	Kalsilite	kl	Pyrrhotite	po
Calcite	cc	Quartz	q	Chalcopyrite	cpy
Chlorite	chl	Sericite	se	Sphalerite	sph
Clinopyroxene	cpx	Pyrite	py	Pyrrhotite	pre

MAP 1B:
ALTERATION AND MINERALIZATION OF THE ONAPING FORMATION,
MORGAN TOWNSHIP, SUDBURY STRUCTURE

Scale 1:5000 - Echelle 1/5000

Metres 100 0 100 200 300 400 Metres

Universal Transverse Mercator Projection
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GEOLOGICAL SURVEY OF CANADA
COMMISSION GÉOLOGIQUE DU CANADA
OTTAWA
08/1999

Recommended citation:
Ames D.E. and Gibbins H.L.,
1995. Alteration and mineralization of the Onaping Formation,
Morgan Township, Sudbury structure, Ontario. Geological Survey
of Canada, OF3717, sheet 2, scale 1:5000.

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FEUILLET 2 DE 2

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LEGEND

Olivine diabase dyke

SUDBURY IGNEOUS COMPLEX

Granophyre

ONAPING FORMATION

INTRUSIONS

Basal intrusion - fine grained, sugary textured + xenoliths /radiating feldspar and actinolite

Flow banded aphanitic andesite dykes and sills with hyaloclastite margins

DOWLING MEMBER (DM)

Lower unit - lapilli tuff to lapillistone

Contact unit - tuff, lapilli tuff, bomb and block-rich base, eutaxitic texture

SANDCHERRY MEMBER (SM)

FLUIDAL- FRAGMENT UNITS (SMFL)

Autobreccia

Lapilli - tuff, bomb rich

Lapilli - tuff, bomb poor

EQUANT SHARD UNITS (SMES)

Lapillistone

Lapilli tuff

Tuff

SYMBOLS

Hyaloclastite

Spherulitic

Flow banding

Block - andesite juvenile

Block - granitoid lithic

Bomb

Cored bomb

Xenolith

Joint

Road

Trail

Carbon boundary (arrow indicates carbon-bearing)

Geology by D. E. Ames, 1994, 1995

Digital cartography by E. Hillary, R. Franklin

Field assistants: Jennifer Fowler, Judd Fee

Map 2A: Geology of the Onaping Formation,
Joe Lake area, Wisner Township,
Sudbury Structure, Ontario

Scale 1:2000 - Echelle 1/2000

Metres 100 0 100 200 Metres

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FILE
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2/10

LEGEND
(See Map 1A legend for context within entire Onaping Formation stratigraphy)

- SUDBURY IGNEOUS COMPLEX**
- 10 Granophyre
- ONAPING FORMATION**
- INTRUSIVE ROCKS**
- 9a Basal intrusion "semi-concordant" xenolith-rich with fragments predominantly of Archean rocks in a fine grained sugary-textured igneous matrix, aphanitic, massive, locally fluidal, block-rich (parts >80%), megablocks
- 8 Aphanitic dykes and sills - flow banded and/or massive with auto-brecciated or intact contacts
- Individual granitoid xenoliths in basal intrusion and aphanitic dykes
- SANDCHERRY MEMBER** (blocky, altered vitric fragments, <35% matrix)
- Equant shard units
- 1 Predominantly lapilli-tuff characterized by equant, plate-like, altered vitric fragments

Note: non-genetic size classification used (Fisher, 1966)

- Geological boundary (defined, approximate).....
- Area of outcrop.....
- Carbon boundary (arrow indicates carbon-bearing).....
- Shear zone.....
- Tuff.....t
- Lapilli-tuff.....lt
- Lapillistone.....lst
- Blocks, modal estimate.....▲ 5
- Bomb.....●
- Strike/dip of dykes.....20/
- Foliation (inclined, vertical, dip unknown).....88/
- Shear foliation (inclined, dip unknown).....88/
- Joint.....20/

Map 3A: Geology of the Onaping Formation, Rockcut Lake Area, Norman Township, Sudbury Structure, Ontario (1:2000)

0 50 100 Metres

Base map from the Ontario Provincial topographic sheets, scale of 1:20000, updated by the Geological Survey of Canada from aerial photograph enlargements

Geology by D.E. Ames, August, 1994

Digital cartography by E. Hillary

Field Assistant: J. Fowler

**Map 3A: Geology
Rockcut Lake Area, Norman Township**

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- LEGEND**
- (See Map 1A legend for context within entire Onaping Formation stratigraphy)
- 13** Drift covered area
- ONAPING FORMATION**
- INTRUSIVE ROCKS**
- 9b** Basal intrusion discordant xenolith-rich pods with a fine-grained igneous textured matrix
- 8** Aphanitic dykes and sills - flow-banded and/or massive with autobrecciated or intact contacts
- DOWLING MEMBER** (lenticular, altered vitric fragments, ~60 % matrix)
- Upper units**
- 7** Thinly bedded, normal to non-graded beds of reworked ash-sized debris and fine tuff
- Middle units**
- 6** Block- and bomb-poor tuffaceous units with ash and lapillistone blocks and rare beds
- Lower units**
- 5a** Conformable, normally graded lapillistone to tuff units containing rounded lithic and vitric blocks and bombs
- Contact units**
- 4** Tuff to lapilli-tuff units with lenticular shard morphology
- SANDCHERRY MEMBER** (blocky, altered vitric fragments, <35% matrix)
- Fluidal fragment units - predominantly lapilli-tuff composed of tabular flow-banded vitric fragments**
- 3a** Massive to autobreccia facies
- 3b** Intermediate facies, lapilli-tuff with tabular fragments, 25-40% matrix
- Transitional units**
- 2** 15-30% equant, plate-like altered vitric fragments, 50-60% flow-banded vitric fragments
- Equant shard units**
- 1** Predominantly lapilli-tuff characterized by equant, plate-like, altered vitric fragments
- Note: non-genetic size classification used (Fisher, 1966)
- Geological boundary (defined, approximate).....
- Area of outcrop.....
- Carbon boundary (arrow indicates carbon-bearing).....
- Shear zone.....
- Tuff..... t
- Coarse tuff..... ct
- Lapilli-tuff..... lt
- Lapillistone..... lst
- Very fine tuff..... vft
- Vitric..... v
- Lithic..... l
- Blocks, modal estimate..... 5
- Bomb, simple, cored.....
- Bedding (inclined, vertical, dip unknown, tops unknown).....
- Foliation (inclined, vertical, dip unknown).....
- Shear foliation (inclined, dip unknown).....
- Joint.....
- Trench, pit.....
- Road, trail.....

LEGEND
(See Map 1A legend for context within entire Onaping Formation stratigraphy)

14 Mafic Dyke (magnetic)

13 Drift covered area

ONAPING FORMATION

INTRUSIVE ROCKS

9b Basal intrusion discordant xenolith-rich pods with a fine-grained igneous textured matrix

DM DOWLING MEMBER (lenticular, altered vitric fragments, ~60 % matrix)

5 Lower units

5a Conformable, normally graded lapillistone to tuff units containing rounded lithic and vitric blocks and bombs

4 Contact units

4b Tuff to lapilli-tuff units with lenticular shard morphology + spatter, fluidal fragments, vitric and lithic blocks, bombs

SM SANDCHERRY MEMBER (blocky, altered vitric fragments, <35% matrix)

3 Fluidal fragment units - predominantly lapilli-tuff composed of tabular flow-banded vitric fragments, <15% equant shards

Transitional units

2 15-30% equant, plate-like altered vitric fragments, 50-60% flow-banded vitric fragments

Equant shard units

1 Tuff characterized by equant, plate-like, altered vitric fragments

Note: non-genetic size classification used (Fisher, 1966)

Geological boundary (defined, approximate).....

Area of outcrop.....

Carbon boundary (arrow indicates carbon-bearing).....

Shear zone.....

Tuff.....t

Coarse tuff.....ct

Lapilli-tuff.....lt

Lapillistone.....lst

Very fine tuff.....vft

Vitric.....v

Lithic.....l

Blocks, modal estimate.....5

Bomb.....

Bedding (inclined, vertical, dip unknown, tops unknown).....

Foliation (inclined, vertical, dip unknown).....

Shear foliation (inclined, dip unknown).....

Joint.....

Trench, pit.....

Map 5A: Geology
Simmons Lake Area,
Dowling Township

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