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Petrology and Metamorphism of Nipissing Diabase of May Township, Ontario

by

Julie A. Blondé

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science

**Department of Earth Sciences
Carleton University
Ottawa-Carleton Geoscience Centre
Ottawa, Ontario**

April, 1996

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Petrology and Metamorphism of Nipissing Diabase of May Township, Ontario

submitted by

Julie A Blondé

in partial fulfilment of the requirements

for the degree of Master of Science

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Chairman.

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ABSTRACT

Metamorphosed Nipissing Diabase, and other mafic rocks, of May Township, in the Sudbury region, demonstrate the complex behaviour of amphibole and plagioclase under greenschist to amphibolite grade conditions. Four metamorphic "zones", are recognised in May Township, by changes in habit and composition of the two main minerals, amphibole and plagioclase.

- 1) "un-recrystallized" zone assemblage: ophitic pyroxene and calcic plagioclase ($An_{32.75}$), minor hornblende
- 2) greenschist zone assemblage: actinolite pseudomorphs after pyroxene, relict pyroxene cores with actinolite rims, and plagioclase (An_{01-66})
- 3) "transitional" zone assemblage: coexisting actinolite and hornblende as patchy intergrowths, or actinolite cores with complete to incomplete hornblende rims, plagioclase (An_{01-50})
- 4) amphibolite zone assemblage: subhedral, poikiloblastic hornblende, plagioclase with clear, more sodic (An_{05-40}) rims and cloudy, altered, more calcic (An_{37-60}) cores, + subhedral garnet

Metamorphic grade in May Township increases northwards from greenschist in the south, through transitional rocks, to amphibolite. The amphibolite zone is bounded to the south by the Serpent River and to the north by the Murray Fault Zone. North of the Murray Fault Zone grade decreases sharply to greenschist, but again increases to intermediate along the northern boundary of May Township, into the Superior Province.

Results of thermobarometry indicate that the geotherm ($>30^{\circ}\text{C}/\text{km}$) was reasonable in comparison with other Precambrian terranes and modern values. The best estimate of the temperature and pressure of equilibration of the amphibolites is $580^{\circ}\text{C} \pm 60^{\circ}\text{C}$ and 4.3 ± 0.8 kbar.

Two structural models are being considered to explain the pattern of metamorphic "zones" of May Township: 1) the amphibolite zone represents a thrust sheet overlying lower grade rocks, 2) the amphibolite zone represents an uplifted thrust block. In both cases the amphibolite zone is bounded to the north by the Murray Fault Zone and to the south by the Serpent River Structural Discontinuity. This "discontinuity" could define the southern limit of the thrust sheet, for case one, or could represent an intact facies boundary, with a metamorphic isograd rather than a structural discontinuity separating amphibolites from lower grade rocks to the south for case two. While both of these interpretations are considered possible, the first is supported by the presence of a lower grade region contained within the amphibolite zone, possibly an exposed window through the overlying amphibolite.

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This thesis is dedicated to my grandparents Barney and Genevieve Blonde and Cletus and Mary Reynolds and to my aunt Sheila Gibbons

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LIST OF SYMBOLS

Symbols used in the Plates

act = actinolite	ttn = titanite	serp = serpentine
hb = hornblende	tlc = talc	serc = sericite
ep = epidote	chl = chlorite	qz = quartz
ap = apatite	px = pyroxene	cz = clinozoisite
pl = plagioclase	ol = olivine	ilm = ilmenite
bt = biotite	gt = garnet	en = enstatite
amph = amphibole (calcic)		

Symbols used in Appendix D

α qa = alpha quartz	ab = albite	an = anorthite
parg = pargasite	fepa = ferro-pargasite	sph = titanite
tr = tremolite	fetr = ferro-tremolite	ilm = ilmenite
tsc = tschermakite	fets = ferro-tschermakite	w = water

CHAPTER 1: INTRODUCTION

1.1 Purpose of Work

The purpose of this thesis is to describe the metamorphism of the Nipissing Diabase of May Township, (ten kilometres west of the town of Espanola) Ontario. Comparison with other studies of metamorphosed mafic rocks show that the Nipissing Diabase of May Township consist largely of disequilibrium assemblages containing relict igneous minerals and textures and assemblages which can vary on an outcrop scale. A number of factors are described as inhibiting the development of equilibrium assemblages including sluggishness of amphibole and plagioclase-forming reactions and variable infiltration of fluids into impermeable diabase. In spite of these difficulties, it has been possible to interpret the petrology of these rocks by detailed petrography and by use of Scanning Electron Microscopy to obtain mineral compositions from areas of local equilibrium.

Four metamorphic zones have been recognized in this study and mapped as shown on Figure 5.1. These metamorphic zones are defined on the basis of mineral textures, mineral assemblages and thermobarometry as described in subsequent chapters of the thesis. Reference will be made to these four zones in presenting the geologic and mineralogic data of Chapters 2, 3, and 4. The zones are described in detail in Chapter 5.

The objective of this study is to further an understanding of the geological history of May Township as revealed in the metamorphic and tectonic history of the diabase. The final chapters of the thesis will use the evidence provided by the metamorphosed

diabase to suggest tectonic environments that are compatible with the distribution of metamorphic grade.

1.2 Previous Work

Various aspects of the mineralogy, petrography, structure, metamorphism and tectonics of the surrounding region have been described in detail by Bennett *et al.* (1991), Brocoum and Dalziel (1974), Buchan and Card (1985), Card (1964) (1968) (1976) (1978a) (1978b), Card *et al.* (1972), Card and Pattison (1973), Card and Palonen (1976), Coleman (1914), Collins (1925), Fairbairn *et al.* (1969), Ginn (1961), (1965), Hriskevich (1968), Lightfoot *et al.* (1986), (1993), Morris (1978), Robertson (1976), Sims *et al.* (1980), (1981), Stockwell (1982), Zolnai *et al.* (1983)

Earliest work in the region to the south-west of Sudbury, consisted largely of resolving the geologic units and assessing the economic potential (Coleman, 1914, Collins, 1925) In the vicinity of May Township, the interest concentrated on the sulfide minerals of the Massey copper belt and resolving the units of the Huronian Supergroup (Coleman, Collins) Interest in the region was stimulated by the discovery of uranium in 1953 (see Robertson *et al.*, 1971). Robertson *et al.* (1969) reviewed the problems of the regional stratigraphic nomenclature and correlation The geology, structure, metamorphism, tectonic history, mineralization of May, and the adjacent townships were mapped and discussed in detail by Robertson *et al.* (1971) The most recent work in the May Township area was undertaken by Steve Jackson of the Ontario Geological Survey during the summer of 1993, and is described in the Ministry of Northern Development and Mines, Summary of Activities, 1993, pages 46-50.

The most recent study by Jackson and Henderson (1993) concentrated on the structural and metamorphic aspects of May Township, as well as adjacent townships of Hallam, Harrow and McKinnon. In particular, these authors studied the metamorphism of the extensive pelitic McKim Formation to determine the tectonic history of the area. This recent study of Jackson is still ongoing and provided the author with an opportunity to conduct field examination and sampling of the Nipissing Diabase of May Township.

CHAPTER 2: REGIONAL GEOLOGY OF THE SOUTHERN PROVINCE

2.1 Southern Province

The Southern Province extends from Minnesota to the Cobalt-Noranda area of Ontario and Quebec (Figure 2.1). It has been described as a discontinuous fold belt approximately 1300 km long and up to 440 km wide and now covers an area of 256 000 km² (Card *et al.*, 1972). This geological/structural province includes Proterozoic supracrustal sedimentary and volcanic sequences that overlie Archean basement rocks, these units are intruded by later Proterozoic mafic and felsic intrusive rocks (Brocoum and Dalziel, 1974, Card, 1964, 1968, 1976, 1978a, 1978b, Card *et al.*, 1972, Card and Palonen, 1976, Card *et al.*, 1984, Ginn, 1965, Robertson *et al.*, 1971, Robertson, 1976, Sims *et al.*, 1980, 1981, Zolnai *et al.*, 1983). As shown in Figure 2.2, May Township is located in the Sudbury region of the Southern Province of Ontario.

2.2 Geology of the Southern Province of Ontario

The Southern Province of Ontario consists mainly of the Huronian Supergroup, a series of early Proterozoic metasedimentary rocks, consisting of four unconformity-bounded, fining upwards sequences (Appendix A, Table A 1). The sedimentary rocks thicken southwards to 10-15 km (Zolnai *et al.*, 1984). The Southern Province is bounded by the Superior Province to the north, by the Grenville Front Tectonic Zone to the south-east, by Paleozoic sediments to the south and by the Mid Continental Rift to the west (Figure 2.1). The age of the Huronian Supergroup is limited by the approximately 2.5 Ga Archean rocks (Fairbairn *et al.*, 1967, *in* Fairbairn *et al.*, 1969) it overlies and the age of the Proterozoic intrusive mafic and felsic rocks it hosts, specifically, the Nipissing Diabase (2.219Ga, Corfu and

Andrews, 1986), Sudbury Diabase (~1.25 Ga, Palmer *et al.*, 1977) and granitic plutons, the Creighton and Murray Granites (2.2 Ga, Gibbins *et al.*, 1971; 2.333 Ga, Frarey *et al.*, 1982) and the Cutler (~1.75 Ga, Wetherill, *et al.*, 1960) and Grenville Front plutons, "Killarney Granites" (1.6-1.73 Ga, Krogh *et al.*, 1971 [in Card *et al.*, 1972]; 1.75 Ga, Card *et al.*, 1984). Rb-Sr dating of the Huronian Supergroup estimates the age to be approximately 2.3 Ga (Knight, 1967, Fairbairn *et al.*, 1967, in Fairbairn *et al.*, 1969). Rocks of the Southern Province of Ontario were deformed by a pre-Nipissing Diabase event and the Penokean Orogeny (~1.8 Ga, Thurston, 1991, p 18).

2.2.1 Structure

In Ontario, the Southern Province can be divided into 3 structural zones, the Cobalt-Noranda region, the Sudbury-Espanola region and the Sault Ste. Marie-Elliot Lake region (Figure 2.2) based on variations in fault and fold trends and intensity of deformation (Card *et al.*, 1972, Card, 1978a). Card *et al.* (1972) further divide the Sudbury-Espanola area into two structural regions separated approximately by the Murray Fault System. In general, south of the Murray Fault System, major structures trend east-west, and to the north major structures trend east-northeast to northeast (Card *et al.*, 1972).

2.2.2.1 Folds

Regional folding is manifested as elongate anticlinoria and synclinoria, with shallow, variable plunges, trending approximately east-west, and north-east, (Zolnai *et al.*, 1984), roughly parallel to major fault systems (Card and Robertson, 1972). In the Sudbury region, folding style is approximately divided by the Murray Fault zone (Card, 1978b). North of the Murray Fault Zone folds are tight, with fold axes trending east to north-east dipping

approximately 80° to the south, slightly curved and overturned to the north, with highly variable plunges resulting in a pattern of doubly-plunging, en echelon series of synclines and anticlines (Card *et al.*, 1972). South of the Murray Fault Zone, the folds are more open structures with near vertical axial traces, trending east-west (Card, 1978b, Robertson, 1976). In regions of the Southern Province east and west of Sudbury, the folding is much less severe. To the west, the Elliot Lake-Sault Ste Marie area, folds are open and concentric with near vertical fold axes and shallow, variable plunges (Sims *et al.*, 1981). To the east, the Cobalt-Noranda region contains two folding trends, one trending north-south and the other east-west, resulting in a pattern of doubly-plunging domes and basins (Sims *et al.*, 1981). Three folding events are recorded, the first being pre-Nipissing Diabase, manifested as a foliation, subparallel to bedding, and the growth of metamorphic muscovite and chlorite in the pelites, this phase of folding is not present in the intrusions of the Nipissing Diabase (Card, 1978a). A pre-Nipissing Diabase folding event is also indicated by paleomagnetic work of Morris (1977). The second and third folding events are syn- and post- Nipissing Diabase, the second resulting in the folding pattern described above and the third is manifested as a crenulation foliation in the pelites, resulting from a minor, non-penetrative, variable intensity folding event trending eastwest-northeast (Card *et al.*, 1972). All three of these folding events could have deformed metamorphic isograds in metapelites of the Huronian sequence. Only the latter two events could have affected the Nipissing Diabase which records metamorphism and deformation younger than 2.219 Ga.

2.2.2.2 Faults

There are two major fault orientations within the Southern Province of Ontario. An earlier set trends east-west or north-east to south-west; this set includes the Murray Fault System, which extends from Coniston at the Grenville Front to Bruce Mines (Figure 2.2). Later faults trend northwest-southeast, and displace the earlier set (see Figure 2.5).

2.2.2.3 Murray Fault Zone

The Murray Fault Zone in the Sudbury region (Robertson, 1976; Ginn, 1965; Card, 1968; Card and Palonen, 1976) is an arc-shaped, concave to the north, system of anastomosing faults trending approximately east-west (see Figure 2.2). Regional dip is near vertical or steeply to the south, although steep dips to the north have been recorded (Robertson, 1976; Ginn, 1965, Card, 1968, Card and Palonen, 1976). This major fault system marks changes in the thickness and character of the Huronian Supergroup as well as changes in the metamorphic facies and structural style (Sims *et al.*, 1981). It will be demonstrated in this study that the Murray Fault influences metamorphic isograds in the Nipissing Diabase; this showing that the fault has been active after the intrusion and metamorphism of the Nipissing Diabase.

Evidence of repeated movement along the Murray Fault Zone indicates periodic activity along the Murray Fault for nearly 1 billion years (Card *et al.*, 1972, Card, 1978*b*). Drastic changes in the thickness and facies of the Huronian strata across the Murray Fault and comparisons to other continental margins, modern and Proterozoic, have lead to the interpretation that initial movement was syn-depositional and involved normal, listric faulting wherein the south side went down (Card and Palonen, 1976, Card, 1976, Card, 1978*b*, Zolnai *et al.*, 1984). Later movement along the fault is evidenced by drag folds, slicken-striations, displaced and absent sedimentary units and discordant diabase dykes (Robertson, 1976; Ginn,

1965; Card, 1968; Card and Palonen, 1976). Vertical movement along the Murray Fault is indicated by steeply plunging slicken-striations on fault surfaces (Card, 1968). The horizontal component is interpreted from such features as subhorizontal slickensides (Sudbury-Espanola region, Card, 1978b) and drag-folds along the fault in Lorne Township (Ginn, 1965), with plunges of 40°W. The common interpretation of these features is reverse dip-slip and right lateral strike-slip faulting, wherein the north side moved east and down relative to the south side (Ginn, 1961, Ginn, 1965, Card, 1978b). Estimates of total displacement, horizontal and vertical, along the Murray Fault range from 1.6 km (Card, 1978b) to 5 km (Sims *et al.*, 1981). The reactivation of normal listric faults in a passive margin regime to reverse thrust faults during later compressional events is common (J. Jackson, 1980). It is apparent that movement along the Murray Fault has been complicated. A study of the metamorphism of the Nipissing Diabase has the potential to distinguish the possible early history of the fault during deposition of the Huronian sequence, from later (post 2.219 Ga) movements.

2.3 Metamorphism of the Southern Province

The Southern Province has been divided into three regions by Card (1978a), on the basis of intensity of regional metamorphism (Figures 2.2 and 2.3). 1) The Sault-Ste-Marie-Elliot Lake area contains subgreenschist (or diagenetic, Card, 1978a) rocks that are mildly deformed, folded, tilted, with open concentric folds that exhibit gentle variable plunges, 2) the Cobalt area, also contains subgreenschist facies rocks in the east, with low greenschist facies rocks in the west. The rocks are moderately folded into open, broad, doubly plunging domes and basins; 3) the Sudbury-Cutler area has subgreenschist to lower amphibolite grade rocks that have been highly deformed into tight folds. The metamorphic zones are arranged

concentrically into elongate nodes, trending approximately east-west, with higher grades corresponding to anticlines and lower grades to synclines (Card, 1964, Card, 1976, Card, 1978b, Card *et al.*, 1972). The metamorphic zones of the Southern Province of Ontario, and for the Sudbury-Manitoulin region are shown in Figures 2.3 and 2.4.

A synthesis of all regional and local studies of the metamorphism of the Sudbury region (Card, 1964, Card, 1968, Card, 1976, Card, 1978a, Card, 1978b, Card *et al.*, 1972, Card and Palonen, 1976, Fairbairn *et al.*, 1969, Ginn, 1965, Jackson and Henderson, 1993, Sims *et al.*, 1980, Sims *et al.*, 1981, Zolnai *et al.*, 1984), confirms that the metamorphic grade varies from lower greenschist to upper amphibolite grade. In a comprehensive compilation of the Sudbury region, Card, 1978a, recognised four facies: sub-greenschist, lower-middle greenschist, middle-upper greenschist and amphibolite, each with distinctive metamorphic mineral assemblages, (see Appendix A, Table A.3). According to Card *et al.* (1972), the presence of coexisting staurolite and andalusite indicates that the region was metamorphosed under the “low pressure-intermediate temperature” type of Miyashiro (1961, page 283, 1968; pp. 805-809, 1973) which is characterised by the assemblages listed in Appendix A, Table A.3. Fox (1971) estimated the P-T conditions of the chloritoid-staurolite transition (which approximates the greenschist to amphibolite transition) in the Agnew Lake region (see Figure 2.2) to be approximately 500 °C to 550 °C and 4.45 kbar to 4.75 kbar. Occurrences of kyanite in sandstone units are attributed to local high pressure areas, possibly in the apices of tight folds (Card, 1978a).

2.4 Tectonic Implications

Interpretation of the metamorphism of the Southern Province, lies in the timing and duration of metamorphic processes. These are indicated by relationships between foliation and porphyroblast growth, and relationships of the metamorphosed sediments to the intrusions (Card, 1978*b*) and paleomagnetic data (Morris, 1978, Buchan and Card, 1985). The metamorphic zones, as described by Card, (1978*b*), are arranged in an elliptical nodal pattern elongated in the direction of major folds and faults, i.e., east-west and northeast-southwest (Card, 1976). The highest grade of metamorphism is found in two areas: 1) immediately south of the Murray Fault, 2) near the Grenville Front (see Figures 2.3, 2.4). Regionally, high grade areas correspond to anticlinoria and low grade areas to synclinoria (Card, 1978*b*). In detail, metamorphic zone boundaries transect fold axes (Card, 1978*b*, Sims *et al.*, 1981). The higher grade areas have been attributed to geothermal highs or "heat pipes" by Card (1978*b*). Felsic intrusions are spatially related to the high grade areas but their ages are either pre-peak metamorphism (Murray, Creighton plutons, 2.1-2.2 Ga) or post -peak metamorphism (Cutler pluton, 1.75 Ga, Grenville Front pluton, 1.6-1.73 Ga).

Card (1978*b*) proposes three main events: 1) an early pre-Nipissing Diabase low grade metamorphism, 2) metamorphic peak, at approximately 1.9Ga, 3) late, post metamorphic peak, deformation. Zolnai *et al.* (1983) summarizes the tectonic history similarly, but in more detail, as six events of expansion and compression: 1) expansion, involving the formation of a shallow sea, and extrusion of basic volcanic rocks, and deposition of the Huronian Supergroup, 2) compression, pre-Nipissing Diabase folding, intrusion of Creighton, Murray Granites; 3) a brief, enigmatic period of expansion, possibly due to renewed hot spot activity, marked by the intrusion of the Nipissing Diabase; 4) horizontal compression and burial between 15 to 20 km,

resulting in ductile deformation and peak metamorphism, 1.9Ga ; 5) continued or renewed compression, manifested as brittle thrusting, folding and a penetrative axial planar cleavage, 6) compression, the Grenville Orogeny, and intrusion of Sudbury Diabase and the right lateral strike slip along the Murray Fault Zone.

2.5 May Township

The study area is located just west of Espanola, and approximately 75 km south-west of Sudbury (Figures 2.4 and 2.5) between the towns of Webbwood and Massey. Transecting the 12 mile square township from east to west are the Transcanada highway and the Serpent River. Early work in the area includes that of Robertson *et al.* (1971); more recent work on May Township was done by Jackson and Henderson (1993).

2.5.1 Geology

The north-west corner of May Township consists of Archean granites. Archean gneisses, and mafic intrusive rocks (Robertson and Siemiatkowska, 1971). The greater part of the township is made up of rocks of the lower two Groups of the Huronian Supergroup, Elliot Lake and Hough Lake, as indicated on Table A.1, Appendix A. Nipissing Diabase makes up approximately 15 percent of the total area. As seen in Figure 2.5, the trend of the intrusions varies; however, most of the larger intrusions, trend north-east-southwest. The dykes are found throughout the township, ranging in size from less than a metre wide and a tens of metres long to very large, tens metres wide, hundreds of metres long and rising tens of metres above the easily eroded metasedimentary rocks.

The Sudbury Diabase dikes, are small and trend NW-SE. Sudbury dikes are distinguished from the Nipissing Diabase primarily by a fresher appearance and the presence of abundant olivine.

2.5.2 Structure

In May Township three sets of folds are found 1) early, isoclinal, recumbent folds and nappes which produce a penetrative mica foliation at a low angle to the bedding, 2) later west-northwest trending folds and, 3) the youngest, east-northeast trending folds (Jackson and Henderson, 1993). The first set was folded along with metagabbro units by the latter two sets (Jackson and Henderson, 1993). May Township contains two main fault orientations (Robertson *et al.*, 1971, Jackson and Henderson, 1993): An earlier set oriented E-NE, including the Murray Fault Zone, which are off-set by later faults and shear zones oriented W-NW. Field work by both Robertson *et al.* (1971) and Jackson and Henderson (1993), shows the southern most fault of the Murray system is marked by a sharp change in lithology from the McKim formation to the Matinenda formation. Based on work in progress, Jackson and Henderson conclude that in May Township the south side of the Murray Fault has moved up and west with respect to the north side.

2.5.3 Metamorphism

Jackson and Henderson (1993) observed boudinage of metagabbro intrusions in the plane of the penetrative mica foliation (see section 2.5.2 above). Emplacement of the metagabbros preceded the major isoclinal folding of Huronian metasediments. Based on a preliminary study of porphyroblast growth, Jackson and Henderson observed that garnet and staurolite both overgrow and are rotated by the penetrative mica foliation. They concluded

that the thermal metamorphic peak was approximately at the same time as this folding event in the area. Jackson and Henderson observed that a set of crenulation foliations post-date the porphyroblast growth; the later crenulations are associated with the generally recognized large-scale folds within the Huronian sequence (Card *et al.*, 1972). Thus later folding that occurred post-thermal peak, about shallowly plunging axes of originally subhorizontal metamorphic zone boundaries, produced the current elliptical metamorphic zonal pattern (Jackson and Henderson, 1993). Later faulting placed amphibolite grade rocks against sub-greenschist to greenschist grade rocks along the Murray Fault (Jackson and Henderson, 1993) (Figure 2.6).

Figure 2.1: Extent and geologic units of the Southern Province, including regions to the west (from Thurston, P.C., *modified* from Sutcliffe in O.G.S. Special Volume 4, 1991, p. 545).

Agnew Lake region
May Township

Figure 2.2: Extent of the Southern Province in Ontario, and its relationship to the surrounding geological provinces. Locations of May township and the Agnew Lake region are indicated (from Bennett et al., 1991, in O.G.S. Special Volume 4, p. 550).

Figure 2.3 Distribution of Metamorphic zones of the Southern Province of Ontario (after Sims *et al.* 1981, p. 381). Note: 1) the three regions of metamorphic grade: i) Sault Ste. Marie - Elliot Lake and ii) Cobalt regions are low grade and iii) Sudbury - Copper region is higher grade; 2) overall elongate east-northwest orientation of zones

Figure 2.4 Metamorphic zones of the Sudbury - Manitoulin area (after Card 1978b, p. 202). The May Township boundary is indicated by a red outline. Note the overall elongate elliptical east-northeast trend of the metamorphic zones

Figure 2.5: Mafic Rock Distribution and sample locations in May Township, Ontario. Modified from Robertson, R.A., Siemiatkowska, K.M., and Assistants, 1971, and Jackson, S.L. and Henderson, I., 1993. Note the Nipissing Diabase outcrops south of the Serpent River and North of the Murray Fault are more continuous and less deformed than those found in between, i.e., north of the Serpent River and south of the Murray Fault.

Figure 2.6: Metamorphic isograds based on pelitic index minerals, from preliminary work of Jackson and Henderson (1993). Note: 1) the higher grade node just north of George Lake; 2) the roughly north-east to south-west orientation of the zones, and 3) the sharp change in grade across the Murray Fault. Map itself is modified from Robertson and Siemiatkowska (1971) and Jackson and Henderson (pers. comm., 1993).

CHAPTER 3: MAFIC ROCKS OF MAY TOWNSHIP

3.1 Introduction

Mafic rocks found within May Township include the predominant Nipissing Diabase, as well as, Archean intrusions and dykes, and the Sudbury Diabase. Other mafic rocks of the Sudbury region include the norites of the Sudbury Igneous Complex (Card, 1978*b*). This chapter reviews previous work on mafic rocks found within the May Township.

3.2 Nipissing Diabase

The Nipissing Diabase is a gabbroic complex, tholeiitic in composition, (Card and Pattison, 1973) and is found throughout the Southern Province and into the adjacent Superior Province to the north (Figure 3.1). The unit occurs as dykes, sills, cone-shaped and irregular intrusions (Card, 1976). The Nipissing Diabase were intruded at 2.219 Ga (based on primary igneous baddeleyite, U-Pb age, Corfu and Andrews, 1986). Their emplacement is believed to have been controlled by pre-existing folds and faults and by the "competency" of the host sedimentary rocks (Card and Pattison, 1973). In detail, the Nipissing Diabase transgress the Huronian Supergroup lithologies and transect early folds (Card, 1972). Tectonically their emplacement is interpreted as representing a brief enigmatic expansional period amidst a major compressional event (Zolnai *et.al.*, 1983)

3.2.1 Primary Igneous Mineralogy and Petrology

Among the comprehensive studies of the minerals, petrography and chemistry of the Nipissing Diabase are: Hriskevich (1968), Jambor (1971), Card and Pattison (1973), Card (1978*a*), Buchan and Card (1985), Lightfoot *et al.* (1986), and Lightfoot *et al.* (1993). In the vicinity of Sudbury, the diabase have recrystallized during metamorphism; igneous minerals are

more scarce and generally only preserved in cores of the larger intrusive bodies (Card and Pattison, 1973). The common igneous assemblage includes pyroxene (augite, pigeonite, orthopyroxene) and plagioclase (labradorite, An_{50-70}) with minor olivine, ilmenite, quartz, potassium feldspar, amphibole, ilmenite, titaniferous magnetite and very minor sulphides such as pyrite and pyrrhotite (Card and Pattison). Elsewhere in the Elliot Lake and Cobalt-Noranda regions, igneous minerals are preserved and the development of metamorphic phases is minor (Figure 2.2) (Card and Pattison).

Large Nipissing Diabase bodies are often differentiated, with chilled margins, an olivine-rich base grading to a pyroxene-rich diabase, and ultimately a quartz and feldspar-rich granophyre assemblage (Card and Pattison, 1973). Card and Pattison divide the Nipissing Diabase into 6 different types based on compositional, mineralogical and textural variations: 1) olivine-bearing hypersthene gabbro, 2) feldspathic pyroxenite, 3) 2-pyroxene gabbro, 4) hornblende gabbro, 5) granophyric gabbro, and 6) granophyre. Chemical trends that accompany the above sequence are decreasing MgO, CaO and increasing iron, Na_2O and K_2O (Card and Pattison). Card and Pattison attribute these 6 types to gravitative settling of early minerals (olivine, orthopyroxene) with extensive development of granophyre brought about by the assimilation of the argillaceous Huronian Supergroup sediments. Lightfoot *et al.* (1993) also concluded, based on major and trace element data, that the mineralogical variations are dominantly a result of low pressure in situ fractional crystallization and assimilation of the host Huronian Supergroup.

3.2.1.1 Primary Igneous Minerals

The petrography of the Nipissing Diabase has been described in detail by Card and Pattison (1973). Plagioclase is commonly zoned in unmetamorphosed and unrecrystallized diabase. Plagioclase composition shows an increase in Na proceeding from the core to the rim in zoned grains and as well from the olivine-rich base to the granophyric phase of differentiated intrusions. Pyroxenes include orthopyroxene, augite and pigeonite (mostly inverted to orthopyroxene). The orthopyroxene occurs as subhedral and euhedral grains, up to several centimetres long, commonly zoned, with increasing iron content towards the rims, with thin exsolution lamellae of diopside. Augite is usually anhedral and shows well developed twinning, as well as exsolution lamellae of orthopyroxene and inverted pigeonite. As a primary igneous mineral, amphibole is minor in the Nipissing Diabase. It occurs as thin discontinuous rims about pyroxenes, except in the hornblende gabbro where it rims and replaces clinopyroxene. Amphiboles include uraltite, actinolite and blue-green hornblende.

Metamorphic minerals recognized by work of Card and Pattison (1973) and Card (1978a) correspond to metamorphic facies of greenschist (actinolite, albite, chlorite, epidote) to amphibolite (hornblende, calcic plagioclase, garnet, biotite) (see Table A.3, Appendix A).

3.3 Archean Mafic Rocks

In May Township, rocks identified as "Archean mafics" by Robertson *et al.* (1971) include large gabbroic-anorthositic intrusions and a series of diabasic dykes. Robertson *et al.*, concluded they are likely late Archean in age as they cannot be traced across the Archean-Proterozoic boundary. Precise age determinations of the anorthositic intrusions and the diabasic dykes are difficult due to their extensively altered state. It has been suggested that some of the diabasic dykes are feeder dykes for the anorthositic intrusions, the basal Huronian

volcanics and the Nipissing Diabase (Robertson *et al.*, 1971, Card *et al.*, 1972, Card and Palonen, 1976). In a detailed petrographic and chemical study of the anorthositic gabbro of May Township, Cape (1973) concluded that the basal Huronian volcanics are not related to the anorthositic intrusions.

The "gabbro-anorthosite" intrusions show variable composition ranging from gabbro to anorthosite with minor granophyre, syenite and granitic segregation (Cape, 1973). The intrusions are described by Cape as generally sill-like or lopolith-like and often layered, with coarse to very coarse grain size. Original calcic plagioclase is extensively saussuritized, original pyroxene is almost totally replaced by actinolite and hornblende (Card and Palonen, 1976). Minor minerals present include quartz, biotite, chlorite (Card and Palonen).

The diabasic dykes have a variable trend but mostly northwest-southeast, and range from 1.5 to 30m wide sharp contacts with host (Card 1978a). They are fine to medium grained, equigranular, porphyritic, porphyroblastic metagabbros, containing mostly amphiboles, altered plagioclase and lesser quartz, micas, chlorite and iron oxides (Cape, 1973, Card and Palonen, 1976).

3.4 Sudbury Diabase

The Sudbury Diabase dyke swarm (~1.25 Ga, Palmer *et al.*, 1977) trends approximately north-west and east-west. Dyke width ranges from a few metres to several hundred metres with a vertical dip (Card, 1976). They vary from the Nipissing swarm in their brownish weathered surface, their abundant olivine, and unmetamorphosed state (Card, 1976) excepting chloritization along fractures (Ginn, 1965).

Figure 3.1: Distribution of Nipissing Diabase intrusions. The Nipissing Diabases are coloured black, the Southern Province is shaded yellow. Note the Nipissing Diabases extend into the Superior Province to the north, but not into the Grenville Province to the south-east. (from Card and Pattison, 1973, p. 9.)

CHAPTER 4: MINERALS AND PETROGRAPHY OF MAFIC ROCKS OF MAY TOWNSHIP

4.1 Introduction

The designation of metamorphic zones in May Township is based on a combination of results from hand specimen examination, petrographic analysis and chemical analysis by microprobe. Hand samples of unmetamorphosed Nipissing Diabase, and metamorphosed diabase are dark, mesocratic, with similar proportions of light (30-40%) and dark (60-70%) minerals. Hand specimens from both lower and higher grade rocks are granoblastic and equigranular; few of the metamorphosed samples show a preferred orientation of mineral grains. The original igneous sub-ophitic fabric is gradually lost with increasing grade but can still be recognized in some of the highest grade samples. The minority of samples showing a fabric by oriented amphibole and plagioclase grains, can be classed into two groups, one of orientations approximately east-north-east and a second orientation, north-west--south-east. The preferred orientation is not often pervasive throughout an entire outcrop but rather is more typically confined to shear zones, a few centimetres to one metre wide. These two orientations correspond to the two main fractures sets observed, as well as the dominant fault systems of the township and the region.

4.2 Petrographic Observations

Petrographic analysis was based on examination of 115 thin sections. The principal minerals observed include: hornblende, plagioclase, actinolite, pyroxene, epidote, clinozoisite, chlorite, biotite, garnet, ilmenite, titanite, quartz and minor rutile, calcite, apatite, talc, sericite. A table of the characteristic mineral assemblages for the metamorphic zones recognized in May Township is found in Appendix A, Table A.2. The amphiboles are generally the most abundant

minerals and exhibit the most obvious changes with grade; plagioclase is the next most abundant mineral followed by biotite, chlorite, garnet, and epidote

4.2.1 Amphiboles

Petrographic study reveals two types of amphiboles: pale green actinolite and blue-green hornblende. Chemical analyses in the following chapter show these amphiboles range through tremolite, actinolite, actinolitic hornblende, magnesio-hornblende, ferro-hornblende, ferro-tschermakitic hornblende, ferro-tschermakite, ferro-pargasitic hornblende and ferro-pargasite (nomenclature after Hawthorne (1983) classification scheme).

Actinolites are found in the "unrecrystallized zone", the greenschist zone and the transitional zone (see Figure 5.1). In the unrecrystallized zone, cross-cutting fractures are marked by replacement of the igneous pyroxenes to, pale, irregular, fibrous actinolite, talc and chlorite (Plate 4.3f). In the greenschist and transitional zones, actinolite, is often the most abundant mineral. It occurs in a variety of forms: acicular and radiating (Plate 4.4c), forming pseudomorphs after pyroxene that often preserve relics of pyroxene in the cores (Plates 4.4b, f), or aggregates of randomly oriented porphyroblasts (Plate 4.4g). Pyroxene twinning and cleavage are occasionally preserved by the replacing actinolite or uranalite or by brown-black inclusions of iron-oxides in parallel lines (Plate 4.4e).

Actinolite and hornblende are found to coexist in the transitional zone. The actinolite remains pale green and slightly pleochroic, often still preserving pseudomorphs of relict pyroxene twinning with a rough, uneven appearance, irregular extinction and birefringence, very fibrous habit and random orientation. The hornblende is darker bluish-green with green,

yellow-green, blue-green pleochroism and a distinctively smoother, more even surface and more uniform birefringence and extinction

Actinolite coexists with hornblende in a number of textural relationships (Plates 4.5a-h). Actinolitic cores are sometimes rimmed sharply and non-gradationally by thick to thin hornblende rims. Actinolite and hornblende also occur together as patchy intergrowths within the same grain. Individual grains of both minerals can be intergrown in a ragged, irregular aggregate of grains. Actinolite and hornblende also coexist, on a very fine scale, that is only resolved by microprobe or Scanning Electron Microprobe analysis (i.e. Appendix C, Plate C.3).

Hornblende often grows next to actinolite, but is also found as distinct prismatic and anhedral grains within and adjacent to plagioclase. Only in samples of Archean mafic rocks are large, well-developed patches of co-existing actinolite and hornblende easily visible under the optical microscope (Plate 4.1a), with both optically and chemically sharp boundaries between the two amphiboles; however they are simultaneously at optical extinction

In the "unrecrystallized" samples, blue-green, subhedral hornblende grains, less than 0.25mm, with green, yellow-green, blue-green pleochroism, grow on the edges of pyroxenes. These hornblendes exhibit sharp, irregular contacts next to pyroxene and euhedral to subhedral crystal faces growing out into the matrix (Plate 4.3a, d, e). They have uniform extinction and birefringence. These blue green hornblendes are often in contact with or adjacent to brown biotite, as well as containing anhedral and euhedral hexagons and tabular inclusions of biotite. Similar amphiboles and biotites, in the metamorphosed mafic rocks of the Sudbury Igneous Complex, have been interpreted as igneous minerals growing from the late stage cooling of the

igneous intrusion (Fleet *et al.*, 1987) Occasional brownish patches within these blue-green hornblendes are either biotite inclusions or pleochroic haloes about zircon and/or titanite inclusions.

The amphibolite grade rocks contain dark blue-green hornblendes, exhibiting blue-green, green, yellow-green pleochroism. The darkness of the amphibole colour is slightly variable, some grains having a very deep blue colour; These occur most often in garnet-bearing samples. The amphibolite grade amphiboles have three forms: 1) mottled, cloudy, paler, inclusion-rich cores with darker green rims of radiating acicular/tabular needles (Plate 4.6a, b), 2) large masses (1-5mm) of subhedral to anhedral acicular/tabular grains (Plate 4.6d, f), 3) well developed subhedral to euhedral tabular grains, containing a few inclusions, with an overall granoblastic/decussate fabric, but occasionally foliated (Plates 4.6c). The first two forms often still maintain a general sense of the sub-ophitic texture of the unmetamorphosed and lower grade rocks.

4.2.2.1 Exsolution Lamellae

Series of fine (less than 1 micron wide), parallel, and slightly anastomosing, exsolution lamellae are found in some hornblendes in every zone. In unrecrystallized samples, exsolution lamellae are found in igneous hornblendes adjacent to pyroxenes (Plate 4.8a). In greenschist samples patches of darker blue-green hornblendes within actinolite grains often contain exsolution lamellae, the lamellae are confined to these areas of blue-green hornblendes and do not extend into the adjacent, coexisting actinolite. The exsolution lamellae are often in the same orientation as twin or exsolution lamellae in the adjacent pyroxene or pyroxene pseudomorphs.

Exsolution lamellae are visible only in amphibole grains that are free of the typical cleavage development of other amphiboles

4.2.2 Plagioclase

Plagioclase is the second most abundant mineral overall. Electron microprobe analyses reveal compositions ranging from albite to labradorite

The unrecrystallized samples maintain the primary sub-ophitic texture of large plagioclases enclosing euhedral pyroxenes or large pyroxenes enclosing smaller plagioclase laths (Plates 4.a, b, c). This texture is gradually lost with increasing grade due to recrystallization. In these lowest grade samples, plagioclase occurs as clear grains, exhibiting twinning and zoning, essentially unaltered except for minor sericite/epidote between plagioclase grains (Plate 4.3a, b, c). In the majority of samples of the greenschist zone, the plagioclases appear almost identical to those in "unmetamorphosed zone", except for a slight increase in the extent of alteration (Plates 4 4b)

In a few greenschist samples, the plagioclase has been completely recrystallized to anhedral albite without twinning and without zoning, this texture is typical of metamorphic rocks. The feldspar grains occupy the interstices between acicular actinolite or occur as irregular, equigranular, granoblastic grains in rocks containing hornblende (Plate 4 4 a)

Plagioclases of the transitional zone are characterized by the preservation of igneous crystals and the partial to complete development of clear recrystallized rims, they are seldom recrystallized, and maintain the lath-like habit of the lower grade samples (Plates 4 5 a, b, e-f) In general, plagioclases coexisting with hornblende in the transitional and amphibolite zones have cloudy, altered cores surrounded by clearer untwinned (sodic) rims (Plates 4 6 a, b,

c, e, f) The cores are replaced by mixtures of sericite, chlorite, epidote and clinozoisite and often show faint relict plagioclase twinning. The clear (sodic) rims are often incomplete and irregular and sometimes so thin that they are only discernible by the change in the grey scale in Scanning Electron Microprobe imaging. For samples where recrystallization is more extensive, irregular plagioclase grains occupy interstices between growing amphiboles. Where plagioclases and quartz occur together, a granoblastic texture is apparent (Plates 4 6c, 4 7b). According to Spry (1969), the brownish-cloudy appearance of most of the plagioclases is due to the presence of extremely fine, submicroscopic inclusions of opaque iron oxides, spinel, garnet, biotite, hornblende, and rutile, caused by elevated temperatures and addition of water and iron during deuteritic, thermal, or low pressure regional metamorphism. Extent of alteration of plagioclase to sericite/epidote/clinozoisite is variable from grade to grade, but is generally most severe in calcic cores or along late fractures.

Plagioclases of Archean mafic rocks are extensively altered and replaced by mixtures of sericite, chlorite, epidote and clinozoisite. Little original plagioclase remains; however the original sub-ophitic texture is maintained (Plate 4.1a, b).

Plagioclases of the Sudbury Diabase exhibit the characteristics of primary igneous minerals including twinning, zoning, little to no alteration products, and a lath-like crystal shape in a sub-ophitic texture (Plate 4.2)

4.2.3 Pyroxene

Pyroxenes present in the May Township Nipissing Diabase are igneous pyroxenes similar to those described in Chapter 3. They occur in the unrecrystallized zone exhibiting diabasic texture with calcic plagioclase in which euhedral plagioclase laths are enclosed by large

anhedral pyroxenes, or euhedral pyroxenes are surrounded by large (1-3mm) plagioclase grains (Plates 4.3 a-c). Many pyroxene grains also exhibit very fine exsolution lamellae, worm-like intergrowths, and herringbone twinning. Alteration of pyroxene to actinolite, talc and chlorite is generally confined to grain boundaries and twin planes, and cross-cutting fractures (Plates 4.3f, g). "Uralite" is used to describe the alteration of pyroxene due to deuteric processes or processes involved with the cooling of a igneous body (Johannsen, 1937). Some pyroxenes contain fine inclusions of sericite, talc or iron oxides along twin planes, resulting in a cloudy brownish appearance (Plate 4.3d, e). Pale green, fibrous and acicular actinolite occurs around mantles of talc rimming pyroxene, actinolite also coexists with talc in the cores themselves. Grains completely replaced by actinolite reflect their origin by showing relict pyroxene twinning, cleavage and habit (Plate 4.4e).

Sudbury Diabase pyroxene is magnesium enstatite, identified by its pale reddish colour. Pyroxene coexists with euhedral laths of plagioclase (Plate 4.2). There is no pyroxene preserved in the Archean mafic rocks.

4.2.4 Biotite

Biotite can be found in most samples in every zone. Its abundance ranges from 3 to 30 percent of the assemblage and generally increases with increasing grade. Biotite occurs as irregular and anhedral to elongate and tabular grains (Plates 4.3b, c, d, e, 4.5a, d, h, 4.6a,d, 4.7a,b). Igneous biotite preserved in the lowest grade rocks varies little from metamorphic biotite found in the higher grade rocks except that it generally has a more euhedral habit. In general biotite abundance increases with increasing grade, however, many amphibolite grade samples contain extremely little or no biotite. Biotite exhibits equilibrium textures with all

other minerals, it is often in contact with ilmenite, and replaces amphibole and is replaced by chlorite

4.2.5 Garnet

In the Nipissing Diabase of May Township, garnet is found only in samples containing the highest grade assemblages. It occurs as anhedral to subhedral grains, highly poikiloblastic containing inclusions of mostly quartz and lesser plagioclase, ilmenite, biotite, amphibole and chlorite (Plates 4.7a, b). In some of the largest grains (range 0.01 to 7mm), there is a higher concentration of inclusions in the core. However there is no helitic texture to indicate the presence of a foliation at the time of growth. In thin section, under plane light, they are pale pink and occasionally show cores slightly more pleochroic.

4.2.6 Chlorite

Chlorite is found in every metamorphic zone. It can be divided into two types based on colour and birefringence, 1) pale green and nonpleochroic, exhibiting anomalous grey-brown interference colours (Plates 4.3f, 4.4c, d, 4.5a), 2) green pleochroism, and anomalous blue-violet interference colours. The first type occurs almost exclusively in lower and transitional grade zones and the second type in transitional and higher grade zones. In low grade rocks, type 1 chlorite is a major stable phase that comprises as much as 30% of the assemblage; grains are anhedral to subhedral or fibrous and radiating in form. Grain size is variable from 0.5 mm to 2mm (Plate 4.5f). In the transitional zone chlorite is much less abundant, 1-5%, found within plagioclase or actinolite cores, or adjacent to hornblende or biotite (Plates 4.6b, c). In the highest grade zone chlorite is still less abundant, <3%, found replacing biotites and in late cross-cutting veins. In a few samples both chlorites occur, type 2 replacing type 1. Type one

is therefore part of an earlier assemblage. Maruyama *et al* (1983) have observed that retrograde chlorites have the anomalous blue interference colour. Cooper (1972) also considered chlorites with anomalous blue-violet interference colours to be relatively lower grade compared to chlorites with anomalous grey-brown interference colours).

In the Archean mafic rocks, chlorite occurs with anomalous brown pleochroism, anhedral to fibrous in habit, within plagioclase grains. There is no chlorite in the Sudbury Diabase.

4.2.7 Epidote and Clinozoisite

Both epidote and clinozoisite occur in almost every sample, in every metamorphic zone, except for the unrecrystallized samples. Epidote exhibits second order interference colours and is colourless to slightly pale yellow-green pleochroism. Clinozoisite is similar in appearance but is colourless with anomalous blue-yellow interference colours (Plate 4 4c, d, g, h). Combinations of epidote and clinozoisite make up as much as 10% of some assemblages, but are generally less than 5%. Their morphology is variable, occurring as distinct subhedral, granoblastic grains, or occupying cross-cutting veins. In the greenschist zone they appear to be in equilibrium with actinolite, and chlorite. Epidote and clinozoisite can be found replacing plagioclase along with sericite and/or chlorite or with chlorite and or calcite infilling late stage fractures.

In the Archean mafic rocks the epidotes occur as small, less than 0.005 mm grains scattered throughout plagioclase, and as larger, approximately 0.08 mm, grains within amphibole grains and are distinctly zoned with high birefringent cores and low birefringent rims (Plates 4 1a, b). There is no epidote or clinozoisite in the Sudbury Diabase.

4.2.8 Ilmenite and Titanite

The Nipissing Diabase almost always contains ilmenite, as a minor phase (1-5%), found in varying quantities through all the metamorphic zones. Ilmenite occurs as small irregular, rounded, elongated grains, less than 0.05 mm (Plates 4.3b, 4.4b, 4.5a,h, 4.6c, 4.7b), scattered throughout the rock and as larger grains, up to 4-5mm, often exhibiting an elongate intergrowth structure (Plates 4.6a,b). Ilmenite is frequently found within amphibole or biotite grains and/or is often rimmed by either titanite or biotite; rutile is often in close proximity. The same is the case for the Archean mafics. Sudbury Diabase has only ilmenite surrounded on most sides by amphibole or biotite, with no rutile or titanite. Titanite occurs as small discrete anhedral grains, generally less than 0.1 mm, or rimming ilmenite, occasionally lozenge shaped titanite is observed.

4.2.9 Minor constituents

Less than 1% of the mineral assemblage is attributable to such minerals as rutile, apatite and calcite. Vivid red-brown rutile is generally found, in samples from all metamorphic zones, as small anhedral grains, adjacent to, or in the immediate vicinity of ilmenite or titanite. Clear, euhedral apatite is present in the amphibolite zone, as small (generally less than 0.05 mm) grains within quartz or plagioclase grains. Calcite is clearly a late stage addition, existing primarily in cross-cutting veins, or as late stage replacement product after amphibole. Talc forms mantles around pyroxene in a few of the "unmetamorphosed" samples. Tiny (less than 0.001mm) prismatic and irregular zircons, with pleochroic brown haloes, are abundant in biotite and hornblende.

4.3 Discussion

The typical metamorphosed mafic rock assemblage of amphibole plus plagioclase is found in the Nipissing Diabase of May Township. There is preservation of diabasic textures into the higher grades, and a lack of complete recrystallization of mineral assemblages. The amphiboles commonly contain relict igneous and metamorphic minerals and textures, and are often multiphase, of coexisting actinolite and hornblende. The plagioclases are largely unrecrystallized and often preserve the igneous habit, twinning and zoning into the highest grades. When recrystallization of plagioclases is apparent, it generally results in the formation of a clear rim around a core showing varying degrees of alteration (excepting the few fully recrystallized greenschist samples, J-34-1 and J-43-1).

Studies of other metamorphosed mafic rocks exhibiting similar mineralogy such as the Sudbury Igneous Complex (M.L. Thomson *et al.*, 1985, Fleet *et al.*, 1987) and the Dore Lake Complex (Kline, 1984), attribute such features to metamorphism under static conditions. According to Brodie and Rutter (1985), mafic rocks are relatively resistant to plastic and brittle deformation. Hydration under static conditions will result in disequilibrium textures. The problems involved in using metamorphosed mafic rocks to determine a metamorphic history are well recognized such as the sensitivity of amphiboles and plagioclases to changes in grade, the lack of reactivity and sluggishness of reactions, and the preservation of relict minerals and textures.

Plate 4 1a Photo (in plane polarized light) of Archean mafic rock, sample I-81-1. Note: 1) the "patchy" nature of the co-existing actinolite (pale green) and hornblende (darker green), 2) the plagioclase is altered to mixtures of sericite, epidote and chlorite. Field of view, 2.6 mm

Plate 4 1b Photo (in plane polarized light) of an Archean mafic rock, sample S-53-1. Note: 1) the severely altered state of the plagioclase to mixtures of sericite, chlorite and epidote. Field of view, 5.2 mm

Plate 4 2 Photo (in plane polarized light) of Sudbury Diabase, sample J-40-1. Note: 1) the obvious diabasic texture, 2) the pale reddish enstatite, 3) the presence of olivine, replaced by green serpentine. Field of view, 5.2 mm

Plate 4 3a Photo (in plane polarized light) of sample 808-1A, a Nipissing Diabase from the "unrecrystallized" zone. Note: 1) the subophitic texture of subhedral pyroxenes and plagioclase laths, 2) localized alteration of the pyroxenes along fractures, and slight alteration of plagioclase along grain boundaries. Field of view, 5.2 mm.

Plate 4 3b Photo (in plane polarized light) of sample I-305-1, a Nipissing Diabase from the "unrecrystallized" zone Note: 1) the subophitic texture wherein large plagioclase grains enclose smaller pyroxenes, 2) the presence of green hornblende and brown biotite. Field of view, 5.2mm

Plate 4 3c Photo (in crossed polarized light) of sample I-305-1, the same view as above Note: 1) the worm-like intergrowths in some of the pyroxene grains (indicated by the number 1), 2) the presence of zoned plagioclase (indicated by the number 2) Field of view, 5.2 mm

Plate 4 3d Photo (in plane polarized light) of sample I-310-1, a Nipissing Diabase from the "unrecrystallized" zone Note 1) the fine black inclusions in the pyroxenes oriented parallel to the twin lamellae (twin lamellae are indicated by the red dashed lines); 2) the contact between the green hornblende and the pyroxene is irregular, while the hornblende not in contact with the pyroxene is more subhedral. Field of view, 1.3 mm

Plate 4 3e Photo (in crossed polarized light) of sample I-310-1, the same view as above Note 1) the hornblende show uniform extinction across the grain Field of view, 1.3mm.

Plate 4 3f Photo (in crossed polarized light) of sample I-302-1, a Nipissing Diabase from the "unrecrystallized" zone. Note 1) the fracture across the sample is marked by localized alteration of the pyroxenes to talc, chlorite and actinolite. Field of view, 1.3mm.

Plate 4 3g Photo (in crossed polarized light) of sample 808-1A, a Nipissing Diabase from the "unrecrystallized" zone. Note 1) the pyroxenes are altered to sericite/talc (extremely high birefringence) along fractures within the grain while the adjacent plagioclase show no significant alteration. Field of view, 2.6mm

Plate 4 4a Photo (in plane polarized light) of sample J-34-1, a Nipissing Diabase from the greenschist zone. Note 1) the sample shows complete recrystallization to actinolite and sodic plagioclase, no relic textures or minerals are present. This type of greenschist sample was found only in two locations in May Township. Field of view, 2.6 mm.

Plate 4 4b Photo (in plane polarized light) of sample 812-1, a Nipissing Diabase from the greenschist zone. Note 1) the pale green actinolite has replaced pyroxene while still maintaining the diabasic texture in the arrangement of the grains, 2) the plagioclases show little alteration and remain roughly lath-like in habit. This sample represents a more typical greenschist zone sample compared to sample J-34-1, shown above. Field of view, 2.6 mm.

Plate 4.4c Photo (in plane polarized light) of sample J-35-1, a Nipissing Diabase from the greenschist zone. Note: 1) the sample contains well-formed acicular, radiating needles of actinolite co-existing with chlorite and subhedral grains of clinozoisite; 2) plagioclase has been extensively replaced by chlorite and clinozoisite. Field of view, 2.6 mm.

Plate 4.4d Photo (in crossed polarized light) of sample J-35-1, the same view as above. Field of view, 2.6 mm.

Plate 4 4e Photo (in plane polarized light) of sample J-51-1, a Nipissing Diabase from the greenschist zone. Original igneous pyroxene has been pseudomorphed by actinolite and fine black oxides which preserve the original herringbone twinning of the pyroxene. Field of view, 1.3 mm

Plate 4 4f Photo (in plane polarized light) of sample J-58-1, a Nipissing Diabase from the greenschist zone. Relic igneous pyroxene is found within an actinolite pseudomorph. The pyroxene is surrounded by talc and actinolite. Field of view, 2.6 mm

Plate 4 4g Photo (in plane polarized light) of sample 801-1, a Nipissing Diabase from the greenschist zone. Note plagioclase is extensively altered to mixtures of epidote and chlorite. The cross-cutting vein consists of clinozoisite. Field of view, 5.2 mm.

Plate 4 4h Photo (in crossed polarized light) of sample 801-1, the same view as above. Field of view, 5.2 mm.

Plate 4 5a: Photo (in plane polarized light) of sample S-528-1, a Nipissing Diabase from the transitional zone (specifically the "George Lake Transitional Zone"). Note the diabasic texture is still preserved. The pyroxenes have been completely replaced by actinolite and magnesio-hornblende. The plagioclases are only slightly altered and maintain their lath-like habit and their very calcic composition. Field of view, 2.6 mm

Plate 4 5b: Photo (in crossed polarized light) of sample S-528-1, the same view as above. Note the chlorites show the anomalous grey-brown interference colours. Field of view, 2.6 mm

Plate 4 5c Photo (in plane polarized light) of sample S-136-2, a Nipissing Diabase from the "George Lake transitional zone" Like the previous sample, S-528-1 (Plates 4.5a,b), this sample contains well-recrystallized actinolite and hornblende which are best distinguished by means of electron microscopy The diabasic texture is less well preserved in this sample The plagioclases remain very calcic and are commonly replaced by mixtures of chlorite, epidote and sericite Field of view, 2.6 mm

Plate 4 5d Photo (in plane polarized light) of sample S-63-2, a Nipissing Diabase from the "George Lake transitional zone" As above, this sample contains well recrystallized amphiboles, and relic calcic plagioclase, and a less well-preserved diabasic texture Field of view, 2.6 mm

Plate 4 5e Photo (in plane polarized light) of sample J-36-1, a Nipissing Diabase from the transitional zone This sample is an example is another type of transitional zone sample wherein actinolite and hornblende are easily visible under the microscope and commonly coexist as patchy intergrowths or having actinolitic cores and hornblende rims. The plagioclases remain calcic and vary in the extent of alteration to sericite, chlorite and epidote Field of view, 2.6 mm

Plate 4 5f Photo (in crossed polarized light) of sample J-36-1, the same view as above. Field of view, 2.6mm

Plate 4 5g Photo (in plane polarized light) of sample J-4-1, a Nipissing Diabase from the transitional zone. This is an example of another type of transitional sample wherein actinolite and hornblende are easily visible under the microscope and commonly coexist as patchy intergrowths or having actinolitic cores with hornblende rims. The plagioclases remain very calcic and show significant alteration to sericite. Field of view, 5.2 mm.

Plate 4 5h Photo (in plane polarized light) of sample J-31-1, a Nipissing Diabase from the transitional zone. The diabasic texture is still well preserved. Field of view, 5.2 mm.

Plate 4 6a Photo (in plane polarized light) of sample J-15-4, a Nipissing Diabase from the amphibolite zone. This sample is fairly typical of the amphibolite zone in that hornblende occurs with poikiloblastic cores and radiating tabular rims. The plagioclases have thin, clear, sodic rims (next to hornblende) and fuzzy calcic cores, with fine inclusions of sericite. Field of view, 5.2 mm.

Plate 4 6b Photo (in plane polarized light) of sample J-10-1, a Nipissing Diabase from the amphibolite zone. This sample is similar to J-15-4 above, in that it contains hornblendes with poikiloblastic cores and radiating rims. Also the plagioclase shows clear, bright rims and fuzzy, brownish cores. In this sample the arrangement of the grains is still vaguely reminiscent of the original diabasic texture. Field of view, 5.2 mm.

Plate 4 6c Photo (in plane polarized light) of sample J-6-4, a Nipissing Diabase from the amphibolite zone. This sample is another type of amphibolite zone sample in that it contains well-formed, subhedral hornblende grains, which are oriented to form a foliation, which is not common in the Nipissing Diabase of May Township. The diabasic texture is completely lost. The plagioclases have clear sodic rims and fuzzy, calcic cores. This sample comes from the same outcrop as the garnet-bearing amphibolite sample J-6-3 (see Plate 4 7a). Field of view, 5.2 mm.

Plate 4 6d Photo (in plane polarized light) of sample J-8-1, a Nipissing Diabase from the amphibolite zone. This sample is another type of amphibolite zone sample in that it contains aggregates of randomly oriented hornblende grains. The original diabasic texture is lost. The plagioclases have calcic cores and sodic rims. Field of view, 5.2 mm.

Plate 4 6e (in plane polarized light) of sample J-10-1, a Nipissing Diabase from the amphibolite zone. This photo shows the clear, sodic rims and fuzzy, altered, calcic cores of the plagioclases common in samples of the amphibolite zone. Field of view, 1.3 mm

Plate 4 6f (in plane polarized light) of sample S-532-1, a Nipissing Diabase from the amphibolite zone (near the "George Lake transitional zone). This sample contains aggregates of randomly oriented hornblende grains. The original diabasic texture is vaguely apparent by the arrangement of the grains. The plagioclases have clear, sodic rims and altered, calcic cores. Field of view, 5.2 mm

Plate 4 7a Photo (in plane polarized light) of sample J-6-3, a garnet-bearing Nipissing Diabase from the amphibolite zone. The garnets of this sample are fairly large and subhedral with inclusions of quartz, plagioclase, biotite and hornblende. The hornblendes are deep blue-green in colour. Field of view, 5.2 mm.

Plate 4 7b Photo (in plane polarized light) of sample 806-7A, a garnet-bearing Nipissing Diabase from the amphibolite zone. This sample contains a distinct foliation, manifested by the preferred orientation of the elongate, tabular hornblende grains. The foliation is not preserved in the inclusions within the garnet porphyroblasts, indication perhaps that deformation succeeded the garnet formation. The plagioclases are completely recrystallized and are oligoclase to andesine in composition. Field of view, 5.2 mm.

Plate 4 8a Photo (in plane polarized light) of sample I-302-1, a Nipissing Diabase from the "unrecrystallized" zone Visible are exsolution lamellae (indicated by the red dashed line) in a hornblende grains attached to a pyroxene grain The exsolution lamellae in the hornblende are often (but not always) parallel to twin lamellae (indicated by the red dashed line) in the adjacent pyroxene Field of view, 0.325 mm

Plate 4 8b Photo (in plane polarized light) of sample I-49-1, a Nipissing Diabase from the amphibolite zone The exsolution lamellae as shown here are not generally not found throughout an entire grain, instead they occur in patches Field of view, 0.13 mm

CHAPTER 5: METAMORPHIC ZONES OF MAY TOWNSHIP

5.1 Introduction

This study assumes a closed system for the major elements of the Nipissing Diabase of May Township. This premise is based on comparisons made by Card and Pattison (1973), (see Appendix B, Table B.1) between the gabbros and metagabbros of the Nipissing Diabase suite across the Southern Province. Card and Pattison concluded that the change from gabbro to metagabbro involves essentially no change in bulk composition except for the addition of water (and possibly minor sulfur, and an increase in the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio). Changes in metamorphic assemblage are therefore due primarily to changes in pressure and temperature.

5.2 Metamorphic Zones of May Township

Four metamorphic zones are recognised in the Nipissing Diabase of May Township based on metamorphic mineral assemblages and textures. These four zones are: "unrecrystallized", greenschist, transitional, and amphibolite (Figure 5.1). The amphiboles were the most useful mineral in distinguishing the zones. The compositions of the plagioclase minerals did not adjust as readily as the amphiboles to changing metamorphic grade.

5.2.1 "Unrecrystallized" Zone

Samples labelled as "unrecrystallized" are those which contain igneous assemblages and textures, with little or no alteration (Plates 4.4a-d). Igneous pyroxene and plagioclase are the main components of rocks from this zone; estimated modal amounts of pyroxene and plagioclase range between 40%-60% to 60%-40%, averaging approximately equal proportions. Minor constituents, including igneous biotite,

hornblende, ilmenite, titanite, generally make up less than 5 percent of the entire rock

Grain boundaries of pyroxene and plagioclase are sharp and uniform Plagioclase maintains a primary igneous habit with twinning and zoning, no recrystallization is evident

Alteration of plagioclase is generally slight, manifested as a cloudiness caused by very fine inclusions of opaque minerals and sericite, alteration is more extensive along plagioclase grain boundaries and along cracks in grains and along late crosscutting fractures, involving replacement by sericite and epidote/clinozoisite (Plate 4.3a,b,f) Both orthopyroxenes and clinopyroxenes show alteration to talc, sericite and actinolite which is most extensive along fractures (Plate 4.3f,g) Often relict pyroxene cores are surrounded by rims of talc, chlorite and actinolite, the timing of this alteration is puzzling, and two cases are considered possible. 1) the mantle of talc is a relic that is overgrown by amphibole along the prograde path, 2) the preferential replacement of pyroxene by talc is a result of later retrograde metamorphism

The "unrecrystallized" samples are being labelled as a metamorphic "zone" Due to the largely massive and impermeable nature of the Nipissing Diabase and the importance of fluids in metamorphic reactions (Winkler, 1979, Fyfe, 1976), it is possible that the characteristics of the unrecrystallized zone result from lack of fluid penetration rather than the P-T conditions

5.2.2 Greenschist Zone

Greenschist zone assemblages are defined essentially by the predominance of actinolite instead of pyroxene A transitional zone between the "unrecrystallized" zone and the greenschist zone was not observed

Actinolite occurs in two forms in this zone: 1) as aggregates of pale green, acicular and fibrous grains, replacing pyroxene as pseudomorphs, preserving pyroxene habit, twinning and cleavage (Plates 4 4b,e,g,h), or 2) as large irregularly-shaped aggregates (Plate 4 4a) in more foliated samples, in which the igneous mineralogy and diabasic texture is completely lost. The second form is only found in two samples, J-34-1 and J-43-1, that show complete recrystallization. Minor blue-green hornblende is sometimes found, but is believed to be relict igneous hornblende.

Plagioclase is less useful as an index mineral as most samples exhibit little change in appearance from the previous zone. The mineral retains an igneous habit, twinning and zoning (Plate 4 4b). Alteration of plagioclase is also similar to that of the previous zone, excepting a few samples which show more extensive alteration to sericite, epidote/clinozoisite and chlorite (Plate 4 4g,h). Microprobe analyses show that the composition of the greenschist plagioclase is very calcic, An₄₀₋₇₀ excepting samples J-34-1, J-43-1 and 816-1C, these contain albitic, recrystallized plagioclase, occupying the interstices between actinolite and showing no twinning or zoning. These samples of actinolite-albite indicate the complete metamorphic assemblage of the greenschist zone of May Township. This assemblage is rarely achieved due to persistence of disequilibrium assemblages of actinolite and igneous plagioclase.

5.2.3 "Transitional" Zone

The definition of the "transitional zone" is somewhat discretionary. It is commonly used to describe a region of gradational change between greenschist and amphibolite grade. Its use in this study follows the precedent of Turner (1981) to describe an

assemblage containing two amphiboles, actinolite and hornblende, or two plagioclases, albite and oligoclase. The transitional zone is marked by the first appearance of hornblende or the first appearance of oligoclase with increasing grade.

Miyashiro (1961, 1973) divided the transitional zone into two subzones based on pressure: higher pressure albite-epidote amphibolite facies, and the lower pressure calcic plagioclase-actinolite hornfels facies. It is difficult to use such a definition in this study as it is not possible to distinguish between what may be relict igneous hornblende or metamorphic hornblende, as well. Scanning Electron Microscopy imaging shows that actinolitic amphiboles are intergrown with hornblendic amphiboles on a very fine scale at conditions experienced by the "unrecrystallized" zone through to the amphibolite zone (Appendix C, Plates C 1, C 2, C.3)

The following chapter will show that amphibole analyses of the transitional zone span a range of compositions, from actinolite to tschermakite, actinolite analyses are from cores of grains and tschermakite compositions from a few areas where the rimming hornblende is a very deep blue-green colour. The majority of transitional zone amphibole analyses fall into the magnesio-hornblende field, between typical greenschist and amphibolite zone compositions (Appendix C, Figure C 1)

As in the greenschist zone, the plagioclases of the "transitional zone" are poor index minerals as a range of compositions from albite to labradorite are found. In general, they still exhibit the igneous characteristics of the previous two zones (Plates 4 5a,b,e,f,h) even in samples with extensively recrystallized amphiboles (Plate 4 5c,d). In some

samples the metamorphic plagioclase occurs as an extremely thin rim, visible only under a Scanning Electron Microscope

The transitional assemblages contain abundant relict features and thus are largely disequilibrium assemblages. Those transitional samples that do exhibit extensive recrystallization of the amphiboles, and do not contain actinolitic cores with hornblende rims, (819-2, 820-1, S-63-2, S-136-2, S-528-1, S-532-1) are generally found in the lower grade zone enclosed within the amphibolite zone (Figure 5.1)

5.2.4 Amphibolite Zone

Assemblages of the amphibolite zone appear to approach equilibrium more closely than the rocks of lower grades. The amphiboles are blue-green hornblendes occurring with three habits: aggregates of acicular, tabular and subhedral fine grains (Plate 4 6d,f), grains with slightly paler blue-green poikiloblastic cores and darker blue-green radiating tabular rims (Plate 4 6a,b), and euhedral to subhedral tabular grains often showing a preferred orientation (Plate 4 6c). Those samples with the first habit contain core compositions closer to typical transitional zone amphiboles and rims of more tschermakitic/pargasitic compositions. The contacts between blue-green hornblende and recrystallized plagioclase are sharp and straight and well formed. Samples showing euhedral to subhedral tabular hornblende and completely recrystallized plagioclase exhibit a granoblastic, decussate texture, these textures suggest an equilibrium state.

In general, plagioclases of the amphibolite zone have cloudy, inclusion-rich, altered calcic cores and recrystallized, clear, untwinned, unzoned sodic rims (Plates 4.6a,b,c,e)

Some of the finer-grained foliated samples contain completely recrystallized plagioclase of albite to oligoclase composition

Three garnet bearing samples are found in the amphibolite zone, and contain subhedral to anhedral poikiloblastic garnets and paragonitic hornblendes of a deeper blue-green colour, compared to samples without garnet from the same outcrop

5.3 Discussion

The metamorphic assemblages observed in May Township agree with those described by Card (1978a) for the entire Southern Province, except for the absence of relict igneous minerals and textures in the description by Card. The "unrecrystallized" zone described above is possibly analogous to the "sub-greenschist" facies of Card. Card defined the subgreenschist facies by assemblages of original (detrital, chemically precipitated or magmatic) minerals and diagenetic and epigenetic minerals, such as uraltic amphiboles, talc, epidote group minerals, magnetite and leucoxene. The "unrecrystallized" zone within May Township is not identified on the regional metamorphic maps of Sims *et al.* (1981), (Figure 2.3)

The metamorphosed mafic rocks of May Township can be compared with other comprehensive studies of mafic rocks metamorphosed to amphibolite grade, both from other areas of the Southern province, and from other parts of the world (Begin, 1989, Begin, 1992, Begin and Carmichael, 1992, Card, 1978a, Cooper, 1972, Fleet *et al.* 1987, Graham, 1974, Grapes, 1975, Grapes *et al.*, 1977, Hietanen, 1973, Laird and Albee, 1981, Sethuraman and Moore, 1973, Terabayashi, 1993, M.L. Thomson *et al.*, 1985). The rocks of May Township are distinguished from many of these studies as they contain no evidence for zeolite, prehnite-pumpellyite facies minerals, and lack complete re-equilibration of the original igneous calcic

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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plagioclases. The rocks of May Township tend to preserve the original igneous minerals, textures, habits and structures. Studies of metamorphosed mafic rocks that do exhibit similar features to May Township include the Sudbury Igneous Complex (Thomson et al., 1985, Fleet et al., 1987) and the Dore Lake Complex, Quebec (Kline, 1984).

Equilibrium assemblages of actinolite and calcic plagioclase have been reported in contact metamorphic rocks by Shido and Miyashiro (1959) and Seki (1961). Such assemblages define the "actinolite-calcic plagioclase hornfels" facies of Miyashiro (1968), and are characteristic of contact metamorphism. There is no large plutonic activity related specifically to the areas of actinolite and calcic plagioclase co-existing in May Township.

5.3.1 Distribution of Metamorphic Zones of May Township

Figure 5.1 shows that the orientation of the metamorphic zones is related to major structural elements such as the Murray Fault Zone and the Serpent River "Structural Discontinuity" (Jackson and Henderson, 1993). There is a sharp change in grade across the southern-most fault of the Murray System. This is shown by the proximity of pairs of greenschist and amphibolite samples across the fault: 812-1 (greenschist) and 811-1 (amphibolite) and J-43-1 (greenschist) and 805-1A (amphibolite) (Figure 5.1). Sample S-104-1 is an amphibolite sample apparently located immediately north of the Murray Fault; this occurrence of amphibolite suggests that the major trace of the fault might be placed to the north of S-104-1.

The Serpent river seems to divide the amphibolite zone from the southerly transitional zone. Whether this is a gradual or sharp transition is not apparent. The Serpent river has been

proposed as a "structural discontinuity" by Jackson and Henderson (1993) based on a study of the metasedimentary rocks of the township.

Boundaries between "unrecrystallized", greenschist and transitional zones in the southern portion of the township are irregular. There is no apparent correlation with any structural elements to explain the irregularity. Possibly the lower grade rocks to the south were affected by a lack of pervasive fluid penetration that inhibited the metamorphic recrystallization of the rocks.

The lower grade node within the amphibolite zone is labelled as transitional. However, this distinction is tentative as some of the samples seem to be border-line greenschist grade. Assemblages of the low grade node seem to progress from actinolite-calcic plagioclase (S-528-1, S-63-2, S-532-1) to hornblende-calcic plagioclase (S-537-2). In the north, the small transitional zone is outlined by five samples, and may be separated from the northern greenschist zone by two faults. Samples 816-1C and J-43-1, occur within the northern greenschist zone and stand out from other greenschist grade samples as they contain appreciable metamorphic albite (instead of relict igneous calcic plagioclase), coexisting with actinolite.

CHAPTER 6: MINERAL CHEMISTRY

6.1 Introduction

In studies of metamorphosed mafic rocks, chemical analyses of amphibole and plagioclase are most often used to better clarify the chemical changes that accompany changes in metamorphic grade (Allen and Goldie, 1985, Arai and Hirai, 1985, Bégin and Carmichael, 1992, Brady, 1974, Compton, 1958, Cooper and Lovering, 1970, Goldsmith, 1982, Graham, 1974, Grapes, 1975, Grapes *et al.* 1977, Hietanen, 1974, Holland and Richardson, 1979, Hynes, 1982, Maruyama *et al.* 1982, Noble, 1962, Plyusnina, 1982, Terabayashi, 1988, 1993). Many authors (i.e., Hietanen, 1974) cite the importance of studying chemical changes in other common coexisting phases such as biotite, epidote/clinozoisite, chlorite and garnet.

6.2 Mineral Chemical Trends

The following minerals were analysed on the Electron Microprobe or Scanning Electron Microprobe: amphibole, plagioclase, biotite, garnet, ilmenite, and titanite. Details of microprobe analysis, and representative analyses are found in Appendix C. Amphibole and plagioclase were given the most attention, as they constitute the largest percentage of the mineralogy and their compositions are needed for thermobarometry.

6.2.1 Amphibole

Amphiboles were measured for 10 oxides: SiO_2 , Al_2O_3 , TiO_2 , Cr_2O_3 , FeO^* (all iron is considered ferrous), MgO , MnO , CaO , Na_2O , K_2O , and chlorine. Representative analyses are listed in Appendix C, Table C.1. Increasing grade from greenschist through to amphibolite grade is marked by increases in Al_2O_3 , TiO_2 , FeO^* , Na_2O , decreases in SiO_2 ,

MgO, Cr_2O_3 , slight decrease in CaO and relatively constant MnO (Figures 6a-h) which agree with established trends (Miyashiro, 1961, 1968, 1973). Plots showing considerable scatter are believed to be partly due to analytical error (i.e., analyzing another mineral underneath the one in question or inclusions of ilmenite, titanite, quartz, plagioclase or replacement products of chlorite, biotite, epidote). In general the trends are obvious and clear. Greenschist samples are fairly compositionally constrained. Transitional zone samples show the widest range of compositions. Transitional zone analyses falling amongst the greenschist samples are from the cores of grains. Transitional zone analyses within or beyond amphibolite zone analyses are from the rims of minerals with deep colour. Amphibolite zone analyses show the best consistency of composition, excepting core values which fall in amongst the transitional zone values. Also exceptional are the garnet-bearing analyses, with higher FeO^*/MgO and Na_2O (Figures 6 l d, g).

The various formula calculation methods for amphiboles produce a wide range in results (see Appendix C, Figure C 2). The interpretation of the calculated formulae introduces error due to the absence of wet chemical analyses to determine true ferric iron. Thus all the amphibole plots are expressed in terms of the oxides for comparison, unless otherwise indicated, to enable direct comparison with work of others.

6.2.1.1 Relative Barometry Based on Amphibole Compositions

There is considerable dispute as to the significance of various components of metamorphic amphibole composition with respect to metamorphic grade, temperature, pressure, and bulk composition.

Increasing aluminum content (specifically, Al^{IV}) with increasing grade is widely described in natural and experimental environments and from various metamorphic regimes (Hietanen, 1974, Grapes, 1974, Cooper and Lovering, 1970, Leake, 1965, Raase, 1974, Kostyuk and Sobolev, 1969, Laird and Albee, 1981). This observation is contrary to Shido and Miyashiro, 1959, Engel and Engel, 1962, Binns, 1965 and Bard, 1970 (in Raase, 1974) who show a decrease in Al^{IV} with increasing grade. However, the Al^{IV} value must be interpreted with caution as Al^{IV} is extremely sensitive to analytical error (Leake, 1965), and, in a complex way, to variations in the pressure, temperature and chemical conditions (Raase, 1974). The determination of Al^{IV} can be affected by the oxidation state at which the rock formed and by individual laboratory techniques (Hynes, 1982). Figure 6.2, using the plot of Leake (1965) and Raase (1974), shows a linear distribution of amphibole analyses, which seems to imply a constant pressure of ~5 kbar for the Nipissing Diabase of May Township.

There is also much debate as to the significance of titanium content. No variation in titanium with metamorphic grade was observed by Hietanen (1974) in the contact metamorphic regime of the Sierra Nevada, nor by Grapes (1975) in regionally metamorphosed rocks of the Hidaka Metamorphic Belt, Japan. Hietanen (1974) concluded that titanium content is variable and not related to metamorphic grade, rather the titanium content of amphibole reflects the available titanium in the host rocks. An increase in titanium with grade is reported by Cooper and Lovering (1970), Raase (1974), Shido and Miyashiro (1959), Engel and Engel (1962), Binns (1965), Bard (1970). Increasing titanium with increasing grade is indicated by a colour change from blue-green,

to green, to brown-green (Raase, 1974) Raase concludes that the effect of pressure on titanium content is insignificant and considers the maximum titanium to be temperature dependent. Conversely, Hynes (1982) states that titanium content is one of the best ways to distinguish between low and medium pressure regimes, whereby lower pressure amphiboles have higher titanium values and medium pressure amphiboles have lower titanium values. Figure 6.3 applies the Hynes plot, which indicates a medium pressure regime for the amphibole analyses of the Nipissing Diabase.

Increase in alkalis (Na,K) with increasing grade, in particular with increasing pressure, in amphiboles of metamorphosed mafic rocks, is reported by many authors (Hietanen, 1974, Grapes, 1974, Shido and Miyashiro, 1959, E.H. Brown, 1977). Brown (1977) proposed a tentative relationship between pressure and Na^{M4} content of amphibole, with the requirement that the assemblage includes calcic amphibole coexisting with magnetite, albite and chlorite (Figure 6.4). When applied to the amphiboles from the Nipissing Diabase of May Township, Brown's plot indicates a relative pressure between 1 and 4 kbar (Figure 6.4). However it is noted that the Nipissing Diabase does not all contain the required assemblage, thus the pressures indicated in Figure 6.4 may be suspect. Shido and Miyashiro (1959) state that alkali content is dependent on both the physical conditions and the bulk rock composition, for example, hornblende coexisting with sodic plagioclase will have more Na (alkalis) and hornblende existing with calcic plagioclase will have less Na. In a comparative study of many amphiboles from different regimes, Hynes (1982) concluded that Na is not a good pressure indicator, due to variations in oxidation state and uncertainties in the calculation of ferric iron.

The much debated calcic amphibole compositional gap has been observed in rocks of all grades and pressure regimes (Allen and Goldie, 1978, Arai and Hirai, 1985, Begin and Carmichael, 1992, Brady, 1974, Cooper and Lovering, 1970, Cooper, 1972, Grapes, 1975, Grapes *et al.*, 1977, Grapes and Graham, 1978). The compositional gap is often interpreted as resulting from a miscibility gap between actinolite and hornblende, especially when accompanied by certain textures, such as actinolitic core surrounded by a hornblendic rim, a parallel or patchy intergrowth, of actinolite and hornblende. Both textures are observed in rocks from May Township and also generally exhibit sharp contacts, both optically and chemically, between the actinolite and hornblende, (see Appendix C, Figure C.3), a feature that is common to other established miscibility gaps between other pairs of amphiboles (i.e. anthophyllite and tremolite or actinolite or hornblende, cummingtonite and grunerite or actinolite or hornblende, Klein, 1968), (Cooper and Lovering, 1970). Grapes and Graham (1978) conclude that the apparent compositional gap is more likely the result of kinetic factors inhibiting complete equilibration rather than a true miscibility gap. Grapes and Graham conclude that the best evidence for a miscibility gap between actinolite and hornblende would be the discovery of separate, distinct grains with equilibrium textures or exsolution lamellae. Such exsolution lamellae have been observed in the present study and appear to indicate that actinolite and hornblende are capable of extensive solid solution under metamorphic conditions.

Hynes (1982) uses histogram plots of $Al(\text{total})-N^+$ (total) to show a distinct gap in composition at medium pressures and no gap at low pressures. The calcic amphiboles of the May Township Nipissing Diabase, when compared to the histograms of Hynes,

(Figure 6 5) do not show a well developed gap with a minimum. Therefore, according to Hynes, the Nipissing Diabase must have been metamorphosed under low pressure conditions

Four compositional plots described by Laird and Albee (1981) of amphiboles from five different metamorphic environments, are used to distinguish between the different regimes; Figure 6 6 shows the location of amphibole analyses from the Nipissing Diabase on these plots. The amphiboles of the Nipissing Diabase of May Township generally lie between the Haast River intermediate pressure regime and the Abukuma low pressure regime

Application of all of these relative grade indicators, seem to indicate a low to medium pressure regime for the Nipissing Diabase. However, the comparisons described above should be regarded with caution due to the overall disequilibrium state of the amphiboles

6.2.2 Plagioclase

Plagioclase compositions of the Nipissing Diabase of May Township do not appear to conform to the compositional sequence observed in other progressively metamorphosed mafic rocks. Representative analyses are listed in Appendix C, Table C 2. As previously discussed, the typical sequence of plagioclase compositions with increasing grade from greenschist to amphibolite is albite changing to oligoclase and then becoming increasingly calcic. In the petrography chapter the core-rim nature of the plagioclase was described, indicating the preservation of relict cores. The sequence of plagioclase compositions shown on Figure 6 7 is atypical. All greenschist samples but two contain

very calcic plagioclase, (An_{39-70}), the two exceptions are samples J-34-1 and J-43-1, which are uniform in texture and range from An_{01-23}

Plagioclases of the transitional zone span a wide range of compositions, from albite to labradorite. The few analyses giving the compositions of albite or oligoclase are generally obtained from near the rims of spotty grains with no clear region of preferred development.

The amphibolite zone plagioclases generally have sodic, albite-oligoclase, clear rims and calcic, andesine-labradorite altered cores. The few finer grained or foliated amphibolite zone samples have uniform composition of albite to oligoclase. There is no apparent gap in plagioclase compositions to indicate intersection with the peristerite gap; thus one might infer that the temperature of metamorphism was above the peristerite gap. Crawford (1966) puts the crest of the gap at approximately 500°C between 5-7 kbar.

Given the lack of complete recrystallization of most of the plagioclases, it is considered imprudent to interpret metamorphic conditions in May Township on the basis of plagioclase compositions.

6.2.3 Garnet

Microprobe analyses show that the garnets are largely almandine and grossular, ranging between 47 to 72% Fe component (almandine) and 43 to 18% Ca component (grossular). Next in abundance is spessartine (approximately 10%) and the least abundant component is pyrope at 2-5%. Representative analyses are listed in Appendix C, Table C-3. Profiles of traverses across the garnets show them to be fairly uniform with cores slightly enriched in Mg and depleted in Fe (Figures 6-8a, b, c).

Compositionally homogeneous garnets indicate growth under almost constant temperature conditions, as temperature is the driving force behind the cation exchange between garnets and other minerals (i.e., biotite) (Spear, 1993). A typical garnet profile from the greenschist to amphibolite facies pelites contains a 'bell'-shaped line for manganese content (Spear). Garnets showing significant zoning generally indicate changing conditions of either temperature or bulk chemical composition (Spear). Garnets formed at high grade often show evidence of re-equilibration by diffusion, as indicated by tight contours at the rims or near inclusions. Late stage diffusion shows up in a line profile as a rapid upturn in the manganese content (Spear). Neither of these types of profiles are found in the Nipissing Diabase garnets.

While garnet is often used as an indicator mineral for mid-upper amphibolite grade in metamorphosed mafic rocks, its appearance is not only a result of pressure and temperature. The development of garnet is very sensitive to chemical composition (Miyashiro, 1968).

6.2.4 Biotite

Biotite analyses were done only on samples containing garnet, (806-2, J-6-3, J-12-2) for the purposes of garnet-biotite thermometry. Representative analyses are listed in Appendix C, Table C.4. Compositions range from 70-80% annite. Compared to biotites of other metamorphosed mafic rocks, they are high in iron, aluminum, sodium, and low in silica, titanium, chromium, manganese, magnesium, calcium, potassium (Begin and Carmichael, 1992, Shido, 1958, Cooper, 1972). Poor totals and low potassium, calcium and sodium values are possibly attributed to contamination by chlorite.

Cooper (1972) observed that biotite composition is not greatly affected by metamorphic grade but rather by the composition of the host rock. Begin and Carmichael (1992) observed an increase in magnesium with increasing grade.

6.2.5 Ilmenite and Titanite

Together, ilmenite and titanite, do not make up more than five percent of a sample of Nipissing Diabase. But despite their small percentage, their composition was analysed by microprobe methods to determine their purity and in return, their effect on hornblende-forming reactions as determined by the thermodynamic plotting program TWEEQU (Berman, 1988, 1990, 1991) which will be discussed in greater detail in the following chapter. Representative analyses are listed in Appendix C. Calculation of the activity of ilmenite and titanite is described in Appendix C.

Titanite is almost the pure stoichiometric mineral, CaTiSiO_5 , (calculated activity ranges from 0.887-0.975), with very little change between samples from different metamorphic zones, or between different morphologies i.e., existing as discrete grains or rimming ilmenite (see Appendix C, Table C.6).

Ilmenite compositions, while nearly pure (calculated activity ranges from 0.727-0.94), do show significant changes with respect to the metamorphic zone (see Appendix C, Table C.5). Ilmenite in "unrecrystallized" zone samples are nearly stoichiometric ilmenite, FeTiO_3 , greenschist ilmenites show a substantial rise in manganese and slight increases in titanium and iron, transitional and amphibolite zone ilmenites lie approximately between "unrecrystallized" zone ilmenites and greenschist ilmenites.

6.3 Discussion

As previously mentioned, any interpretation of the chemistry of the minerals of the Nipissing Diabase should be undertaken with caution. Textural features described in chapter 4, attest to the overall disequilibrium of the assemblages. Chemical analyses only add to this conclusion in revealing the divergent compositions of coexisting actinolites and hornblendes as well as the changes in plagioclase composition.

Figure 6.1a: Plot of Al_2O_3 vs. SiO_2 for amphiboles of Nipissing Diabases. Note: 1) overall increase in Al_2O_3 and decrease in SiO_2 with increasing grade; 2) linear relationship between SiO_2 and Al_2O_3 content; 3) wide distribution of transitional zone amphiboles; 4) greatest density of amphibolite zone amphiboles. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1b: Plot of TiO_2 vs. SiO_2 for amphiboles of Nipissing Diabases of May Township. Note: 1) slight increase in TiO_2 with increasing grade; 2) wide distribution of transitional amphiboles; 3) amphibolite zone amphiboles show the greatest density of results. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1c: Plot of Cr_2O_3 vs. SiO_2 for amphiboles of Nipissing Diabases of May Township. Note: 1) overall low Cr_2O_3 content; 2) rapid decrease in Cr_2O_3 with increasing grade. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1d: Plot of ratio FeO^*/MgO vs. SiO_2 . FeO^* indicates that all iron is considered Fe^{2+} . Note: 1) the increase in FeO^* and decrease in MgO with increasing grade; 2) wide distribution of transitional amphiboles; 3) higher FeO^*/MgO values for amphiboles from garnet-bearing amphibolite zone samples. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1e: Plot of MnO vs. SiO_2 for amphiboles of the Nipissing Diabases of May Township. Note: 1) fairly constant MnO values for amphiboles from all grades; 2) decrease in SiO_2 with increasing grade; 3) wide distribution of transitional zone amphiboles. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1f: Plot of CaO vs. SiO_2 for amphiboles of Nipissing diabases of May Township. Note: 1) slight decrease in CaO with increasing grade; 2) wide distribution of transitional zone amphiboles; 3) high density of amphibolite zone amphibole results, 4) amphiboles from garnet-bearing amphibolites generally have the lowest CaO. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1g: Plot of Na_2O vs. SiO_2 for amphiboles of Nipissing Diabases of May Township. Note: 1) increase in Na_2O with increasing grade; 2) wide distribution of transitional zone amphiboles; 3) higher Na_2O values for amphiboles from garnet-bearing sample J-6-3 (indicated above). Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.1h: Plot of K_2O vs. SiO_2 for amphiboles of Nipissing Diabases of May Township. Note: 1) increase in K_2O with increasing grade; 2) wide distribution of transitional zone amphiboles; 3) higher K_2O values for amphiboles from garnet-bearing amphibolite zone and a few amphibolite zone amphiboles. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.2: Plot of Al^{IV} vs. Si for amphiboles from Nipissing Diabases of May Township. Al^{IV} and Si are calculated on the basis of a 23 oxygen formula, and all iron is considered Fe^{2+} . The plot is found in Raase (1974, p.233; who modified it from Leake, 1965). Raase uses the relationship between Al^{IV} and Si as a pressure estimate based on the comparison of amphiboles from several different pressure regimes. When applied to the amphiboles of this study, the result, as plotted above, implies a fairly constant pressure of ~5 kbar for the Nipissing Diabases of May Township. Relative error indicated by the horizontal and vertical dimensions of the symbols.

Figure 6.3: Plot of Ti content vs. $Al(\text{total})$ content for amphiboles of Nipissing Diabases of May Township (amphiboles normalized to 23 oxygen with all iron considered Fe^{2+}). The plot is taken from Hynes (1982, p. 121). Hynes considers Ti content to be one of the best indicators of relative pressure. The straight line is taken from Hynes and used for comparison only. Applying observations of Hynes to the amphiboles of this study, a medium pressure regime is indicated. Relative error indicated by the vertical and horizontal dimensions of the symbols.

Figure 6.4: Relative Barometry. The above plot is taken from Brown (1977, p. 69) in which Brown proposes that the Na^{M_4} content of amphiboles can provide a tentative estimate of the pressure of metamorphism. Brown normalized the amphiboles to maximized Fe^{3+} and Na^{M_4} . The amphiboles of the Nipissing Diabase of May Township were normalized using the method of Brown and plotted above, where they indicate a low to intermediate pressure regime between 1 to 4 kbar.

Figure 6.5: Histogram of Al(total)-Na(total) frequency in amphiboles of Nipissing Diabases of May Township. Amphiboles are normalized to 23 oxygens and all iron is considered Fe^{2+} . The histogram is taken from Hynes (1982, p. 122). In comparing amphiboles from various metamorphic regimes, Hynes observed that medium pressure amphiboles will produce a significant gap when plotted in the histogram as above, with a distinct minimum indicated above and low pressure amphiboles will not produce a significant gap or a distinct minimum. The amphiboles from this study when plotted using Hynes histogram do not produce a significant gap where indicated and therefore following Hynes' observation, the amphiboles are from a relatively low pressure regime.

Figure 6.6: Relative Barometry. The above plot is taken from Spear (1993, p.440) which is a reproduction from Laird and Albee (1981) in which Laird and Albee compared amphiboles from several metamorphic regimes. Laird and Albee normalized the amphiboles to have a total of 13 cations less $\text{Ca} + \text{Na} + \text{K}$ except those amphiboles where $\text{Ca} + \text{Na} \leq 2$, in which case the amphiboles were normalized to total 15 cations less K. The amphiboles of the Nipissing Diabase of May Township were accordingly normalized and plotted above. Amphiboles from the Nipissing Diabase plot closest to the Haast River and the Abukuma terranes which are low pressure and intermediate pressure series respectively.

Figure 6.7 : Plot of relative frequency of plagioclase compositions from Nipissing Diabases of May Township. Note: 1) the low albite amount in greenschist zone plagioclases; 2) the abundance of calcic plagioclases (i.e. An50-70) in greenschist and transitional zone plagioclases; 3) the most consistent and confined compositions of plagioclases (mostly oligoclase) from the amphibolite zone samples.

Figure 6.8 a, b, c: Garnet compositional zoning profiles from garnet-bearing amphibolite zone samples 806-7A, J-6-3 and J-12-2. Note: 1) generally only moderate zoning is apparent; 2) cores are generally iron poor and calcium rich; 3) in general, rims are iron rich and calcium poor; 4) magnesium and manganese are fairly constant.

almandine = $\text{Fe}/(\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca})$

pyrope = $\text{Mg}/(\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca})$

spessartine = $\text{Mn}/(\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca})$

grossular = $\text{Ca}/(\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca})$

Figure 6.8a

Figure 6.8b

Figure 6.8c

CHAPTER 7: THERMOBAROMETRY

7.1 Introduction

The most essential requirement for thermobarometric analysis is complete equilibrium among phases. The attempt to determine the pressures and temperatures at which the Nipissing Diabase of May Township equilibrated is hampered by the lack of pervasive textural equilibrium among all phases, and the apparent lack of reactivity of amphiboles and plagioclases (i.e., as manifested by the preservation of relict minerals and textures). Those samples that are considered the best equilibrated and thus provide the best estimates of the pressures and temperatures imposed, fulfil four criteria: 1) textural equilibrium, where the textures are clearly metamorphic in character (i.e. Plates 4.6c, 7.1a,b,c), 2) consistent chemical analyses within a sample of *both* amphiboles and plagioclases, 3) reasonable compositions, considering the inherently sluggish nature of reactions involving plagioclase and amphibole (Liou et al 1974), and 4) reproducible pressure and temperature results from analyses of different locations within the same sample. Few samples examined in the present study fulfil all four criteria.

7.2 Method

The pressures and temperatures of equilibrium were obtained primarily through application of the GEO-CALC thermodynamic software, "TWEEQU" (Berman, 1988, 1990, 1991). Additional thermometers used in this study include the garnet-biotite exchange thermometer (Hodges and Spear, 1982) and the amphibole-plagioclase thermometer (Holland and Blundy, 1994).

7.3 "TWEEQU"

The thermobarometric software program, referred to as, "TWEEQU", "Thermobarometry With Estimation of EQUilibrium state" was developed by Berman (1991). TWEEQU was used in this study as it contains thermodynamic data and solid solution models for appropriate calcic amphiboles including tremolite, ferro-tremolite, tschermakite, ferro-tschermakite, pargasite and ferro-pargasite. Mader and Berman (1992) warn that pargasite and ferro-pargasite should be incorporated into the TWEEQU calculations with caution as the thermodynamic data have not been confirmed. TWEEQU uses the requirement that the change in Gibbs free energy for an equilibrium must be zero, and uses all combinations of the selected components to calculate a plot of stable equilibria. For a system in equilibrium, all calculated equilibria should intersect at one point, that being the pressure and temperature of equilibrium, and the degree to which this is achieved is an indication of the degree of equilibrium among phases (Berman, 1991).

Given the predominance of disequilibrium assemblages in the Nipissing Diabase (discussed in Chapters 4, 5, 6) many combinations of analytical results of amphiboles and plagioclases were used in TWEEQU. Preference was given to those amphibole and plagioclase analyses that were adjacent, and therefore had the best opportunity to equilibrate (Holland and Blundy, 1994). Where this was not possible, averages of amphibole and plagioclase rim compositions were used, followed by extreme values, to provide an idea of the range in pressure, temperature implicit in the analytical data. This range includes uncertainty due to disequilibrium as well as the effects of possible re-equilibration during retrograde metamorphism.

7.3.1 Results

In general, samples from the amphibolite zone best fulfil all four considerations for equilibrium. The best example of this is sample J-6-4 which is texturally well-equilibrated (Plate 4.6c), compositionally reasonable, consistent and confined (Figures 6.1a-h). A typical TWEEQU plot for sample J-6-4 is shown in Figure 7.1, which indicates a concentration of equilibria about a single point. A list of the equilibria generated by TWEEQU for the plot shown in Figure 7.1 is listed in Appendix D. Other combinations of adjacent amphibole and plagioclase analyses for sample J-6-4 produce a reasonably consistent range of pressures and temperatures (Figure 7.2). Including estimated error, the intersections range from approximately 2 to 6.9 kbar and 470°C to 700°C. The locations of these adjacent analyses from sample J-6-4 are shown in Plates 7.1a,b,c. The plates also show the euhedral to subhedral form of the amphiboles and the clear rims and altered cores of the plagioclases.

There were no systematic differences in the pressures and temperatures produced from completely recrystallized amphibolite samples compared to those from samples with abundant relict features. The range of estimated P and T, likely reflect the prevailing disequilibrium conditions in most amphibolite samples.

Of the three garnet-bearing samples, only sample 806-7A meets all the four considerations, described in Section 7.1. This specimen exhibits good textural equilibrium (see Plate 4.7b) and consistent amphibole, plagioclase, and biotite chemistry; the garnets show only slight zonation with no post peak metamorphism re-equilibration rim. Garnet rim analyses were used with adjacent biotites to measure the most likely equilibrium compositions. When

evaluated using the TWEEQU program, the pressures and temperatures obtained for garnet-bearing samples J-12-2 and J-6-3 are much higher than those from garnet-free samples from the same outcrop (*e.g.*, J-6-4). Figure 7.3 shows the pressure and temperature intersection points of the garnet-amphibolites with respect to the other amphibolites. The three garnet-bearing samples are found within a small area, bounded on three sides by faults (Figure 2.5), it is possible that this small block has been uplifted from greater depth and therefore higher metamorphic grade. However, a comparison of P-T estimates between garnet amphibolites and non-garnet bearing amphibolites from single outcrops indicates that this is not the case. The presence of garnet is more likely due to bulk compositions with higher iron possibly resulting from localized contamination by the host pelites, and metasomatism. It would be worthwhile to carry out future research on the fault-bounded block of garnet-bearing amphibolites. It is possible that the P-T estimates based on garnet equilibria are correct and the amphibole-plagioclase data are incorrect, if this is so, then the "Webbwood block" could have been emplaced from greater depths than the surrounding rocks. The differences between estimated P-T conditions for garnet-bearing and garnet-free amphibolites could be attributed to possible inaccuracies in thermodynamic data for amphibole components.

Greenschist and transitional zone samples produced questionable pressure and temperature estimates. No samples fulfil all four criteria stated in Section 7.1. A few samples such as J-34-1, J-43-1 and 820-1, are extensively recrystallized and contain reasonable compositions but produce geologically inexplicable results. Both greenschist and transitional zone samples contain abundant calcic plagioclase (igneous) and a wide range of amphibole

compositions (Figures 6 1a-h) Even such samples can result in narrow error estimates according to the TWEEQU software.

7.4 Amphibole-Plagioclase Thermometer

The amphibole-plagioclase thermometers used herein were calculated by the method of Holland and Blundy (1994). The temperatures generated were produced using a Microsoft Excel spreadsheet and macro developed by Fred Ford (pers. comm., 1994).

The thermometers are based on two equilibria (Holland and Blundy, 1994):

From the basic amphibole formula: $A_{0.1}(M1-5)_8(T1,T2)_8O_{22}(OH,Cl,F)_2$, these thermometers are based on the simultaneous substitution of Na and/or K into the vacant A-site with Al^{IV} substituting for Si in the T1 site, or expressed simply as the exchange vector, $(Na,K)Al^{IV} \leftrightarrow \square Si$ (Blundy and Holland, 1990). Within the compositional restrictions specified, Holland and Blundy suggest results with an error of $\pm 40^\circ C$ for rocks equilibrated between $400^\circ C$ to $1000^\circ C$, and 1 to 15 kbar.

7.4.1 Results

For the amphiboles and plagioclase analyses of the Nipissing Diabase, the best results usually come from adjacent and/or rim compositions, similar to the TWEEQU results. There is generally agreement between the two methods. Figure 7.4 is a plot of the Holland and Blundy (1994) thermometers for sample J-6-4. The corresponding TWEEQU result using the same amphibole and plagioclase analyses, is indicated on Figure 7.4, and is in fair agreement

with the Holland and Blundy results. The three garnet-bearing amphibolites also show good correlation between the TWEEQU results and the Holland and Blundy thermometer. Poor results are obtained from greenschist and transitional samples using the Holland and Blundy thermometer, largely due to the fact that fewer analyses fall within the compositional ranges for amphiboles and plagioclases required by the calibration.

7.5 Garnet-Biotite Exchange Thermometer

The garnet-biotite thermometer is based on the exchange of magnesium and iron cations between garnet and biotite (Hodges and Spear, 1982, [consider all iron to be Fe^{2+}]), and can be expressed as the reaction,

Temperature calculations were carried out using a Microsoft Excel spreadsheet program created by Fred Ford (pers. comm., 1993, 1994, 1995).

As described in Chapter 6 (see also analyses in Appendix C), the biotites are compositionally uniform except for pervasive chlorite alteration, and the garnets show only slight zonation and no evidence of late stage cation exchange. This is typical of fairly well-equilibrated garnets in many metamorphic environments (Spear, 1993). Thus analyses used in the thermometer were taken from the rim, along with adjacent biotites, as a best estimate of the minerals in equilibrium. However this assumption may lead to error if undetected re-equilibration has taken place after the peak of metamorphism. Possibly more detailed microprobe work would clarify this possibility. All iron in the biotites was considered to be ferrous. There is reasonable agreement, between the temperatures produced from the Hodges

and Spear calculation and the TWEEQU result (Figure 7.5). There is also fair agreement between the best TWEEQU results from the amphibole plagioclase data described previously and the temperatures produced with the garnet-biotite equilibria for samples J-6-3 and 806-7A (Figure 7.5), but poor comparison for sample J-12-2, attesting, perhaps, to the lack of equilibration between garnet and biotite in that sample.

7.6 Discussion

There is good correlation between the various methods for amphibolite zone samples, indicating, perhaps, that they more closely approached equilibrium. However, while the amphibolite results constrain the temperature, they give a poor definition of a specific pressure.

Possible sources of error include analytical imprecision, geological uncertainty (Spear, 1993), unconfirmed thermodynamic data, solid solution models attempting to accommodate for miscibility gaps and exsolution lamellae, and analytical error including the estimation of ferric iron. Disequilibrium assemblages involving amphiboles and plagioclases are common and attributed to the complex crystal chemistry of these two minerals. Amphiboles contain eight cation sites, which can accommodate a large number of elements with a variety of charges and ionic radii (Hawthorne, 1983). Plagioclases can create problems in thermobarometry due to the sluggish nature of plagioclase subsolidus reactions (Grove et al., 1984) and the presence of the peristerite gap (Blundy and Holland, 1990).

The average temperature and pressure of equilibration of the amphibolite TWEEQU results is $580 \pm 60^\circ\text{C}$ and 4.3 ± 0.8 kbar (using the P-T results of the best equilibrated sample, J-6-4). These results are in good agreement with the pressure-temperature field inferred from

the regional amphibolite grade pelitic assemblages described by Card (1978a) (see Figure 7.2) and with the 1971 study by Fox, who determined that the pressure and temperature conditions were approximately 4.45-4.75 kbar and 500-550 °C, based on the coexistence of chloritoid and staurolite in pelites from the nearby Agnew Lake area (see Figure 2.2). As well the results obtained in this chapter are in reasonable agreement with the relative barometry as shown in Figures 6.2-6.5, which estimated a low to intermediate pressure regime, however, as mentioned in Chapter 6, given the disequilibrium state of the Nipissing Diabase amphiboles, the qualitative barometric results are suspect.

Figure 7.2: TWEEQU Results of Amphibolite Sample, J-6-4. Note: 1) all P-T points plotted are the result of adjacent amphibole and plagioclase analyses; 2) shaded P-T field is the possible P-T field (surmised from the P-T grid of Holland and Powell (1990) for pelitic rocks) for metamorphic pelitic assemblages observed by Card (1978a).

Figure 7.3: TWEEQU results for amphibolite samples and garnet-bearing amphibolite samples from the same outcrops (error is less than $\sim 50^{\circ}\text{C}$ and $\sim 1\text{kbar}$). Note 1) higher pressures and temperatures are generated by TWEEQU using amphiboles and plagioclases from the garnet-bearing amphibolites compared to results from non-garnet-bearing amphibolites; 2) there is a large pressure difference between samples J-6-3 and J-6-4, compared to the results between samples 806-7A and 806-2; this possibly indicates that pressures and temperatures calculated by TWEEQU for sample J-6-3 are misleading and that amphibole and plagioclase compositions have been affected by metasomatic processes with the host pelitic rocks.

Figure 7.4: Results using the amphibole-plagioclase thermometer of Holland and Blundy (1994) for amphibolite sample J-6-4 (amphibolite analysis #8, plagioclase analysis #8, see plate 7.1c). Also indicated is the TWEEQU result using the same analyses. Note the good agreement between the two thermometers and the TWEEQU result.

Figure 7.5: Results of the garnet-biotite thermometer (using calculations of Hodges and Spear (1982)) for sample 806-7A using average of biotites and average of garnet rim analyses. Also indicated is the garnet-biotite equilibria generated by using the same garnet and biotite average analyses in TWEEQU and the P-T intersection point from TWEEQU using amphibole and plagioclase analyses from the same sample. There is good agreement between the three methods.

Plate 7.1a: Photo of amphibolite sample J-6-4 (in plane polarized light) Adjacent amphibole and plagioclase analyses used in the TWEEQU program and plotted in Figure 7.2, are indicated: amphibole analysis #1 and plagioclase analyses #10 and #11 Note the euhedral and subhedral green hornblendes and the plagioclase with the clear rim and the altered core. Field of view, 1.3 mm.

Plate 7.1a: Photo of amphibolite sample J-6-4 (in plane polarized light) Adjacent amphibole and plagioclase analyses used in the TWEEQU program and plotted in Figure 7.2, are indicated: amphibole analysis #3 and plagioclase analyses #16 and #17 Note the euhedral and subhedral green hornblendes and the plagioclase with the clear rim and the altered core. Field of view, 1.3 mm.

Plate 7.1a: Photo of amphibolite sample J-6-4 (in plane polarized light) Adjacent amphibole and plagioclase analyses used in the TWEEQU program and plotted in Figure 7.2, are indicated: amphibole analysis #8 and plagioclase analysis #8 Note the euhedral and subhedral green hornblendes and the plagioclase with the clear rim and the altered core. Field of view, 1.3 mm.

CHAPTER 8: DISCUSSION

8.1 Introduction

The study of the metamorphic zones in the Nipissing Diabase of May Township establishes the following (see Figures 2.5 and 5.1): 1) the Murray Fault marks a sharp change in metamorphic grade from amphibolite in the south to greenschist in the north, 2) metamorphic zones are in a north-east, south-west orientation, with an increase in grade from south to north, 3) the Serpent River corresponds in a general way to the southern boundary of the amphibolite grade, 4) there is a low grade zone (the "George Lake transitional zone") within the amphibolite zone that coincides with an antiform mapped by Jackson and Henderson (1993), 5) the petrographic, chemical and thermobarometric studies indicate a low-pressure, moderate temperature regime, with an estimated geothermal gradient of approximately 35°C/km (see Figure 7.2), 6) Both regionally described pelitic assemblages and amphibolites have equilibrated at the same P and T, suggesting that the main episode of metamorphism is younger than the emplacement of the Nipissing Diabase (2.219 Ga, Corfu and Andrews, 1986).

The lack of pervasive foliation and recrystallization of the Nipissing Diabase in May Township makes interpretation of the timing of peak metamorphism and folding difficult. Two foliations are found in the Nipissing Diabase of May Township. One foliation trends approximately SW-NE and the second trends approximately NW-SE. These foliations in pelitic rocks have been described in May Township by Jackson and Henderson (1993) and on a regional basis by Card (1978a). However, in the Nipissing Diabase, the timing of metamorphism cannot be associated with a particular foliation.

8.2 Metamorphic Cross Sections

8.2.1 Background

An attempt to construct a metamorphic cross section of May Township uses data derived from P-T estimates and is based on a set of assumptions: 1) the most reliable P-T estimates obtained from thermobarometry come from sample J-6-4. The average of the results shown in figure 8.1 are $580 \pm 59^{\circ}\text{C}$ and 4.3 ± 0.8 kbar. At this location, the diabase is texturally well-equilibrated with recrystallized amphiboles and plagioclases, consistent chemistry of amphiboles and plagioclases, and tight concentration of pressures and temperatures generated in thermobarometric calculations; 2) the pressure and temperature quoted above are used to calculate an "average linear geotherm" at the peak of metamorphism, $35^{\circ}\text{C}/\text{km} \pm 2$. This value is supported by the fact that the geotherm passes through the inferred P-T field of the pelitic assemblage, staurolite-chlorite-andalusite-muscovite, described by Card (1978a) for the Southern Province (see Figure 8.1). When compared to other geotherms, ie. $\sim 10^{\circ}\text{C}/\text{km}$ for the Proterozoic shield of southern India (Ganguly *et al.*, 1995) and $\sim 50^{\circ}\text{C}/\text{km}$ reported in the Slave Province (Chouinard, 1995), the estimated geotherm appears to be reasonable; however it is less than the geotherm of 70 to $150^{\circ}\text{C}/\text{km}$ reported by Card (1978a).

8.2.2. Dip of isograds

The dip of the isograds in May Township has been estimated in two ways. Thermobarometry of the amphibolite zone and the greenschist zone is used to obtain an

estimate of this dip. A second approach is based on experimental research by Liou *et al* (1974) who measured the temperature at which aluminous amphiboles first appear in metabasic rocks.

Thermobarometry of the greenschist zone is based on sample J-34 (see Figure 5.1), for which the average pressure and temperature are calculated to be 2.67 ± 2.3 kbar and $417 \pm 60^\circ\text{C}$ (Figure 8.2). As previously described in Chapter 4, this sample exhibits equilibrium textures; however the chemistry of the amphiboles and the plagioclases leads to wide uncertainty in the calculated pressures and temperatures. Assuming a linear geotherm perpendicular to the isograds, the map distance between samples J34 and a projected J-6-4 onto the J34 geotherm is approximately 4.4 km (see Figures 8.4a,b). Based on the thermometry of sample J34, the change in temperature between J34 and J-6-4 is 163° , which corresponds to a distance of 4.6 km along a $35^\circ\text{C}/\text{km}$ geotherm, and a near vertical dip of the isograds.

Liou *et al.* (1974) have measured a temperature of 475°C at 2 kbar for the first appearance of aluminous amphiboles (see Figure 8.5) at the change from greenschist to transitional zone rocks. Applying this temperature to the greenschist-transitional zone boundary in Figures 8.4 a, b, leads to a calculated dip of 43° for metamorphic isograds.

The calculations described above indicate that isograds defined by mafic rocks in May Township are dipping to the south at a significant angle or possibly even vertical.

(Figure 8 6a). While these estimates are imprecise, they independently suggest significant structural disruption of isograds following the peak of metamorphism.

The dip of isograds as determined in the preceding paragraphs is of interest in understanding the structural significance of the George Lake transition zone rocks. A very large regional synform could account for these rocks as an infolded remnant. However, field data do not support such a hypothesis. Jackson and Henderson (1993) have described an antiformal structure within the George Lake transition zone rocks.

The existence of the George Lake transition zone rocks is based on five well crystallized and fully hydrated samples as indicated in Figure 5.1. It would, however, be helpful to undertake additional field work to substantiate the existence of lower grade rocks in the vicinity of George Lake. If this zone of apparently anomalous metamorphic rocks is confirmed, then a more complex structural history for the area is indicated. For example, a nappe-like structure of amphibolite rocks thrust over the lower grade greenschist and transitional zone rocks would allow an independent metamorphic history for the greenschist-transition zone rocks and amphibolites of May Township (see Figure 8 6b). Shallowly dipping isograds beneath the structurally emplaced amphibolites would be compatible with a window of antiformal transition zone rocks now exposed beneath the hypothetical fault.

Jackson and Henderson (pers. comm., 1993) have proposed that the Serpent River corresponds to a "Structural Discontinuity", in which case, the change across the Serpent River from transitional zone in the south to amphibolite zone to the north could be a fault

with significant displacement. However no obvious evidence for the existence of a major fault can be detected on a regional scale (see for example, Card, 1978b)

The map pattern of Nipissing Diabase is shown in Figure 2.5. It can be observed that the dikes within the amphibolite zone are more sinuous than within the lower grade zones. South of the Serpent River and to the north of the Murray Fault, the diabase dikes are linear in an east-west direction. The lack of foliation within the dikes indicates that they have not been transposed into this dominantly east-west orientation. By contrast, dikes within the amphibolite zone between the Serpent River and the Murray Fault are irregular in orientation. This variation in outcrop pattern of diabase dikes within the amphibolite zone is consistent with a distinctive structural history for the amphibolites.

Neither of the two estimates of the cross-sectional geology of May Township is completely satisfactory (see Figures 8.6 a,b). The first estimate is based on the simplest geological assumptions but its identification of steeply dipping isograds cannot explain the George Lake transition zone rocks. The second hypothesis is speculative without confirmation on the basis of field mapping, except for the identification of the Serpent River as a possible structural discontinuity by Jackson and Henderson (pers. comm., 1993).

The emergence of such different hypotheses can assist future field work by identifying areas that should receive close attention. For instance, the existence of low grade rocks near George Lake requires confirmation. The nature of the contact between

the amphibolite grade rocks and lower grade rocks should be examined carefully for a possible structural break

8.2.3 Movement along the Murray fault

According to the cross section in Figure 8.6a, the peak of metamorphism was followed by south-side up movement along the Murray Fault, placing higher grade rocks of the south against lower grade rocks to the north. This is supported by the sharp change in grade across the Murray Fault, best shown by samples 811 and 812 and J-43 and 805 (see Figure 5.1). An estimate of the displacement along the Murray fault is calculated using the change in pressure between sample J-6-4 (4.3 ± 0.8 kbar) and J-43 (3.1 ± 2.5 kbar), and is found to be approximately 5 km. The one exception is sample S-104, an amphibolite zone sample, found just north of the apparent southern limit of the Murray Fault System; this anomaly could be due to uncertainty in the location of the fault rather than mis-interpretation of the mineralogy of the sample.

The metamorphic cross section shown in Figure 8.5b does not allow a determination of the relative vertical movement along the Murray Fault. This interpretation requires a tectonic history that is different for exposed amphibolites and greenschist/transitional rocks.

8.3 May Township Pelitic Metamorphism

Preliminary metamorphic zones in the pelites of May Township (Jackson and Henderson, 1993) are shown in Figure 2.6. The location of zones within the pelitic rocks

agree with results from the Nipissing Diabase, in the general northeast-southwest trend of the zones and the sharp change in grade across the Murray Fault. The mapped pelitic zones do not show a low grade area within the amphibolite zone near George Lake.

Jackson and Henderson (1993) have proposed a possible sequence of events to explain the structure and metamorphism of the McKim formation in May Township: 1) large scale recumbent folding, 2) peak thermal metamorphism and growth of metamorphic porphyroblasts approximately synchronous with the large-scale folding, 3) folding, faulting, shearing about east of north-east trends, and later about west of north-west trends.

8.4 Regional Metamorphism

A regional map of the metamorphic zones of the Southern Province is found in Sims *et al.*, (1981) and is reproduced in Figure 2.3. The earlier regional map shows agreement with this study and that of Jackson and Henderson (1993), in the orientation and distribution of metamorphic zones. Regional geologic factors that have been identified include: metamorphic zones are elongate parallel to the Murray Fault Zone, major anticlinoria (the Baldwin Anticlinorium, the McGregor Bay and Lake Panache structures, Card, 1978), correspond to higher grade areas and synclinoria to low grade regions (the Porter and Bass Lake structures, Zolnai *et al.*, 1983, Sims *et al.*, 1981), in detail metamorphic zones transgress fold axes (Card, 1978a).

Card (1978a), Sims *et al.*, (1981) state that the transgression of metamorphic zones across fold axes indicates that peak metamorphism outlasted major folding or was superimposed on it. Card proposes the following sequence of events: 1) early deformation

and growth of early metamorphic minerals, 2) peak metamorphism and development of high grade rocks, with porphyroblast growth pre, syn and post- (Penokean) folding, 3) late stage deformation (faulting). Jackson and Henderson (1993) proposed that the peak of metamorphism was approximately synchronous with the development of early (pre-Penokean) recumbent folds and nappes. The present study indicates that peak metamorphism was reached after intrusion of the Nipissing Diabase (2.219 Ga).

Figure 8.1. TWEEQU Results for amphibolite sample, J-6-4. Note: 1) all P-T points plotted are the result of adjacent amphibole and plagioclase analyses, 2) shaded P-T field is the possible P-T field for metamorphic pelitic assemblages of the Southern Province, observed by Card (1978a) and plotted on the P-T pelitic grid of Holland and Power (1990); 3) the geotherm indicated is based on calculations using an average density of $\sim 2.7 \text{ g/cm}^3$.

Figure 8.2: TWEQU results for greenschist zone sample J-34-1 note: 1) all points are the result of using one amphibole analysis and several different plagioclase analyses from sample J-34; 2) there is a wide range in the temperature estimates and a narrower range in the pressure estimates; 3) the gap in the temperature estimates is possibly due to encounters with the peristerite gap, as it corresponds to a gap in the composition of the plagioclases analyses between An_{02} and An_{08} .

Figure 8.3: TWEQU results for greenschist zone sample J-43-1. Note: there is a better concentration of results compared to sample J-34-1 (Figure 8.2) however there is still a large temperature range and pressure error.

Figure 8.4 a & b: Estimation of the dip of the isograds

Figure 8.4 a: schematic map showing the assumptions made to calculate a possible dip for the isograds. Sample J-6-4 is used for the pressure and temperature of the amphibolite zone, and sample J-34-1 is used for the temperature and pressure of the greenschist zone. The map distance between projected sample J-6-4 and sample J-34-1 is measured to be 4.4 km. It is assumed that the lines of constant grade are parallel to each other and perpendicular to the geotherm (as indicated above). For a scale map see Figures 2.5 and 5.1.

Figure 8.4 b: cross-sectional schematic diagram for dip estimation, wherein X = the horizontal distance between greenschist sample J-34-1 and projected amphibolite sample J-6-4, as shown above in Figure 8.4a. However as shown in Figure 8.4a, the measured distance between the two samples is also the distance between the lines of constant grade (assuming they are parallel to each other and perpendicular to the geotherm). When these two values approach each other, by the trigonometry, it would lead to a near vertical dip of the lines of constant grade (isograds). When X is greater than Y , the dip of the isograds is less than 90 degrees.

Figure 8 5: P-T fields for greenschist, transitional, amphibolite and epidote-amphibolite zone from experimental work of Liou et al., (1974, p. 628). At 2 kbar pressure, the temperature of the change from greenschist to transitional grade is $\sim 475^{\circ}\text{C}$.

Figure 8.6a: This cross section proposes a dip of isograds between 43° and 90° . It is based on the simplest geological assumptions and cannot account for the "George Lake transitional zone."

Figure 8.6bi: Second hypothetical model attempts to explain the George Lake transitional rocks by proposing the emplacement of a thrust sheet of amphibolite grade rocks atop lower grade rocks. The George Lake transitional zone is a window of lower grade rocks, exposed through the overlying sheet.

Figure 8.6bu: Another possibility of Figure 8.6bi, wherein the overlying thrust sheet includes a synform to account for the George Lake transitional zone.

CHAPTER 9: CONCLUSIONS

1. Peak metamorphism was reached after intrusion of the Nipissing Diabase (2 219Ga) as the peak metamorphic conditions indicated by the diabase agree with conditions inferred from pelitic assemblages of Card (1978a)
2. P-T results from the best recrystallized sample of amphibolite indicate conditions of $580^{\circ}\text{C} \pm 60^{\circ}\text{C}$ and 4.3 ± 0.8 kbar. These data indicate a geothermal gradient of $\sim 35^{\circ}\text{C}/\text{km}$ on the assumption of an average rock density of $2.7 \text{ g}/\text{cm}^3$.
3. Four metamorphic zones are recognised in this study: 1. unrecrystallized zone (preserved igneous textures and minerals), 2. greenschist zone (actinolite, $\pm$ albite), 3. transitional (actinolite, hornblende, $\pm$ albite and/or oligoclase), 4. amphibolite (hornblende, oligoclase-andesine, $\pm$ garnet). These zones are similar to zones described elsewhere, for example Dore Lake Complex, Quebec, Kline, (1984), Sudbury Igneous Complex, Thompson, M L *et al* , (1985) and Fleet *et al* , (1987), they are also not unique in that elements of them have been described elsewhere in regimes characterised by incomplete equilibrium
4. Exsolution lamellae of actinolite and hornblende attest to the existence of a actinolite-hornblende miscibility gap under the conditions encountered.
5. Sharp grain boundaries between adjacent actinolite and hornblendes suggest local equilibrium
6. Penetrative foliation is lacking in almost all of the best-recrystallized rocks of the amphibolite zone

7. Mineral assemblages of the Nipissing Diabase contain abundant relict igneous minerals and textures.
8. The few samples that do contain completely recrystallized and equilibrated assemblages indicate that conditions did exist for the completion of metamorphic reactions, but these conditions were not prevalent. The Nipissing Diabase of May Township frequently preserves disequilibrium textures.
9. Microprobe analyses of the main minerals, amphibole and plagioclase, revealed a wide range of compositions for both minerals. Few greenschist samples contained the typical albite plagioclase. Igneous calcic plagioclase persisted into the transitional zone and in a few cores of plagioclase grains from the amphibolite zone. While amphibolite samples generally showed more complete equilibration and recrystallization, many amphibolite samples still contain cores of relict lower grade phases. Thus an analysis of mineral chemistry supports textural evidence of frequent disequilibrium in metadiabase of May Township.
10. The results obtained from thermobarometry indicate that the amphibolite samples are the best equilibrated and give the most consistent results (i.e. closest to the P-T field of amphibolite grade rocks), while transitional and greenschist yielded poorer, i.e. larger error or anomalous results, due to their disequilibrium state.
11. Further work is required to determine whether the garnet-bearing amphibolite samples within the "Webbwood Block", are the result of local contamination with the host pelites or result from possibly higher grade metamorphism.

12. An anomalous area of transition zone rocks within amphibolite zone rocks has been located north of George Lake

13. Two possible metamorphic cross sections are presented. One interpretation (Figure 8.5a) is based on the simplest geological assumptions but leads to steeply dipping isograds (between 43° and vertical), such steeply dipping isograds cannot reasonably explain the George Lake transition zone rocks. An alternative hypothesis (Figure 8.5b) places a unconformity between rocks of the amphibolite facies and lower grade rocks. The second hypothesis is speculative without confirmation on the basis of field mapping, except for the identification of the Serpent River as a possible structural discontinuity by Jackson and Henderson (pers. comm., 1993)

REFERENCES

- Abbott, Jr., R.N., 1982. A petrogenic grid for medium and high grade metabasites. *American Mineralogist*, vol. 67, pp. 865-876.
- Allen, J.M., and Goldie, R., 1978. Coexisting amphiboles from the Noranda area, Quebec: extension of the actinolite-hornblende miscibility gap to iron-rich bulk compositions. *American Mineralogist*, vol. 63, pp. 205-209.
- Apter, M.J., Liou, J.G., 1983. Phase Relations among Greenschist, Epidote-Amphibolite, Amphibolite in a basalt system. *American Journal of Science*, vol. 283-A, pp. 328-54.
- Arai, S. and Hirai, H., 1985. Compositional variation of calcic amphiboles in Mineoka metabasites, central Japan, and its bearing on the actinolite-hornblende miscibility relationship. *Lithos*, vol. 18, pp. 187-199.
- Bard, J.P. 1970. Composition of Hornblendes formed during the Hercynian progressive metamorphism of the Aracena metamorphic belt (SW Spain). *Contributions to Mineralogy and Petrology*, vol. 28, pp. 117-134.
- Bégin, N.J., 1989. P-T Conditions of Metamorphism Inferred from the Metabasites of the Cape Smith Belt, Northern Quebec. *Geoscience Canada*, vol. 16, pp. 151-154.
- Bégin, N.J., 1992. Contrasting mineral isograd sequences in metabasites of the Cape Smith Belt, northern Québec, Canada: three new bathograds for mafic rocks. *Journal of Metamorphic Geology*, vol. 10, pp. 685-704.
- Bégin, N.J. and Carmichael, D.M., 1992. Textural and Compositional Relationships of Ca-Amphiboles in Metabasites of the Cape Smith Belt, Northern Québec. Implications for a Miscibility Gap at Medium Pressure. *Journal of Petrology*, vol. 33, pp. 1317-1343.
- Bennett, G., B.O. Dressler, Robertson, J.A., 1991. The Huronian Supergroup and Associated Intrusive Rocks *in* *Geology of Ontario*, O.G.S. Special Volume 4, Part I, (eds.) P.C. Thurston, H.R. Williams, R.H. Sutcliffe, G.M. Scott) pp. 549-591.
- Berman, R.G., 1988. Internally-consistent thermodynamic data for stoichiometric minerals in the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{H}_2\text{O}-\text{CO}_2$. *Journal of Petrology*, vol. 29, pp. 445-522.
- Berman, R.G., 1990. Mixing properties of Ca-Mg-Fe-Mn garnets. *American Mineralogist*, vol. 75, pp. 328-344.

- Berman, R.G., 1991: Thermobarometry Using Multi-Equilibrium Calculations: A New Technique with Petrological Applications. *Canadian Mineralogist*, vol. 29, pp. 833-855.
- Bickford, M.E., Van Schmus, W.R., 1986. Proterozoic history of the midcontinent region of North America. *Geology*, vol. 14, pp. 492-496
- Binns, R.A., 1965: The mineralogy of metamorphosed basic rocks from the Willyama complex, Broken Hill District, New South Wales. Part 1. Hornblendes. *Mineralogical Magazine*, vol. 35, pp. 306-326.
- Blundy, J.D., and Holland, T.J.B., 1990: Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contributions to Mineralogy and Petrology*, vol. 104, pp. 208-224
- Bohlen, S.R., Essene, E.J., 1980. Evaluation of coexisting garnet-biotite, garnet-clinopyroxene, and other Mg-Fe exchange thermometers in Adirondack granulites: Summary. *Geological Society of America Bulletin*, vol. 91, pp. 107-109.
- Bohlen, S.R., and Lindsley, D.H., 1987: Thermometry and Barometry of Igneous and Metamorphic Rocks. *Annual Reviews of Earth and Planetary Science*, vol. 15, pp. 397-420.
- Bonnicksen, B., 1969. Metamorphic Pyroxenes and Amphiboles in the Biwabik Iron Formation, Dunka River Area, Minnesota. *Mineralogical Society of America Special Paper*, vol. 2, pp. 217-239.
- Brady, J.B., 1974: Coexisting Actinolite and Hornblende from West-Central New Hampshire. *American Mineralogist*, vol. 59, pp. 529-535.
- Brocoum, S.J., Dalziel, I.W.D., 1974: The Sudbury Basin, the Southern Province, the Grenville Front and the Penokean Orogeny. *Geological Society of America Bulletin*, vol. 85, pp. 1571-1580.
- Brodie, K.H., Rutter, E.H., 1985. Chapter 6 On the Relationship between Deformation and Metamorphism, with Special Reference to the Behaviour of Basic Rocks, *in* *Advances in Physical Geochemistry*, vol. 4, Metamorphic Reactions Kinetics, Textures, and Deformation, Thompson, A.B., and Rubie, D.C., (eds.) Springer-Verlag, New York.
- Brown, W.L., 1962: Peristerite Unmixing in the Plagioclase and Metamorphic Facies Series. *Norsk Geologisk Tidsskrift*, vol. 42, pp. 354-382.
- Brown, E.H., 1977. The Crossite Content of Ca-Amphibole as a Guide to Pressure of Metamorphism. *Journal of Petrology*, vol. 18, pp. 53-72

- Buchan, K.L. and Card, K.D., 1985: Preliminary comparison of petrographic and paleomagnetic characteristics of Nipissing Diabase intrusions in northeastern Ontario in Current Research, Part A, Geological Survey of Canada, Paper 85-1A, pp 131-140
- Cape, D.F., 1973: A petrologic and geochemical study of a gabbro anorthositic gabbro intrusion and neighbouring volcanics, northwest corner of May Township B Sc Thesis, University of Windsor, 59p
- Card, K.D., 1964: Metamorphism in the Agnew Lake Area, Sudbury District, Ontario, Canada Geological Society of America Bulletin, v 75, p 1011-1030
- Card, K.D., 1968: Geology of the Dension-Waters Area District of Sudbury, Ontario Department of Mines Geological Report 60
- Card, K.D., 1976: Geoscience Report 131, Geology of the Espanola-Whitefish Falls Area, District of Sudbury, Ontario Ontario Division of Mines, pp 33-45
- Card, K.D., 1978a: Metamorphism of the Middle Precambrian (Aphebian) Rocks of the Eastern Southern Province; *in* Metamorphism in the Canadian Shield, (J.A. Fraser and W.W. Heywood, eds.), Geol. Surv. Can., Paper 78-10, pp. 269-282
- Card, K.D., 1978b: Geology of the Sudbury-Manitoulin Area, Districts of Sudbury and Manitoulin, Ontario Geological Survey Report 166
- Card, K.D., Church, W.R., Franklin, J.M., Frarey, M.J., Robertson, J.A., West, G.F., Young, G.M., 1972: The Southern Province, in Variations in Tectonic Styles in Canada, R.A. Price, editor, pp. 335-380
- Card, K.D., and Pattison, E.F., 1973: Nipissing Diabase of the Southern Province, Ontario, Geological Association of Canada Special Paper No. 12, pp 7-30
- Card, K.D., Palonen, P.A., 1976: Geology of the Dunlop-Shakespeare Area, District of Sudbury, Ontario Department of Mines Geoscience Report 139
- Champness, P.E., Lorimer, G.W. 1976: Chapter 4.1 Exsolution in Silicates, pp 174-204, *in* Electron Microscopy in Mineralogy, H.R. Wenk(ed.) Springer-Verlag Pub., New York.
- Chouinard, A., 1995: Low-pressure high-temperature metamorphic relationships between the Aniak River volcanic belt and the Kangguyak gneiss belt, northwestern Slave Province. M.Sc. Thesis, Carleton University, 133p

- Coleman, A. P., 1914. The Pre-cambrian Rocks north of Lake Huron; Ontario Bureau of Mines, vol. 23, part 1, pp. 202-236.
- Collins, W.H., 1925. North Shore of Lake Huron. Geological Survey of Canada Memoirs 143, 160p.
- Compton, R.R., 1958. Significance of Amphibole Paragenesis in the Bidwell Bar Region, California. *American Mineralogist*, vol. 43, pp. 890-907.
- Cooper, A.F., and Lovering, J.F., 1970. Greenschist Amphiboles from Haast River, New Zealand. *Contributions to Mineralogy and Petrology*, vol. 27, pp. 11-24.
- Cooper, A.F., 1972. Progressive metamorphism of Metabasic Rocks from the Haast Schist Group of Southern New Zealand. *Journal of Petrology*, vol. 13, pp. 457-492.
- Corfu, F., and Andrews, A.J., 1986. A U-Pb age for mineralized Nipissing diabase, Gowganda, Ontario. *Canadian Journal of Earth Sciences*, vol. 23, pp. 107-109.
- Crawford, M.L., 1966. Composition of plagioclase and associated minerals in some schists from Vermont, U.S.A., and South Westland, New Zealand, with inferences about the peristerite solvus. *Contributions to Mineralogy and Petrology*, vol. 13, pp. 269-294.
- Deer, W.A., Howie, R.A., Zussman, J., 1992. *An Introduction to the Rock Forming Minerals*. Longman Scientific and Technical, New York, pp. 148-174.
- Droop, G.T.R., 1987. A general equation for estimating Fe³⁺ concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineralogical Magazine*, vol. 51, pp. 431-435.
- Engel, A.E.J., Engel, C.G., 1962. Hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York. *Bull. Geol. Soc. Am.* vol. 73, pp. 1499-1514.
- Essene, E.J., 1989. The current status of thermobarometry in metamorphic rocks, *from* Daly, J.S., Cliff, R.A., and Yardley, B.W.D. (eds), *Evolution of Metamorphic Belts*, Geological Society Special Publication No. 43, pp. 1-44.
- Fairbairn, H.W., Hurley, P.M., Pinson, W.H., 1967. Rb-Sr age and initial Sr⁸⁷/Sr⁸⁶ of the Huronian section south-west of Sudbury, Ontario. 15th Annual rept. M.I.T.-1381-15, U.S. Atomic Energy Comm., pp. 53-60.
- Fairbairn, H.W., Hurley, P.M., Card, K.D., Knight, C.J., 1969. Correlation of radiometric ages of Nipissing diabase and Huronian metasediments with Proterozoic orogenic events in Ontario. *Canadian Journal of Earth Sciences*, vol. 6, pp. 489-497.

- Fleet, M.E., Barnett, R.L., Morris, W.A., 1987: Prograde metamorphism of the Sudbury Igneous Complex. *Canadian Mineralogist*, vol. 25, pp. 499-514
- Frarey, M.J., Loveridge, W.D., Sullivan, R.W., 1982: A U-Pb zircon age for the Creighton Granite, Ontario. *In* Current Research, part C. Geological Survey of Canada, Paper 82-1C, pp. 129-132.
- Fox, J.S., 1971: Coexisting chloritoid and staurolite and the staurolite-chlorite isograd from the Agnew Lake area, Ontario, Canada. *Geological Magazine*, vol. 108, pp. 205-219
- Fuhrman, M.L., Lindsley, D.H. 1988: Ternary-feldspar modelling and thermometry. *American Mineralogist*, vol. 73, pp. 201-216.
- Fyfe, W.S., 1976: Chemical Aspects of Rock Deformation. *Phil. Trans. Roy. Soc. London*, vol. 283A, pp. 221-228.
- Ganguly, J., Singh, R.N., Ramana, D.V., 1995: Thermal perturbation during charnockitization and granulite facies metamorphism in southern India. *Journal of Metamorphic Petrology*, vol. 13, p. 419-430
- Ghent, E.D., and Stout, M.Z., 1986: Garnet-Hornblende Thermometry, $\text{CaMgSi}_2\text{O}_6$ Activity, and the Minimum Pressure Limits of Metamorphism for Garnet Amphibolites. *Journal of Geology*, vol. 94, pp. 736-743
- Ginn, R.M., 1961: Geology of Pater Township. Ontario Department of Mines, Geological Report 5, 36p.
- Ginn, R.M., 1965: Geology of Naim and Lorne Townships, District of Sudbury. Ontario Department of Mines Geological Report, No. 35, 46 p.
- Gittos, M.F., Lorimer, G.W., Champness, P.E., 1974: An electron-microscopic study of precipitation (exsolution) in an amphibole (the hornblende-grunerite system). *Journal of Materials Science*, vol. 9, pp. 184-192
- Goldsmith, J.R., 1982: Review of the behaviour of plagioclase under metamorphic conditions. *American Mineralogist*, vol. 67, pp. 643-652
- Graham, C.M., 1974: Metabasite Amphiboles of the Scottish Dalradian. *Contributions to Mineralogy and Petrology*, vol. 47, pp. 165-185
- Graham, C.M., and Powell, R., 1984: Garnet-hornblende geothermometer calibration, testing, and application to the Pelona Schist, Southern California. *Journal of Metamorphic Petrology*, vol. 2, pp. 13-31

- Graham, C.M., Maresch, W.D., Welch, M.D., Pawley, A.R., 1989: Experimental Studies on Amphiboles: a review with thermodynamic perspectives. *European Journal of Mineralogy*, vol. 1, pp. 535-555.
- Grapes, R.H., 1975: Actinolite-Hornblende Pairs in Metamorphosed Gabbros, Hidaka Mountains, Hokkaido. *Contributions to Mineralogy and Petrology*, vol. 49, pp. 125-140.
- Grapes, R.H., Hashimoto, S., Miyashita, S., 1977: Amphiboles of a Metagabbro-Amphibolite Sequence, Hidaka Metamorphic Belt, Hokkaido. *Journal of Petrology*, vol. 18, pp. 285-318.
- Grapes, R.H. and Graham, C.M., 1978: The actinolite-hornblende series in metabasites and the so-called miscibility gap: A review. *Lithos*, vol. 11, pp. 85-97.
- Grove, T.L., Baker, M.B., Kinzler, R.J., 1984: Coupled CaAl-NaSi diffusion in plagioclase feldspar: experiments and application to cooling rate speedometry. *Geochim. Cosmochim. Acta.*, vol. 48, pp. 2113-2121.
- Hallimond, A.F., 1943: On the Graphical Representation of the Calciferous Amphiboles. *American Mineralogist*, vol. 28, pp. 65-89.
- Harte, B., Graham, C.M., 1975: The Graphical Analysis of Greenschist to Amphibolite Facies Mineral Assemblages in Metabasites. *Journal of Petrology*, vol. 16, pp. 347-370.
- Hawthorne, F.C., 1983: The Crystal Chemistry of Amphiboles. *Canadian Mineralogist*, vol. 21, pp. 173-480.
- Hietanen, A., 1974: Amphibole Pairs, Epidote Minerals, Chlorite, and Plagioclase in Metamorphic Rocks, Northern Sierra Nevada, California. *American Mineralogist*, vol. 59, pp. 22-40.
- Hodges, K.V., Spear, F.S., 1982: Geothermometry, geobarometry and the new Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. *American Mineralogist*, vol. 67, pp. 1118-1134.
- Hoffman, P.F., 1988: United Plates of America, The Birth of a Craton: Early Proterozoic Assembly and Growth of Laurentia. *Annual Reviews of Earth and Planetary Science Letters*, vol. 16, pp. 543-603.
- Holland, T.J.B., Richardson, S.W., 1979: Amphibole Zonation in Metabasites as a Guide to the Evolution of Metamorphic Conditions. *Contributions to Mineralogy and Petrology*, vol. 70, pp. 143-148.

- Holland, T., and Powell, R., 1990: Calculated mineral equilibria in the pelite system, KFMASH (K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O). *Canadian Mineralogist*, vol. 75, pp 367-380.
- Holland, T., Blundy, J., 1994: Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. *Contributions to Mineralogy and Petrology*, vol. 116, pp. 433-447.
- Hriskevich, M.E., 1968: Petrology of the Nipissing Diabase Sill of the Cobalt Area, Ontario, Canada. *Geological Society of America Bulletin*, vol. 79, pp 1387-1404
- Hurlbut, C.S., Klein, C., 1977: *Manual of Mineralogy*, 19th ed., John Wiley and Sons Inc., U.S.A. ***p.
- Hynes, A., 1982: A Comparison of Amphiboles from Medium- and Low- Pressure Metabasites. *Contributions to Mineralogy and Petrology*, vol. 81, pp. 119-125
- Innes, D.G., Colvine, A.C., 1984: Chapter 3, The regional Metallogenic Setting of Sudbury, p 45-56 in *The Geology and Ore Deposits of the Sudbury Structure*, edited by E.G. Pye, A.J. Naldrett, P.E. Giblin, Ontario Geological Survey, Special Volume 1, 603p
- Jackson, J.A., 1980: Reactivation of basement faults and crustal shortening in orogenic belts. *Nature*, vol. 283, pp. 343-346.
- Jackson, S.L., and Henderson, I., 1993: Precambrian Geology of May Township and parts of McKinnon, Harrow and Hallam Townships, District of Sudbury, With an Emphasis on the McKim Formation. Ministry of Northern Development and Mines, Summary of Field Work and Other Activities, Ontario Geological Survey Miscellaneous Paper 162, pp.46-50.
- Jackson, S.L., and Henderson, I., 1993. O.G.S., M.N.D.M., Open File Map 233, Precambrian Geology of May Township, District of Sudbury
- Jambor, J.L., 1971: The Nipissing Diabase. *Canadian Mineralogist*, vol. 11, pp 38-75
- Jenkins, D.M., 1988: Experimental study of the join Ti - $Tsch$: A reinvestigation. *Contributions to Mineralogy and Petrology*, vol. 99, pp. 392-400.
- Johannsen, A., 1937: *A Descriptive Petrography of the Igneous Rocks*, Volume 3, the intermediate rocks. University of Chicago Press, Chicago. 360p.
- Knight, C.J., 1967: Rubidium-strontium isochron ages of volcanic rocks of the north shore of Lake Huron, Ontario, Canada. Unpubl. Ph.D. Thesis, University of Toronto

- Klein, Jr., C. 1968. Coexisting Amphiboles. *Journal of Petrology*, vol. 9, pp. 281-330.
- Kline, S. W., 1984. Iron-rich Hornblende plus Albite in Low-Pressure Metabasites, Chibougamau, Quebec. *Canadian Mineralogist*, vol. 22, pp. 391-399.
- Kohn, M.J., and Spear, F.S., 1989. Empirical calibration of geobarometers for the assemblage garnet + hornblende + plagioclase + quartz. *American Mineralogist*, vol. 74, pp. 77-84.
- Kohn, M.J., and Spear, F.S., 1990. Two new geobarometers for garnet amphibolites, with applications to southeastern Vermont. *American Mineralogist*, vol. 75, pp. 89-96.
- Kostyuk, E. A., Sobolev, V.S., 1969. Paragenetic types of calciferous amphiboles of metamorphic rocks. *Lithos*, vol. 2, pp. 67-82.
- Krogh, T.E., Davis, G.L., and Frarey, M.J., 1971. Isotopic ages along the Grenville Front in the Bell Lake Area, Southwest of Sudbury, Ontario. *Annual Report Geophys. Lab., Carnegie Inst., Yearbook 69, 1969-1970*, pp. 337-339.
- Laird, J., and Albee, A., 1981. Pressure, Temperature, and Time Indicators in Mafic Schist: Their Application to Reconstructing the Polymetamorphic History of Vermont. *American Journal of Science*, vol. 281, pp. 127-175.
- Leake, B.E., 1965. The Relationship Between Tetrahedral Aluminum and the Maximum Possible Octahedral Aluminum in Natural Calciferous and Subcalciferous Amphiboles. *American Mineralogist*, vol. 50, pp. 843-851.
- Leake, B.E., 1968. A Catalog of Analyzed Calciferous and Subcalciferous Amphiboles Together with their Nomenclature and Associated Minerals. *Geological Society of America Special Paper 98*, pp. 5-27.
- Leake, B.E., 1978. Nomenclature of Amphiboles. *Canadian Mineralogist*, vol. 16, pp. 501-520.
- Lee, S.R., Cho, M., 1995. Tectonometamorphic evolution of the Chuncheon amphibolite, Central Gyeonggi massif, S. Korea. *Journal of Metamorphic Geology*, vol. 13, pp. 315-328.
- Lightfoot, P.C., Conrod, D., Naldrett, A.J., and Evensen, N.M., 1986. Petrologic, Chemical, Isotopic, and Economic Potential Studies of the Nipissing Diabase. *in Geoscience Research Grant Program Summary of Research*, Milne, V.G., (ed), Ontario Geological Survey Miscellaneous Paper 130, pp. 87-105.

- Lightfoot, P.C., DE Souza, H., and Doherty, W., 1993: Differentiation and source of the Nipissing Diabase intrusions, Ontario, Canada. *Canadian Journal of Earth Sciences*, vol. 30, pp. 1123-1140.
- Liou, J.G., Kuniyoshi, S., and Ito, K., 1974: Experimental Studies of the Phase Relations Between Greenschist and Amphibolite in a Basaltic System. *American Journal of Science*, vol. 274, pp. 613-632.
- Mader, U.K., Berman, R.G., 1992: Amphibole Thermometry: a thermodynamic approach, *Current Research, Part E: Geological Survey of Canada Paper 92-1E*, pp. 393-400.
- Maruyama, S., Liou, J.G., Suzuki, K., 1982: The Peristerite Gap in Low-Grade Metamorphic Rocks. *Contributions to Mineralogy and Petrology*, vol. 81, pp. 268-276.
- Maruyama, S., Suzuki, K., Liou, J.G., 1983: Greenschist-Amphibolite Transition Equilibria at Low Pressures. *Journal of Petrology*, vol. 24, pp. 583-604.
- McMullin, D., Berman, R.G., Greenwood, H.J., 1991: Calibration of the SGAM thermobarometer for pelitic rocks using data from phase equilibrium experiments and natural assemblages. *Canadian Mineralogist*, vol. 29, pp. 889-908.
- Miyashiro, A., 1961: Evolution of Metamorphic Belts. *Journal of Petrology*, vol. 2, pp. 277-311.
- Miyashiro, A., 1968: Metamorphism of mafic rocks, in Hess, H.H., and Poldervaart, A., eds., *Basalts*: New York, John Wiley and Sons, Inc., pp. 799-834.
- Miyashiro, A., 1973: *Metamorphism and Metamorphic Belts*. Wiley and Sons, New York.
- Miyashiro, A., 1994: *Metamorphic petrology*. New York, Oxford University Press, 404p.
- Morris, W.A., 1977: Paleomagnetism of the Gowganda and Chibougamau Formations: Evidence for a 2200 m.y. old folding and remagnetization event of the Southern Province. *Geology*, vol. 5, pp. 137-140.
- Morris, W.A., 1979: A positive test between Nipissing diabase and Gowganda argillites. *Canadian Journal of Earth Sciences*, vol. 16, pp. 607-611.
- Noble, D.C., 1962: Plagioclase Unmixing and the Lower Boundary of the Amphibolite Facies. *Journal of Geology*, vol. 70, pp. 234-240.
- Oba, T., 1980: Phase Relations in the Tremolite-Pargasite Join. *Contributions to Mineralogy and Petrology*, vol. 71, pp. 247-256.

- Oba, T., and Yagi, K., 1987 Phase Relations on the Actinolite-Pargasite Join *Journal of Petrology*, vol 28, pp 23-36
- Palmer, H.C., Merz, B.A., Hyatsu, A., 1977. The Sudbury dikes of the Grenville Front region: paleomagnetism, petrochemistry and K-Ar age studies *Canadian Journal of Earth Sciences*, vol. 14, pp. 1867-1887.
- Pan, Y., and Fleet, M.E., 1993 Polymetamorphism in the Archean Hemlo - Heron Bay greenstone belt, Superior Province: P-T variations and implications for tectonic development *Canadian Journal of Earth Sciences*, vol., 30, pp. 985-996.
- Plyusnina, L.P., 1982 Geothermometry and Geobarometry of Plagioclase-Hornblende Bearing Assemblages *Contributions to Mineralogy and Petrology*, vol. 80, pp. 140-146.
- Raase, P., 1974 Al and Ti Contents of Hornblende, Indicators of Pressure and Temperature of Regional Metamorphism *Contributions to Mineralogy and Petrology*, vol. 45, pp. 231-236
- Robertson, J.A., Card, K.D., Frarey, M.J., 1969 The Federal-Provincial Committee on Huronian Stratigraphy: Progress Report, Ontario Department of Mines, MP31, 26p.
- Robertson, J.A., Siemiatkowska, K.M., and assistants, 1971 May Township, District of Sudbury, Ontario Dept. Mines, Preliminary Geological Map P.702, scale, 1 inch to ¼ mile, Geology
- Robertson, J.A., Siemiatkowska, K.M., and assistants, 1971 Hallam Township, District of Sudbury, Ontario Dept. Mines, Preliminary Geological Map P.703, scale, 1 inch to ¼ mile, Geology
- Robertson, J.A., 1976 Geology of the Massey Area, Districts of Algoma, Manitoulin and Sudbury Ontario Department of Mines Geoscience Report 136
- Robinson, P., Spear, F.S., Schumacher, J.C., Laird, J., Klein, C., Evans, B.W., Doolan, B.L.: 1982 Chapter 1: Phase Relations of Metamorphic amphiboles: Natural Occurrence and Theory. p 1-211 *In* Reviews in Mineralogy, vol 9B, Amphiboles: Petrology and Experimental Phase Relations, Veblen, D.R., Ribbe, P.H eds., M.S.A. publication.
- Ross, M., Papike, J.J., and Weiblen, P.W., 1968 Exsolution in Clinoamphiboles. *Science*, vol. 159, pp 1099-1102,
- Ross, M., Papike, J.J., Shaw, K.W., 1969. Exsolution Textures in Amphiboles as Indicators of Subsolidus Thermal Histories. *Mineralogical Society of America Special Paper*, vol.2, pp 275-299

- Sampson, G.A., Fawcett, I.J., 1977. Coexisting Amphiboles from the Hastings Region of Southeastern Ontario. *Canadian Mineralogist*, vol. 15, pp. 283-296.
- Schumacher, J.C., 1991. Empirical ferric iron corrections: necessity, assumptions and effects on selected geothermobarometers. *Mineralogical Magazine*, vol. 55, pp. 3-18.
- Seki, Y., 1962. Calcareous Hornfelses in the Arisu District of the Kitakami Mountains, North-eastern Japan. *Japanese Journal of Geology and Geography*, vol. 32, pp. 55-78.
- Sethuraman, K. and Moore, Jr., J.M., 1973. Petrology of Metavolcanic Rocks in the Bishop Corners-Donaldson Area, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, vol. 10, pp. 589-614.
- Shido, F., 1958. Plutonic and Metamorphic Rocks of the Nakoso and Iritono Districts in the Central Abukuma Plateau. *Journal of the Faculty of Science, University of Tokyo*, vol. 11, pp. 131-217.
- Shido, F. and Miyashiro, A., 1959. Hornblendes of Basic Metamorphic Rocks. *Journal of the Faculty of Science University of Tokyo*, vol. 12, pp. 85-102.
- Sims, P.K., Card, K.D., Morey, G.B., Peterman, Z.E., 1980. The Great Lakes tectonic zone -- A major crustal structure in central North America. *Geological Society of America Bulletin*, vol. 91, pp. 690-698.
- Sims, P.K., Card, K.D., Lumbers, S.B., 1981. Evolution of early Proterozoic basins of the Great Lakes region; in *Proterozoic Basins of Canada*, F.H.A. Campbell, editor, Geological Survey of Canada Paper 81-10, pp. 379-397.
- Smelik, E.A., Nyman, M.W., Veblen, D.R., 1991. Pervasive Exsolution within the calcic amphibole series: TEM evidence for a miscibility gap between actinolite and hornblende in natural samples. *American Mineralogist*, vol. 76, pp. 1184-1204.
- Spear, F.S., 1981. Amphibole-Plagioclase Equilibria: An Empirical Model for the Relation $\text{Albite} + \text{Tremolite} = \text{Edenite} + 4\text{Quartz}$. *Contributions to Mineralogy and Petrology*, vol. 77, pp. 355-364.
- Spear, F.S., 1981. An Experimental Study of Hornblende Stability and Compositional Variability in Amphibolite. *American Journal of Science*, vol. 281, pp. 697-734.
- Spear, F.S., 1993. *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineralogical Society of America, BookCrafters, Inc. Chelsea, Michigan, 799p.

- Stockwell, C H., 1982: Proposals for time classification and correlation of the Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield: part 1. Geological Survey of Canada Paper 80-19
- Sutton, J and Watson, J., 1951 Varying Trends in the Metamorphism of Dolerites. Geological Magazine, vol 88, pp. 25-35.
- Terabayashi, M , 1988: Actinolite-forming reaction at low pressure and the role of Fe²⁺-Mg Substitution. Contributions to Mineralogy and Petrology, vol. 100, pp. 268-280.
- Terabayashi, M., 1993. Compositional evolution in Ca-amphibole in the Karmutsen metabasites, Vancouver Island, British Columbia, Canada. Journal of Metamorphic Geology, vol. 11, pp.677-690
- Thompson, A B., 1976. Mineral Reactions in Pelitic Rocks:II. Calculations of some P-T-X (Fe-Mg) Phase Relations American Journal of Science, vol. 276, pp. 425-454
- Thomson, J.B , Jr , Laird, J, and Thomson, A.B., 1982. Reactions in Amphibolite, Greenschist and Blueschist. Journal of Petrology, vol. 23, pp. 1-27.
- Thomson, M.L , Barnett, R.L , Fleet, M.E , Kerrich, R , 1985: Metamorphic Assemblages in the South-Range Norite and Footwall Mafic Rocks near the Kirkwood Mine, Sudbury, Ontario. Canadian Mineralogist, vol , 23, pp. 173-186
- Thurston, P.C., 1991. Geology of Ontario: Introduction *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, part 1 pp. 3-25
- Thurston, P.C., 1991: Proterozoic Geology of Ontario. Introduction; *in* Geology of Ontario, O.G.S. Special Volume 4, Part1, (eds.) P.C. Thurston, H.R., Williams, R.H. Sutcliffe, G.M Scott), pp. 543-546
- Turner, F.J., 1981. Metamorphic Petrology, 2nd Nipissing diabase Edn. McGraw and Hill, New York, 524pp.
- Wetherill, G W , Davis, G L., Tilton, G.R., 1960: Age measurements on minerals from the Cutler Batholith, Culter, Ontario Journal of Geophysical Research, vol. 65, pp. 2461-2466
- Will, T.M., Powell, R , Holland, T., and Guiraud, M., 1990: Calculated greenschist facies mineral equilibria in the system CaO-FeO-MgO-Al₂O₃-SiO₂-CO₂-H₂O. Contributions to Mineralogy and Petrology, vol. 104, pp. 353-368
- Winkler, H.G F , 1979. Petrogenesis of Metamorphic Rocks Springer-Verlag, New York.

- Wu, J., Milkereit, B., Boerner, D., 1994: Timing constraints on deformation history of the Sudbury Impact Structure. *Canadian Journal of Earth Sciences*, vol. 31, pp. 1654-1660.
- Zolnai, A.I., Price, R.A., Helmstaedt, H., 1983: Regional Cross section of the Southern Province adjacent to Lake Huron, Ontario: implications for the tectonic significance of the Murray Fault Zone. *Canadian Journal of Earth Science*, vol. 21, pp. 447-456.

APPENDIX A

Table A.1 Huronian Supergroup Units (after Innes and Colvine, 1984, p. 51, Figure 3.3)

GROUP	FORMATION	LITHOLOGY
Cobalt	Bar River	sandstone, siltstone
	Gordon Lake	siltstone
	Lorrain	sandstone, conglomerate
	Gowganda	conglomerate, sandstone
Quirke Lake	Serpent	siltstone, sandstone
	Espanola	limestone, siltstone
	Bruce	conglomerate
Hough Lake	Mississagi	sandstone
	Pecors	siltstone
	Ramsey Lake	conglomerate
Elliot Lake	McKim	siltstone
	Matinenda	conglomerate
	Salmay Lake, Stobie, Copper Cliff, Elsie Mountain, Livingstone Creek, Thessalon, Pater, Dollyberry	conglomerates, mafic and felsic volcanics

Table A.2 Metamorphic Assemblages of Nipissing Diabase of May Township

Metamorphic Zone	Characteristic Mineral Assemblage (igneous minerals are in italics, minor minerals are in parentheses)
"Unrecrystallized"	<i>pyroxene</i> + <i>calcic plagioclase</i> + <i>ilmenite</i> ± <i>biotite</i> ± <i>hornblende</i> (talc, sericite, epidote, clinozoisite, actinolite)
Greenschist	actinolite ± albite + quartz ± <i>pyroxene</i> + <i>calcic plagioclase</i> (biotite, ilmenite, titanite, epidote, clinozoisite, sericite)
Transitional	actinolite + hornblende + quartz ± albite ± oligoclase + <i>calcic plagioclase</i> (ilmenite, titanite, biotite, epidote, clinozoisite, sericite)
Amphibolite	hornblende + oligoclase-andesine (rims) + quartz + biotite ± garnet + ilmenite + titanite + <i>calcic plagioclase</i> (cores), (epidote, sericite, apatite)

Table A.3: Metamorphic Assemblages of Major Rock Types of the Southern Province of Ontario (Card, 1978a, p. 274)

	Subgreenschist Facies	Low to Middle Greenschist Facies	Middle to Upper Greenschist Facies	Lower Amphibolite Facies
Pelitic Metasediments	Clay Minerals			
		Muscovite (Paragonite)		
		Chlorite		
		Albite		
			Oligoclase-Andesine	
		Biotite		
			Garnet	
Quartzitic Metasediments	Kaolinite			
	Diaspore			
		Pyrophyllite		
		Muscovite		
		Albite - Oligoclase		
		Biotite		
			Garnet	
Calcareous Metasediments	Calcite (dolomite)			
		Muscovite		
		Chlorite		
		Biotite		
		Albite		
			Oligoclase-Andesine	
		Scapolite		
		Tremolite-Actinolite		
Mafic Igneous Rocks	Original Magmatic Minerals			
		Epidote		
		Talc		
		Chlorite		
		Albite		
			Oligoclase-Andesine	
		Actinolite		
			Hornblende	
			Garnet	

APPENDIX B

Table B.1 Bulk Rock Analyses of Nipissing Diabases and Metamorphosed Nipissing Diabases of the Southern Province (Card and Pattison, 1973, Card, 1978a)

analyses	1	2	3	4	5	6	7	8	9	10	11	12
	<i>gabbros</i>			<i>metagabbros</i>								
SiO ₂	49.97	50.61	49.97	54.00	51.00	51.98	48.60	54.60	52.40	48.80	48.34	50.89
Al ₂ O ₃	17.44	7.24	17.44	13.80	13.60	14.69	9.16	14.60	15.10	17.60	18.03	14.60
Fe ₂ O ₃	2.19	4.39	2.19	1.03	1.05	0.85	4.65	1.22	6.07	1.80	1.28	1.52
FeO	6.90	7.18	6.90	9.79	6.87	8.70	6.48	7.43	7.50	5.12	8.15	8.08
MgO	7.79	9.69	7.79	5.90	11.00	7.50	9.57	6.30	4.50	7.23	8.45	8.38
CaO	11.05	18.47	11.05	11.00	12.60	11.46	18.41	11.70	8.73	10.30	9.82	9.94
Na ₂ O	1.96	0.71	1.96	1.71	1.12	1.83	0.53	2.16	2.09	2.64	2.08	1.65
K ₂ O	0.48	0.24	0.48	0.49	0.24	0.51	0.20	0.54	0.88	1.69	0.60	0.55
H ₂ O ⁺	0.53	0.24	0.53	0.28	0.98	1.35	1.29	0.82	1.73	3.32	1.52	1.76
H ₂ O ⁻	0.22	-----	0.22	0.12	0.18	0.08	-----	0.23	0.15	0.41	0.23	0.28
CO ₂	0.39	0.05	0.39	0.10	0.05	0.04	0.07	0.16	0.25	0.12	0.33	0.27
TiO ₂	0.30	0.34	0.30	0.70	0.36	0.62	0.32	0.58	0.98	0.48	0.28	0.19
P ₂ O ₅	0.70	0.03	0.07	0.04	0.03	0.06	0.03	0.04	0.09	0.02	0.07	0.03
S	0.08	-----	0.08	0.01	0.04	-----	-----	0.03	0.08	0.05	0.09	0.08
MnO	0.12	0.22	0.12	0.19	0.17	0.18	0.25	0.16	0.17	0.15	0.14	0.14
Cr ₂ O ₃	0.09	0.27	0.09	-----	-----	-----	0.30	-----	-----	-----	0.03	0.05
V ₂ O ₃	0.07	-----	-----	-----	-----	-----	0.02	-----	-----	-----	0.04	0.09
total	99.57	99.70	99.57	99.20	99.30	99.85	99.88	100.60	100.70	99.70	99.39	98.42

1- pyroxene gabbro (Card and Pattison)
2-two-feldspar pyroxenite (Card)
3-two-pyroxene gabbro (Card)
4-two pyroxene gabbro (Card)
5- two-pyroxene gabbro (Card)
6- chilled gabbro (Card)
7-Card and Pattison #1 metagabbro
8-Card and Pattison #4 metagabbro
9-Card and Pattison #5 metagabbro
10- Card and Pattison #7 metagabbro
11-metagabbro (Card and Pattison)
12-metagabbro (Card and Pattison)

APPENDIX C

Electron Microprobe Analyses and Scanning Electron Microprobe Analyses

Compositions of amphiboles, plagioclases, biotites, garnets, ilmenites, and titanites were analyzed at Carleton University on two instruments, 1) by energy dispersive spectrometry (EDS), using a JEOL JSM6400 Scanning Electron Microscope equipped with a Link eXL LZ4 X-ray analyzer, and 2) by energy dispersive spectrometry (EDS) on a Cambridge Microscan 5 electron Microprobe. Accelerating potential was set at 20 kV. Average live counting time was 100 seconds. Iron content in appropriate minerals is calculated as FeO.

Representative results of microprobe analyses for the critical minerals of the Nipissing Diabases are found in the following tables:

Mineral	Table	Mineral	Table	Mineral	Table
Amphibole	C.1	Garnet	C.3	Ilmenite	C.5
Plagioclase	C.2	Biotite	C.4	Titanite	C.6

Amphiboles

Six different formula calculation methods (Robinson *et.al*, 1982, Holland and Blundy, 1992) were used to estimate the amount of ferric iron. Results are shown in Figure C.2 below and show the range of results between the different calculation methods. The range in results will vary distinctions of the cations with respect to metamorphic grade, and any conclusions drawn from interpretation of the recalculated formulae encourages error in the absence of wet chemical analyses to determine true ferric

iron Thus any plots are expressed in terms of the oxides themselves unless otherwise indicated, to compare with work of others.

Calculation of Ilmenite and Titanite Activities

Ilmenite $[\text{Fe}]_A[\text{Ti}]_B\text{O}_3$

symbol		symbol	
a_{FeTiO_3}	activity of ilmenite	n_{Ti}	molar proportion of TiO_2 (in site B)
x_{Fe}	molar fraction of FeO	n_{Mn}	molar proportion of MnO (in site A)
x_{Ti}	molar fraction of TiO_2	n_{Mg}	molar proportion of MgO (in site A)
n_{Fe}	molar proportion of FeO (in site A)	n_{Cr}	molar proportion of Cr_2O_3 (in site B)

$$\therefore a_{\text{FeTiO}_3} = x_{\text{Fe}} \cdot x_{\text{Ti}} \quad \text{where } x_{\text{Fe}} = n_{\text{Fe}}/(n_{\text{Fe}} + n_{\text{Mn}} + n_{\text{Mg}}) \text{ and } x_{\text{Ti}} = n_{\text{Ti}}/(n_{\text{Ti}} + n_{\text{Cr}})$$

Titanite $[\text{Ca}]_A[\text{Ti}]_B[\text{Si}]_C\text{O}_5$

symbol		symbol	
a_{CaTiSiO_5}	activity of titanite	n_{Ca}	molar proportion of CaO (in site A)
x_{Ti}	molar fraction of TiO_2	n_{Al}	molar proportion of Al_2O_3 (in site B and C)
x_{Ca}	molar fraction of CaO	n_{Mn}	molar proportion of MnO (in site A)
x_{Si}	molar fraction of SiO_2	n_{Fe}	molar proportion of FeO (in site B)
n_{Ti}	molar proportion of TiO_2 (in site B)	n_{Si}	molar proportion of SiO_2 (in site C)

$$\therefore a_{\text{CaTiSiO}_5} = x_{\text{Ca}} \cdot x_{\text{Ti}} \cdot x_{\text{Si}} \quad \text{where } x_{\text{Ca}} = n_{\text{Ca}}/(n_{\text{Ca}} + n_{\text{Mn}}) \text{ and } x_{\text{Ti}} = n_{\text{Ti}}/(n_{\text{Ti}} + n_{\text{Fe}} + n_{\text{Al}})$$

$$\text{and } x_{\text{Si}} = n_{\text{Si}}/(n_{\text{Si}} + n_{\text{Al}})$$

Figure C.1: Plot of amphiboles from Nipissing Diabases of May Township. Chemical divisions and nomenclature is for calcic amphiboles (where $(Na+K)A < 0.5$ and $Ti < 0.5$) after Hawthorne (1983). Note :1) the wide distribution of transitional zone amphiboles; 2) the greatest consistency of amphibolite zone amphiboles; 3) only a few amphiboles from garnet-bearing samples are present, as most of the other are pargasitic amphiboles (where $(Na+K)A \leq 0.5$). Relative error is indicated by the horizontal and vertical dimensions of the symbols.

Figure C.2: Comparative amphibole formula calculation results. Results for six different formula calculation methods are indicated above. Relative error is indicated by the horizontal and vertical dimensions of the symbols.

Figure C.3: Plot of analyses indicated in Plates C.1, C.2, C.3. Note the very close proximity of the analyses of the exsolution lamellae in Plate C.1, and the greater distance between the analyses from the amphibolite grade samples. The measured compositions are not considered to be reliable analyses of coexisting amphiboles; the S.E.M. does not provide the necessary resolution to obtain analyses of individual lamella.

Plate C.1: S.E.M. Backscatter image of exsolution lamellae from sample I-302-1 ("unrecrystallized" zone). Analyses indicated are plotted in Figure C.3 and listed in Table C.1.

Plate C.2: S.E.M. Backscatter image of exsolution lamellae and coexisting actinolite (dark grey) and hornblende (light grey) from sample I-49-1 (amphibolite zone). Note the sharp contact between the actinolite and hornblende. The exsolution lamellae were too fine to obtain representative results. Analyses are plotted in Figure C.3 and listed in Table C.1.

Plate C.3: S.E.M. Backscatter image of patchy, coexisting actinolite (dark grey) and hornblende (light grey) from sample J-15-4 (amphibolite zone). Analyses indicated are plotted in Figure C.3 and listed in Table C.1.

Table C.1 Representative Amphibole Analyses

*all iron is considered Fe²⁺

zone	"unrecrystallized"					greenschist		greenschist		transitional		transitional		transitional				
sample	J-302-1 (analyses in Plate C 1)					J-34-1		812-1		J-4-1		820-1		S-528-1				
	aveg	std dev	n	1	2	3	4	5	aveg	std dev	n	aveg	std dev	n	aveg	std dev	n	
SiO ₂	49.93	1.70	10	48.78	48.99	49.14	49.29	49.18	53.89	1.42	13	52.83	0.35	23	44.79	4.18	45.53	2.78
TiO ₂	0.27	0.12	10	0.4	0.46	0.45	0.44	0.43	0.11	0.14	13	0.06	0.04	23	0.18	0.10	0.35	0.07
Al ₂ O ₃	5.53	1.21	10	5.54	5.64	5.78	5.63	5.79	3.49	1.33	13	2.66	0.20	23	10.56	5.94	13.27	2.95
Cr ₂ O ₃	0.19	0.09	10	0.19	0.18	0.17	0.13	0.21	0.30	0.21	13	0.00	0.00	23	0.06	0.00	0.01	0.04
FeO*	13.67	0.98	10	13.23	14.09	13.54	15.13	13.23	10.00	0.96	13	14.29	0.20	23	19.04	1.52	14.50	1.08
MnO	0.28	0.04	10	0.15	0.16	0.14	0.24	0.24	0.21	0.03	13	0.25	0.04	23	0.31	0.11	0.26	0.04
MgO	15.92	0.88	10	14.74	15.11	14.69	15.38	14.99	16.99	1.16	13	14.72	0.40	23	9.28	3.12	10.39	1.86
CaO	11.34	1.11	10	12.22	11.77	11.98	10.8	12.07	12.56	0.17	13	12.63	0.21	23	11.54	0.57	12.20	0.24
Na ₂ O	0.52	0.19	10	0	0.54	0	0.63	0	0.08	0.28	13	0.12	0.13	23	0.78	0.57	0.97	0.29
K ₂ O	0.37	0.25	10	0.52	0.54	0.55	0.56	0.55	0.05	0.10	13	0.02	0.02	23	0.53	0.22	0.27	0.07
Cl	0.10	0.07	10	0.12	0.12	0.11	0.11	0.1	0.01	0.03	13	0.01	0.01	23	0.11	0.04	0.02	0.03
F	0.09	0.00	10	0	0	0	0	0	0.00	0.00	13	0.00	0.00	23	0.00	0.00	0.00	0.00
Sum	98.02	0.63	10	95.89	97.6	96.55	98.34	96.79	97.67	0.58	13	97.59	0.77	23	97.13	0.72	97.76	0.84

zone	amphibolite					amphibolite					amphibolite					gamet-bearing amphibolite					
sample	J-49-1 (analyses indicated in Plate C 2)					J-6-4 (analyses indicated in Plate C 3)					J-6-4 (analyses indicated in Plates 7 1a-c)					806-7A					
	aveg	std dev	n	1	2	3	4	5	6	7	1	2	3	4	5	aveg	std dev	n	aveg	std dev	n
SiO ₂	49.42	49.37	40	40.24	40.84	49.07	49.07	49.07	49.07	49.07	45.21	51.14	49.65	45.5	44.61	41.30	0.16	39	44.79	4.18	45.53
TiO ₂	0.36	0.36	40	0.27	0.42	0.52	0.52	0.52	0.52	0.52	0.44	0.79	0.16	0.35	0.43	0.19	0.06	44	0.18	0.10	0.35
Al ₂ O ₃	5.02	5.46	40	16.19	15.02	5.48	5.48	5.48	5.48	5.48	10.11	2.9	4.95	9.28	9.88	4.26	0.31	17	10.56	5.94	13.27
Cr ₂ O ₃	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.06	0.00	
FeO*	17.78	18.54	40	19.47	19.68	18.03	18.03	18.03	18.03	18.03	18.39	16.51	16.59	18.09	18.31	16.33	0.16	21	19.04	1.52	14.50
MnO	0.29	0.33	40	0.25	0.25	0.28	0.28	0.28	0.28	0.28	0.24	0.28	0.3	0.32	0.36	0.32	0.09	0.12	0.31	0.11	
MgO	11.26	11.69	40	5.96	6.47	11.36	11.36	11.36	11.36	11.36	9.53	13.51	12.43	9.76	9.65	12.78	0.22	4.05	10.56	5.94	
CaO	11.66	11.57	40	11.81	11.89	11.88	11.88	11.88	11.88	11.88	11.94	11.95	12.1	11.7	11.82	12.11	0.14	11	11.54	0.57	12.20
Na ₂ O	0	0	40	1.77	0.85	0	0	0	0	0	0.84	0.62	0	1.1	0.83	0	0.27	1.99	0.78	0.22	0.26
K ₂ O	0.12	0.09	40	0.86	0.6	0.15	0.15	0.15	0.15	0.15	0.28	0	0.11	0.29	0.24	0	0.05	0.76	0.26	0.11	0.26
Cl	0.12	0.14	40	0.07	0.08	0.12	0.12	0.12	0.12	0.12	0	0	0	0	0	0	0.00	0.06	0.00	0.00	0.00
F	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00
Sum	96.03	97.55	40	96.89	96.12	96.89	96.89	96.89	96.89	96.89	96.98	97.7	96.29	96.39	96.27	96.31	0.34	97	97.13	0.72	97.76

Table C.2: Representative Plagioclase Analyses

Table C.3 Representative Garnet Analyses (from garnet-bearing amphibolite samples)

Sample #	806-7A				J-12-2				J-6-3			
	rim avg n=8	std dev	core avg n=4	std dev	rim avg n=5	std dev	core avg n=10	std dev	rim avg n=21	std dev	core avg n=7	std dev
SiO ₂	37.20	0.31	36.92	0.17	37.07	0.38	37.35	0.37	36.84	0.36	36.77	0.17
Al ₂ O ₃	20.95	0.18	21.00	0.33	21.12	0.24	21.07	0.33	20.74	0.25	20.59	0.30
TiO ₂	0.03	0.06	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00
FeO*	30.14	0.60	29.18	0.40	26.11	0.43	24.56	0.40	31.35	0.47	30.25	0.78
MnO	3.34	0.19	4.28	0.35	4.54	0.32	4.63	0.35	2.85	0.17	3.01	0.14
MgO	1.05	0.18	1.09	0.07	0.57	0.12	0.60	0.07	1.08	0.10	1.03	0.10
CaO	7.91	0.52	7.73	0.22	10.27	0.45	12.01	0.22	6.73	0.30	7.65	0.81
TOTAL	100.62	0.74	100.19	0.57	99.69	0.69	100.26	0.57	99.59	0.71	99.30	0.58
formula based on 12 oxygens												
Si	2.98	0.01	2.98	0.02	2.98	0.02	2.98	0.02	2.99	0.02	2.99	0.02
Al	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01
Sum Z	3.00	0.00	3.00	0.00	3.00	0.01	3.00	0.00	3.00	0.02	3.00	0.01
Al	1.97	0.01	1.97	0.02	1.99	0.01	1.97	0.02	1.97	0.01	1.96	0.02
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	1.97	0.01	1.97	0.02	1.99	0.01	1.97	0.02	1.97	0.01	1.96	0.02
Fe*	2.02	0.04	1.97	0.02	1.76	0.03	1.64	0.02	2.13	0.03	2.06	0.05
Mn	0.23	0.01	0.29	0.03	0.31	0.02	0.31	0.03	0.20	0.01	0.21	0.01
Mg	0.13	0.02	0.13	0.01	0.07	0.01	0.07	0.01	0.13	0.01	0.13	0.01
Ca	0.68	0.04	0.67	0.02	0.89	0.03	1.03	0.02	0.59	0.03	0.67	0.07
Sum Fe to Ca	3.06	0.02	3.06	0.02	3.02	0.03	3.05	0.02	3.04	0.02	3.06	0.01
Fe/(Fe+Mg)	0.94	0.01	0.94	0.00	0.96	0.01	0.96	0.00	0.94	0.01	0.94	0.01
Mg/(Fe+Mg)	0.06	0.01	0.06	0.00	0.04	0.01	0.04	0.00	0.06	0.01	0.06	0.01
almandine	0.66	0.01	0.64	0.01	0.58	0.01	0.54	0.01	0.70	0.01	0.67	0.02
spessartine	0.07	0.00	0.10	0.01	0.10	0.01	0.10	0.01	0.06	0.00	0.07	0.00
pyrope	0.04	0.01	0.04	0.00	0.02	0.00	0.02	0.00	0.04	0.00	0.04	0.00
grossular	0.22	0.01	0.22	0.01	0.29	0.01	0.34	0.01	0.19	0.01	0.22	0.02

* all iron is considered Fe²⁺

almandine=Fe/(Fe+Mn+Mg+Ca)

spessartine=Mn/(Fe+Mn+Mg+Ca)

pyrope=Mg/(Fe+Mn+Mg+Ca)

grossular=Ca/(Fe+Mn+Mg+Ca)

Table C.4: Representative Biotite Analyses
(from garnet-bearing amphibolite samples)

Sample #	806-7A		J-12-2		J-6-3	
	aveg n=5	std dev	aveg n=5	std dev	aveg n=11	std dev
SiO ₂	34.66	0.24	34.36	0.17	33.09	0.39
Al ₂ O ₃	17.17	0.27	16.47	0.24	16.70	0.16
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00
TiO ₂	2.62	0.25	2.53	0.14	2.47	0.17
FeO*	26.26	0.25	26.14	0.25	30.36	0.55
MnO	0.06	0.07	0.14	0.09	0.00	0.01
MgO	5.61	0.38	5.83	0.04	4.30	0.20
CaO	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	9.59	0.08	9.22	0.27	8.09	0.37
Na ₂ O	0.00	0.00	0.00	0.00	1.01	0.27
Cl	0.04	0.03	0.00	0.00	0.00	0.00
total	96.02	0.31	94.68	0.22	96.06	0.47
formula based on 11 oxygens						
Si	2.72	0.01	2.73	0.01	2.65	0.04
Al	1.28	0.01	1.27	0.01	1.35	0.04
Sum	4.00	0.00	4.00	0.00	4.00	0.00
Al	0.31	0.02	0.28	0.02	0.23	0.02
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.15	0.02	0.15	0.01	0.15	0.02
Fe ²⁺	1.72	0.02	1.74	0.02	2.03	0.08
Mn	0.00	0.00	0.01	0.01	0.00	0.01
Mg	0.66	0.04	0.69	0.00	0.51	0.05
Sum	2.85	0.01	2.87	0.02	2.92	0.08
Ca	0.00	0.00	0.00	0.00	0.00	0.00
K	0.96	0.01	0.94	0.03	0.83	0.07
Na	0.00	0.00	0.00	0.00	0.16	0.09
Sum	0.96	0.01	0.94	0.03	0.98	0.13
Cl	0.01	0.00	0.00	0.00	0.00	0.00
Fe/(Fe+Mg)	0.72	0.01	0.72	0.00	0.80	0.01
Mg/(Fe+Mg)	0.28	0.01	0.28	0.00	0.20	0.01

* all iron is considered Fe²⁺

Table C.5: Representative Ilmenite Analyses

Metamorphic Zone		"unrecrystallized"										amphibolite J-6-4				gamet-bearing amphibolites J-6-3			
Sample #		I-302-1		I-305-1		813-1D		814-1		J-1-2		J-31-1		J-6-4		J-6-3		J-12-2	
		aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev
		n=10		n=9		n=9		n=5		n=9		n=9		n=6		n=8		n=10	
TiO ₂		50.40	0.31	51.70	0.27	53.07	0.82	53.89	1.73	51.67	1.16	51.88	0.43	51.99	0.42	51.80	0.24	52.48	0.33
Cr ₂ O ₃		0.19	0.04	0.22	0.07	0.05	0.02	0.13	0.04	0.09	0.04	0.07	0.04	0.13	0.03	0.04	0.07	0.01	0.02
FeO*		46.51	0.31	47.93	0.38	43.72	1.17	40.93	2.88	44.08	0.87	45.52	0.83	46.13	0.09	46.32	0.41	45.84	0.37
MnO		0.79	0.13	1.06	0.17	3.47	0.17	4.53	1.48	2.88	0.97	2.12	0.84	2.24	0.10	1.28	0.27	2.09	0.12
MgO		0.70	0.15	0.45	0.09	0.68	0.08	0.24	0.12	0.79	0.53	0.60	0.09	0.39	0.17	0.51	0.07	0.23	0.15
total		98.59	0.51	101.36	0.51	100.99	1.18	99.72	1.74	99.50	1.64	100.19	0.60	100.88	0.43	99.95	0.21	100.64	0.54
*all iron is considered Fe ²⁺																			
formula based on 3 oxygens																			
Ti		0.97	0.00	0.97	0.00	0.99	0.01	1.02	0.03	0.98	0.01	0.98	0.00	0.98	0.00	0.99	0.00	0.99	0.00
Cr		0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺		1.00	0.00	1.00	0.01	0.91	0.02	0.86	0.06	0.93	0.00	0.96	0.02	0.97	0.00	0.98	0.01	0.96	0.01
Mn		0.02	0.00	0.02	0.00	0.07	0.00	0.10	0.03	0.07	0.00	0.05	0.02	0.05	0.00	0.03	0.01	0.04	0.00
Mg		0.03	0.01	0.02	0.00	0.03	0.00	0.01	0.00	0.03	0.02	0.02	0.00	0.01	0.01	0.02	0.00	0.01	0.01
total		2.02	0.00	2.03	0.01	2.01	0.01	1.98	0.03	2.02	0.01	2.01	0.00	2.02	0.00	2.01	0.00	2.01	0.00
Fe ²⁺ and Fe ³⁺ calculated by Droop's (1987) Method																			
Sample #		aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev	aveg	std dev
		n=10		n=9		n=9		n=5		n=9		n=9		n=6		n=8		n=10	
TiO ₂		50.40	0.31	51.70	0.27	52.96	0.97	53.89	1.73	51.78	1.19	51.88	0.43	51.99	0.42	51.80	0.24	52.48	0.33
Cr ₂ O ₃		0.19	0.04	0.22	0.07	0.05	0.03	0.13	0.04	0.09	0.04	0.07	0.04	0.13	0.03	0.04	0.02	0.01	0.02
Fe ₂ O ₃		3.55	0.49	3.68	0.46	1.24	0.78	0.29	0.55	2.47	1.69	2.25	0.26	2.67	0.69	2.15	0.55	1.30	0.62
FeO		43.32	0.46	44.62	0.38	42.60	0.96	40.68	2.58	41.96	2.01	43.50	1.01	43.73	0.66	44.39	0.51	44.67	0.33
MnO		0.79	0.13	1.06	0.17	3.47	0.18	4.53	1.48	3.19	0.14	2.12	0.84	2.24	0.10	1.28	0.27	2.09	0.12
MgO		0.70	0.15	0.45	0.09	0.68	0.08	0.24	0.12	0.79	0.53	0.60	0.09	0.39	0.17	0.51	0.07	0.23	0.15
total		98.95	0.52	101.72	0.53	101.00	1.23	99.75	1.75	100.28	1.01	100.42	0.58	101.14	0.41	100.17	0.23	100.78	0.56
formula based on 3 oxygens																			
Ti		0.96	0.00	0.96	0.00	0.99	0.01	1.02	0.03	0.98	0.02	0.98	0.00	0.97	0.01	0.98	0.01	0.99	0.01
Cr		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺		0.07	0.01	0.07	0.01	0.02	0.01	0.01	0.01	0.05	0.03	0.04	0.01	0.05	0.01	0.04	0.01	0.02	0.01
total		1.04	0.01	1.04	0.00	1.01	0.01	1.02	0.02	1.02	0.02	1.02	0.00	1.03	0.01	1.02	0.01	1.01	0.01
Fe ³⁺		0.92	0.01	0.92	0.01	0.88	0.01	0.85	0.05	0.88	0.04	0.91	0.02	0.91	0.01	0.93	0.01	0.93	0.01
Mn		0.02	0.00	0.02	0.00	0.07	0.00	0.10	0.03	0.07	0.00	0.05	0.02	0.05	0.00	0.03	0.01	0.04	0.00
Mg		0.03	0.01	0.02	0.00	0.03	0.00	0.01	0.00	0.03	0.02	0.02	0.00	0.01	0.01	0.02	0.00	0.01	0.01
total		0.97	0.01	0.96	0.00	0.98	0.01	0.96	0.05	0.98	0.02	0.98	0.00	0.97	0.01	0.98	0.01	0.99	0.01

Table C.6: Representative Titanite Analyses

metamorphic zone sample	greenschist 814-1		amphibolite J-39-2		amphibolite 806-2		amphibolite J-6-4		garnet-bearing amphibolite J-12-2	
	aveg n=9	std dev	aveg n=10	std dev	aveg n=10	std dev	aveg n=10	std dev	aveg n=10	std dev
SiO ₂	29.50	0.24	30.97	3.82	30.13	0.17	29.77	0.34	29.27	0.41
Al ₂ O ₃	0.86	0.15	2.64	2.95	1.09	0.22	1.37	0.21	1.42	0.28
TiO ₂	39.66	0.34	36.28	6.08	38.56	0.54	37.92	0.33	39.12	0.96
FeO*	0.24	0.11	1.38	2.31	0.37	0.07	0.26	0.07	0.80	0.80
MnO	0.04	0.06	0.09	0.12	0.03	0.04	0.02	0.03	0.05	0.04
CaO	27.83	0.23	25.90	2.91	28.16	0.25	28.13	0.31	27.40	0.63
Cl	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.01	0.01
TOTAL	98.16	0.63	97.27	2.08	98.34	0.69	97.48	0.85	98.06	0.65
Formula based on 20 oxygens										
Si	3.93	0.02	4.12	0.44	4.00	0.01	3.99	0.01	3.90	0.06
Al	0.07	0.02	0.07	0.05	0.01	0.01	0.01	0.01	0.09	0.04
sum	4.00	0.00	4.19	0.40	4.00	0.01	4.00	0.00	4.00	0.01
Al	0.06	0.03	0.34	0.49	0.17	0.04	0.20	0.04	0.13	0.08
Ti	3.97	0.02	3.64	0.62	3.85	0.04	3.82	0.04	3.92	0.08
Fe	0.03	0.01	0.16	0.27	0.04	0.01	0.03	0.01	0.09	0.09
sum	4.06	0.02	4.13	0.18	4.06	0.02	4.05	0.01	4.14	0.10
Mn	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Ca	3.97	0.02	3.70	0.43	4.00	0.02	4.03	0.02	3.92	0.08
sum	3.97	0.02	3.71	0.43	4.01	0.02	4.04	0.02	3.92	0.08
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* all iron is considered to be Fe²⁺

APPENDIX D

A list of all the equilibria generated by the program "TWEEQU" (Berman 1988,1991) using the amphibole (analysis #8, see Plate 7.1c and Table C.1) and plagioclase (analysis #8, see Plate 7.1c and Table C.2) analyses from sample J-6-4 from the amphibolite zone. For a diagram of the equilibria see Figure 7.1 (inset of Figure 7.2) and Figure D.1. The symbols used for the mineral names are those used in the TWEEQU program and are listed in the List of Symbols on page xx.

- 1) $8 \alpha qz + 2 \text{parg} = \text{tsc} + \text{tr} = 2 \text{ab}$
- 2) $21 \text{ab} + 15 \text{sph} + 3 \text{fetr} + 28 \text{tsc} = 21 \text{parg} + 74 \alpha qz + 15 \text{ilm} + 35 \text{an} + 10 \text{w}$
- 3) $3 \text{ab} + 3 \text{sph} + 4 \text{tsc} + \text{fets} = 3 \text{parg} + 10 \alpha qz + 3 \text{ilm} + 7 \text{an} + 2 \text{w}$
- 4) $3 \text{fepa} + 20 \text{tsc} + 12 \text{sph} + 12 \text{ab} = 28 \text{an} + 12 \text{ilm} + 40 \alpha qz + 15 \text{parg} + 8 \text{w}$
- 5) $10 \text{ab} + 60 \text{sph} + 12 \text{fetr} + 75 \text{tsc} = 0 \text{parg} + 37 \text{tr} + 60 \text{ilm} + 140 \text{an} + 40 \text{w}$
- 6) $20 \alpha qz + 30 \text{sph} + 6 \text{fetr} + 35 \text{tsc} = 21 \text{tr} + 30 \text{ilm} + 70 \text{an} + 20 \text{w}$
- 7) $150 \alpha qz + 15 \text{sph} + 3 \text{fetr} + 35 \text{parg} = 28 \text{tr} + 15 \text{ilm} + 35 \text{an} + 35 \text{ab} + 10 \text{w}$
- 8) $2 \text{ab} + 12 \text{sph} + 11 \text{tsc} + 4 \text{fets} = 2 \text{parg} + 5 \text{tr} + 12 \text{ilm} + 28 \text{an} + 8 \text{w}$
- 9) $4 \alpha qz + 6 \text{sph} + 5 \text{tsc} + 2 \text{fets} = 3 \text{tr} + 6 \text{ilm} + 14 \text{an} + 4 \text{w}$
- 10) $22 \alpha qz + 3 \text{sph} + \text{fets} + 5 \text{parg} = 4 \text{tr} + 3 \text{ilm} + 7 \text{an} + 5 \text{ab} + 2 \text{w}$
- 11) $2 \text{ab} + 12 \text{sph} + 15 \text{tsc} + 3 \text{fepa} = 5 \text{parg} + 5 \text{tr} + 12 \text{ilm} + 28 \text{an} + 8 \text{w}$
- 12) $8 \alpha qz + 12 \text{sph} + 14 \text{tsc} + 3 \text{fepa} = 3 \text{parg} + 6 \text{tr} + 12 \text{ilm} + 28 \text{an} + 8 \text{w}$
- 13) $120 \alpha qz + 12 \text{sph} + 25 \text{parg} + 3 \text{fepa} = 20 \text{tr} + 12 \text{ilm} + 28 \text{an} + 28 \text{ab} + 8 \text{w}$
- 14) $40 \alpha qz + 24 \text{sph} + 25 \text{tsc} + 6 \text{fepa} = 15 \text{tr} + 24 \text{ilm} + 56 \text{an} + 6 \text{ab} + 16 \text{w}$
- 15) $6 \text{parg} + 5 \text{fets} + 24 \alpha qz = 6 \text{ab} + 3 \text{fetr} + 8 \text{tsc}$

- 16) $6 \text{ ab} + 36 \text{ sph} + 8 \text{ tsc} + 37 \text{ fets} = 6 \text{ parg} + 15 \text{ fetr} + 36 \text{ ilm} + 84 \text{ an} + 24 \text{ w}$
- 17) $4 \alpha\text{qz} + 6 \text{ sph} + 7 \text{ fets} = 3 \text{ fetr} + 6 \text{ ilm} + 14 \text{ an} + 4 \text{ w}$
- 18) $5 \text{ fepa} + 3 \text{ parg} + 32 \alpha\text{qz} = 8 \text{ ab} + 4 \text{ fetr} + 4 \text{ tsc}$
- 19) $8 \text{ ab} + 48 \text{ sph} + 60 \text{ tsc} + 37 \text{ fepa} = 45 \text{ parg} + 20 \text{ fetr} + 48 \text{ ilm} + 112 \text{ an} + 32 \text{ w}$
- 20) $21 \text{ fepa} + 28 \text{ tsc} + 24 \text{ sph} + 16 \alpha\text{qz} = 56 \text{ an} + 24 \text{ ilm} + 12 \text{ fetr} + 21 \text{ parg} + 16 \text{ w}$
- 21) $30 \alpha\text{qz} + 3 \text{ sph} + 7 \text{ fepa} = 5 \text{ fetr} + 3 \text{ ilm} + 7 \text{ an} + 7 \text{ ab} + 2 \text{ w}$
- 22) $4 \text{ fets} + 3 \text{ parg} = 3 \text{ fepa} + 4 \text{ tsc}$
- 23) $3 \text{ ab} + 3 \text{ sph} + 5 \text{ fets} = 3 \text{ fepa} + 10 \alpha\text{qz} + 3 \text{ ilm} + 7 \text{ an} + 2 \text{ w}$
- 24) $5 \text{ fets} + 3 \text{ tr} = 3 \text{ fetr} + 5 \text{ tsc}$
- 25) $40 \alpha\text{qz} + 3 \text{ fetr} + 10 \text{ parg} = 5 \text{ fets} + 8 \text{ tr} + 10 \text{ ab}$
- 26) $10 \text{ ab} + 60 \text{ sph} + 8 \text{ tr} + 75 \text{ fets} = 10 \text{ parg} + 33 \text{ fetr} + 60 \text{ ilm} + 140 \text{ an} + 40 \text{ w}$
- 27) $5 \text{ fepa} + 4 \text{ tr} = 4 \text{ fetr} + 5 \text{ parg}$
- 28) $10 \text{ fepa} + 3 \text{ tr} + 40 \alpha\text{qz} = 10 \text{ ab} + 8 \text{ fetr} + 5 \text{ tsc}$
- 29) $2 \text{ ab} + 12 \text{ sph} + 4 \text{ fetr} + 15 \text{ tsc} = 2 \text{ fepa} + 9 \text{ tr} + 12 \text{ ilm} + 28 \text{ an} + 8 \text{ w}$
- 30) $3 \text{ fepa} + 5 \text{ parg} + 32 \alpha\text{qz} = 8 \text{ ab} + 4 \text{ tr} + 4 \text{ fets}$
- 31) $24 \alpha\text{qz} + 5 \text{ tsc} + 6 \text{ fepa} = 8 \text{ fets} + 3 \text{ tr} + 6 \text{ ab}$
- 32) $8 \text{ ab} + 48 \text{ sph} + 60 \text{ fets} + 25 \text{ parg} = 33 \text{ fepa} + 20 \text{ tr} + 48 \text{ ilm} + 112 \text{ an} + 32 \text{ w}$
- 33) $6 \text{ ab} + 36 \text{ sph} + 25 \text{ tsc} + 20 \text{ fets} = 6 \text{ fepa} + 15 \text{ tr} + 36 \text{ ilm} + 84 \text{ an} + 24 \text{ w}$
- 34) $16 \alpha\text{qz} + 24 \text{ sph} + 28 \text{ fets} + 15 \text{ parg} = 15 \text{ fepa} + 12 \text{ tr} + 24 \text{ ilm} + 56 \text{ an} + 16 \text{ w}$
- 35) $8 \alpha\text{qz} + 2 \text{ fepa} = \text{fets} + \text{fetr} + 2 \text{ ab}$
- 36) $2 \text{ ab} + 12 \text{ sph} + 15 \text{ fets} = 2 \text{ fepa} + 5 \text{ fetr} + 12 \text{ ilm} + 28 \text{ an} + 8 \text{ w}$

Figure D.1: A larger, more detailed version of Figure 7.1, showing all of the equilibria generated by TWEEQU using the amphibole (analysis #8, see plate 7.1c and Table C.1) and plagioclase (analysis #8, see Plate 7.1c, Table C.2) analyses from amphibolite zone sample J-6-4. The numbers labeling the equilibria correspond to those listed on the previous two pages.

END

2 1 - 1 1 - 9 6

FIN