INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

Metamorphism of the Proterozoic Rocks Associated with the Sudbury Structure

by

Zsuzsanna Magyarosi

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
March, 1998

© 1998, Zsuzsanna Magyarosi

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-32431-1

The undersigned hereby recommend to
The Faculty of Graduate Studies and Research
acceptance of the thesis

**Metamorphism and Deformation of the Rocks Associated with the Sudbury
Structure**

submitted by
Zsuzsanna Nagygyarosi
in partial fulfilment of the requirements
for the degree of Master of Science

Chairman,
Department of Earth Sciences

Thesis Supervisor

Carleton University

April, 1998

ABSTRACT

In the area near Worthington, 5 km southwest of the Sudbury Structure, five metamorphic zones were mapped in metapelites: 1. Chlorite - biotite zone, 2. Garnet zone, 3. Chloritoid zone, 4. Staurolite - chlorite zone, and 5. Staurolite - biotite zone.

The temperature and pressure of peak metamorphism were estimated using TWEEQU, INVEQ and the garnet - biotite thermometer. The temperature ranged between 443 and 571 °C and the pressure ranged between 2463 and 4630 bars. The field observations and detailed petrography suggest that the metamorphism was syndeformational.

The sequence of the assemblages and isograds in the Worthington area is consistent with the metamorphic grids of Albee (1965, 1972), Kepezhinskis and Khlestov (1977), Harte and Hudson (1979) and Stuwe and Ehlers (1997); it does not support the grid of Spear and Cheney (1989) and Wang and Spear (1991).

Detailed petrography of the Sudbury Breccia from the Worthington area and the deformation and metamorphism of the Whitewater Group suggest that the Sudbury Structure and the rocks of the Southern Province were metamorphosed during the Penokean Orogeny. The grade of metamorphism in the South Range of the Sudbury Structure decreases from amphibolite (southeast) to lower greenschist (middle of the Basin); in the North Range it increases again and reaches amphibolite facies metamorphism northeast of the Sudbury Structure on the basis of tremolite - talc - calcite assemblages in metacarbonates of the Espanola Formation.

ACKNOWLEDGMENTS

First of all, I would like to thank my supervisor Dr. George Skippen for providing me the opportunity to do a Masters, for his financial support and all of the helpful consultations.

Many thanks goes to Dr. Dave Watkinson for all of his support, advice and encouragement throughout the whole project.

Wanda Carter is thanked for her assistance in the field during the summer of 1996, for staying calm in every crazy situation, for carrying the rocks and paddling in the Spanish River.

I thank all of the support staff at Carleton University including Peter Jones for his assistance on the Scanning Electron Microprobe, Mike Jackson and Anette Briggs for preparing the samples, Dan Marshall for his help with the computers and Sheila Thayer for helping me with all kinds of administrative problems.

I would like to thank all of my friends at Carleton for their support during the whole time and for all of the fun we had together. You made my life very enjoyable.

A special thanks goes to my family, especially my mother, for supporting me and for their faith in me.

TABLE OF CONTENTS

	page
Table of Contents	v
List of Figures	vii
List of Tables	ix
List of Photos	x
List of Appendices	xi
Symbols	xii
 CHAPTER 1: INTRODUCTION	 1
1.1. Purpose of the Thesis	1
1.2. Location	
1.3. Regional Geology	3
1.3.1. Regional Structural Geology	6
1.3.2. Metamorphism of the Southern Province	6
1.3.3. Deformation and Metamorphism of the Sudbury Basin	9
1.3.4. Chronology of Events in the Sudbury-Cutler Area and the Sudbury Basin	9
1.4. Geology of Drury and Lorne Townships	12
1.4.1. Stratigraphy	12
1.4.2. Structural Geology of the Area	13
1.4.3. Metamorphism	14
 CHAPTER 2: METAMORPHIC MAP OF THE WORTHINGTON AREA	 15
2.1. Chlorite - Biotite Zone	15
2.2. Garnet Zone	15
2.3. Chloritoid Zone	19
2.4. Staurolite - Chlorite Zone	20
2.5. Staurolite - Biotite Zone	20
2.6. Discussion	21
 CHAPTER 3: PETROGRAPHY AND GEOCHEMISTRY	 23
3.1. McKim Pelites in the Worthington Area	23
3.1.1. Deformation and Metamorphism	23
3.1.2. AFM Diagrams	28

3.2. Sudbury Breccia in McKim Pelites	28
	page
3.3. Sudbury Structure	32
3.4.1. Onwatin Formation	32
3.4.2. Onaping Formation	33
3.4. Calc - Silicate Samples of the Espanola Formation Northeast of the Sudbury Structure	33
 CHAPTER 4: THERMOBAROMETRY	 37
4.1. Methods	37
4.2. Results	40
4.2.1. Worthington Area	40
4.2.2. Samples of the Onaping Formation and from the Lindsley, Vermilion and Copper Cliff South Mines	45
4.3. Discussion of the Results	45
4.4. Estimation of the Temperature from the Espanola Formation Samples Northeast of the Sudbury Structure	50
 CHAPTER 5: COMPARISON OF THE WORTHINGTON AREA TO OTHER METAMORPHIC GRIDS FOR PELITES	 53
 CHAPTER 6: TEMPORAL RELATIONSHIP OF THE PENOEKIAN OROGENY RELATIVE TO THE SUDBURY EVENT	 65
6.1. Sudbury Breccia	65
6.2. Rocks of the Sudbury Basin	66
6.3. Discussion	66
 CHAPTER 7: CONCLUSIONS	 72
 REFERENCES	 74
 APPENDICES	 80

LIST OF FIGURES

	page
Figure 1: Areas of study	2
Figure 2: The eastern Southern Province	2
Figure 3: Subdivision of the Penokean Fold Belt	7
Figure 4: Distribution of metamorphic zones in the eastern Southern Province	7
Figure 5: Metamorphic zones and isograds in Worthington area	17
Figure 6: The composition of the minerals in garnet zone represented on an AFM diagram	29
Figure 7: The composition of the minerals in chloritoid zone represented on an AFM diagram	29
Figure 8: The composition of the minerals in staurolite zone represented on an AFM diagram	29
Figure 9: The appearance of the staurolite - biotite assemblage	29
Figure 10: Sequence of the reactions and assemblages in the Worthington area represented on AFM diagrams	30
Figure 11: Free energy surfaces of minerals represented in composition - free energy space	39
Figure 12: Partial molar free energies of the end-members of two minerals in equilibrium	39
Figure 13: A single equilibrium that corresponds to a single pair of intersecting tie lines in the equilibrium tangent plane	39
Figure 14: The "best fit" plane to partial molar free energies of the end-members	39
Figure 15: The misfit of each individual end-member	39
Figure 16: TWEEQU plot of sample H-1 from Worthington area	43

	page
Figure 17: TWEEQU plot of sample H-4 from Worthington area	43
Figure 18: TWEEQU plot of sample N-8 from Worthington area	44
Figure 19: TWEEQU plot of sample AE-2 from Worthington area	44
Figure 20: Temperature and pressure results in Worthington area	46
Figure 21: Metamorphic grid for calc-silicates	51
Figure 22: Sequence of the reactions in the KFMASH system	54
Figure 23: Sequence of the assemblages and reactions in the Worthington area	56
Figure 24: The Albee grid	57
Figure 25: The Kepezhinskas and Khlestov and the Harte and Hudson grids	57
Figure 26: The grids of Spear and Cheney, and Wang and Spear	59
Figure 27: The Powell and Holland grid	61
Figure 28: The grid of Stuwe and Ehlers	63
Figure 29: Metamorphism and deformation of the Sudbury Structure and the rocks of the Southern Province	68
Figure 30: TWEEQU plot of sample N-8 with a simple activity model for chlorite	88
Figure 31: TWEEQU plot of sample N-8 with the chlorite activity model of Holland and Powell (1990) with no amesite	88
Figure 32: TWEEQU plot of sample N-8 with the chlorite activity model of Holland and Powell (1990) with amesite	88

LIST OF TABLES

	page
Table 1: Stratigraphy of the Huronian Supergroup	5
Table 2: Chronology of Events in the Sudbury - Cutler area and the Sudbury Basin	10
Table 3: Mineral assemblages in each metamorphic zone in Worthington area	16
Table 4: Mineralogy of the samples used for petrography in Worthington area	24
Table 5: Mineralogy of the calc-silicate samples of Espanola Formation northeast of the Sudbury Structure	35
Table 6: Composition of the garnets in Worthington area	41
Table 7: Pressure and temperature results estimated by samples from Worthington area used for thermobarometry	41
Table 8: Temperature results estimated by samples of Onaping Formation, Lindsley Mine, Vermilion Mine and Copper Cliff South Mine	48
Table 9: Composition of the garnets and biotites in samples of Onaping Formation, Lindsley Mine, Vermilion Mine and Copper Cliff South Mine	49

LIST OF PHOTOS

	Page
Photo 1 . a. Chloritoid porphyroblast (Sample R1-3a)	26
b. Same as the previous photo under crossed polars.	26
c. Abundant chloritoid pophyroblasts (Sample Z-2)	26
d. Same as the previous photo under crossed polars.	26
 Photo 2. a. Abundant staurolite porphyroblasts (Sample W-5)	 27
b. Muscovite and chlorite forming pseudomorph after staurolite. (Sample R-4)	27
c. Staurolite porphyroblasts (Sample W-5)	27
 Photo 3. a. Sudbury Breccia in Worthington area	 31
b. Same as the previous photos	31
c. Garnet porphyroblast in the chloritoid zone (Sample N-8)	31
d. Garnet porphyroblast in the garnet zone (Sample H-1)	31
 Photo 4. a. and b. Euhedral garnet porphyroblasts in the Onaping Formation. (Sample AV-605)	 34
c. Talc and dolomite in siliceous marbles (Sample ESP-1)	34
d. Amphibole (Mg-rich actinolite) with calcite in the siliceous marble (Sample ESP-2)	34

LIST OF APPENDICES

APPENDIX 1: Description of the minerals in the Worthington area	80
APPENDIX 2: Description of the minerals in the Espanola Formation	84
APPENDIX 3: Activity of chlorite	86
APPENDIX 4: Composition of plagioclase	89
APPENDIX 5: Composition of muscovite	91
APPENDIX 6: Composition of chlorite	92
APPENDIX 7: Composition of biotite	95
APPENDIX 8: Composition of garnet	97
APPENDIX 9: Composition of chloritoid	99
APPENDIX 10: Composition of staurolite	100
APPENDIX 11: Composition of amphibole	101

SYMBOLS

p = pressure

T = temperature

t = time

b.y. or G.a. = billion years

TWEEQU = Thermobarometry With Estimation of Equilibration

INVEQ = Inverse Chemical Equilibrium

Als = Aluminosilicates

Cd = Cordierite

Tc = Talc

AFM diagrams = Minerals and bulk compositions plot in Al, Fe and Mg triangular diagrams

The symbols for the rest of the minerals are used according to Kretz (1983)

CHAPTER 1: INTRODUCTION

1.1 Purpose of the thesis

The main purpose of this thesis is to examine the metamorphic history of the rocks of the Sudbury - Cutler area and the Sudbury Basin. Further objectives are the construction of the pressure (p) - temperature (T) - time (t) path for surface rocks and a comparison of the metamorphic histories of rocks within the Sudbury Structure and adjacent rocks from the Southern Province. The timing of the metamorphism in the Sudbury area is a matter of debate. Some scientists suggest that the Sudbury Basin and the Southern Province experienced the same metamorphic history (Brocoum and Dalziel, 1974). Card (1978) and Morris (1984) propose that the Penokean Orogeny started before the Sudbury Event and affected the Sudbury Basin to a lesser extent. A comparison of the metamorphism of rocks within the Sudbury Basin with rocks adjacent to the Basin is therefore included in this study.

Another aspect of this work is the petrology of rocks involving the phases quartz, muscovite, plagioclase, garnet, chlorite, chloritoid, biotite and staurolite. The phase relations among these minerals have not yet been established due to a lack of thermodynamic data. The present field study will document the sequence of mineral assemblages observed in the Southern Province to the west of the Sudbury Structure near Worthington, Ontario.

1.2 Location

The main area of study, the Worthington area, is located 5 km west of the Sudbury Structure, along the High Falls Road near the town of Worthington (figure 1). It includes

Figure 1: Areas of study: 1. Worthington area, 2. Calc-silicate samples of the Espanola Formation, 3. Onaping Formation samples, 4. Vermilion Mine, 5. Lindsley Mine, 6. Copper Cliff South Mine

Figure 2: The eastern Southern Province (Bennett et al., 1991)

the southern part of Drury Township, the southeastern part of Hyman Township into the Agnew Lake area, and the northern part of Lorne Township. The area contains mainly pelitic rocks, which are intruded by Nipissing Diabase and Olivine Diabase dykes of the Sudbury Swarm. A further area of interest is within the Sudbury Basin, in the Whitewater Group. Samples from outside the Sudbury Basin were collected along Highway 17 west of Sudbury, along highway 114 northwest of Sudbury and from the Lindsley, Vermilion and Copper Cliff South mines. Metacarbonate rocks of the Espanola Formation to the northeast of the Sudbury Structure were also studied.

1.3 Regional Geology

The Southern Province consists of all rocks that have been affected by the Penokean Orogeny; it forms a belt extending from Minnesota to the Cobalt- Noranda area, 1280 km long and up to 440 km wide (Card et al., 1972), (figure 1). To the north it unconformably overlies the Superior Province, which consists of Archean granites, metavolcanics and metasediments. To the south and southeast it is bounded by the Grenville Province; the zone of contact is called the Grenville Front (Easton, 1992). Phanerozoic sediments unconformably overlie the Southern Province to the south.

The rocks of the Southern Province consist of clastic sediments, minor tholeiitic volcanic and intrusive rocks (Card et al., 1972, Bennett et al., 1991). The source of the sediments is thought to be to the north-northwest within the rocks of the Superior Province (Card et al., 1972). The Southern Province is subdivided into five units: Port Arthur Homocline, Lake Superior Basin, Nipigon Basin, Penokean Fold Belt and Cobalt Plate (Card et al., 1972). Each of these units has a distinctive stratigraphy and shows a

different amount of deformation and grade of metamorphism (table 1). The eastern Southern Province (Penokean Fold Belt) consists of sediments of the Huronian Supergroup and Sudbury Basin (figure 2).

The rocks of the **Huronian Supergroup** were deposited between 2.5 b.y. ago, the youngest age for Archean rocks, and 2.219 b.y. ago, the age of Nipissing Diabase, which intrudes the Huronian rocks (Van Schmus, 1965, Fairbairn et al., 1969, Corfu and Andrews, 1986). The deposition was cyclical with four groups of formations, each of which proceeds from deposition in a deep water environment to deposition in shallow water: Elliot Lake Group, Hough Lake Group, Quirke Lake Group, and Cobalt Group (Robertson et al., 1969, Roscoe, 1969). The first three groups are known as the Bruce Series (Collins, 1925). According to Card (1978) the contacts between groups are conformable, but Zolnai (1984) argues that the contacts are unconformable.

The **Sudbury Basin** is an oval-shaped structure that is ~58 km long and ~26 km wide (Rousell, 1975). The Whitewater Group occurs within the Basin and consists of, from the bottom to the top, the Onaping, the Onwatin, and the Chelmsford formations (Rousell, 1972, Dressler et al., 1984). The Sudbury Basin was formed by the Sudbury Event (shock metamorphism), that resulted in the formation of Sudbury Breccia and intrusion of the Sudbury Igneous Complex. (Gibbins and McNutt, 1975b). The Basin overlies the Sudbury Igneous Complex, which intruded the Basin. The contacts within the Whitewater Series are thought to be conformable (Dressler et al., 1984).

COBALT GROUP**BAR RIVER FORMATION (sandstone)****GORDON LAKE FORMATION (siltstone)****LORRAIN FORMATION (sandstone)****GOWGANDA FORMATION (conglomerate, sandstone, siltstone)****QUIRKE LAKE GROUP****SERPENT FORMATION (sandstone)****ESPANOLA FORMATION (calcareous siltstone, limestone)****BRUCE FORMATION (conglomerate)****HOUGH LAKE GROUP****MISSISSAGI FORMATION (sandstone)****PECORS FORMATION (siltstone)****RAMSAY LAKE FORMATION (conglomerate)****ELLIOT LAKE GROUP****MCKIM FORMATION (greywacke, siltstone)****MATINENDA FORMATION (sandstone, conglomerate)****COPPER CLIFF FORMATION (mafic and felsic volcanics)****ELSIE MOUNTAIN - FROOD-STOBIE FORMATIONS (mafic
volcanics and greywacke)**

Table 1: Stratigraphy of the Huronian Supergroup (modified after Card, 1971a, 1971b)

1.3.1 Regional Structural Geology

The Penokean Fold Belt can be subdivided into three main tectonic zones based on the variations in intensity of deformation: the Sudbury - Espanola area, the Sault Ste. Marie - Elliot Lake area, and the Sudbury Basin (Card, 1978), (see figure 3).

The **Sudbury - Espanola** area is the most strongly deformed zone (Card, 1972). The faults of the Murray System subdivide it into two zones. In the southern subzone the faults and fold axes trend east-west, and the fold axes plunge gently. In the northern subzone, faults and fold axes trend east-northeast to northwest. Later folding trending east-west affected both subzones and the intensity of this later deformational event decreases from north to south. The Murray System consists of steeply dipping major faults striking east-west in the south and northeast-southwest in the north and east (Card, 1972). Repeated movements occurred along most of them (Card et al., 1972; Card, 1978). The initial movements probably downthrew to the south causing rapid thickening of Huronian formations across them (Card, 1978; Zolnai, 1984), (see figure 2).

1.3.2 Metamorphism of the Southern Province

Rocks of the Southern Province have been altered during Proterozoic orogenic events. The grade of metamorphism ranges from diagenesis to lower amphibolite facies (Card, 1978; Jackson and Henderson, 1993). According to Card, the rocks went through a "low pressure - intermediate temperature" metamorphism.

The rocks of the Sudbury - Espanola area represent the highest grade of metamorphism within the Penokean Fold Belt (Card, 1978). The grade varies from low

Figure 3: Subdivision of the Penokean Fold Belt (Card, 1978)

Figure 4: Distribution of metamorphic zones in the eastern Southern Province (Card, 1978)

greenschist (chlorite zone) to amphibolite facies (staurolite zone). Card describes the sequence of metamorphic zones found in the area: subgreenschist; chlorite, biotite; garnet, chloritoid and staurolite zones. The mineral assemblages along the Grenville Front reach hornblende hornfels facies. Kyanite is present in the Lorrain quartzite in the Whitefish Falls area (Card, 1978); the lack of kyanite elsewhere in the area suggests that kyanite at Espanola results from a locally higher pressure.

The pressure and temperature conditions were calculated in a few studies. Card (1964) said that the temperature was lower than 650°C , because no granitic melt was observed. Fox (1971), studying the rocks in the Agnew Lake area, estimated a temperature range between 500 and 550°C , and pressure between 4.45 and 4.75 kilobars. The basis of these estimations by Fox was the presence of the assemblage chloritoid, biotite, garnet, chlorite, which defines a univariant line in pressure - temperature space. He used the grid constructed by Albee (1965). Blonde (1996) studied the metamorphosed Nipissing Diabase in May Township, to the west of the present study. Blonde used plagioclase - amphibole thermobarometry to estimate a peak metamorphic condition of $580 \pm 60^{\circ}\text{C}$ and 4.3 ± 0.8 kilobars.

Metamorphic rocks are distinctive within each of the two tectonic subzones described above for the Sudbury - Espanola area. Rocks located north of the Murray Fault are within the greenschist facies (Card, 1978). South of the Murray Fault, higher grade rocks outcrop as elliptical "nodes" superimposed on the lower grade rocks. Blonde (1996) interpreted these nodes as tectonic windows through thrust sheets of varying metamorphic grade.

1.3.3 Deformation and metamorphism of the Sudbury Basin

The Sudbury Basin was deformed and metamorphosed during Proterozoic orogenic events (Card et al., 1972; Brocoum and Dalziel, 1974). The Sudbury Basin is located north of the Murray Fault, but major faults of the Murray System transect the Basin, parallel to the long axis of the Sudbury Basin (Rousell, 1975). Rocks in the South and East Ranges of the Sudbury Basin display foliation and lineation striking parallel to the long axis of the Basin (see figure 1); these structures gradually fade out as they pass into the North Range (Rousell, 1975). Northeasterly plunging folds are also present in the South Range; the axes of the folds are parallel to the foliation (Rousell, 1975).

The grade of metamorphism inside the Sudbury Basin ranges from lower to upper greenschist facies metamorphism and decreases toward the north (Rousell, 1975; Fleet et al., 1987). Rousell (1975) and Easton (1996) mapped the biotite isograd and suggested that the isograds are also parallel to the long axis of the Basin. As the Sudbury Igneous Complex in the North Range is approached, the metamorphic grade slightly increases again (Fleet et al., 1987). Cowan and Schwerdtner (1994) suggest that the Sudbury Basin originated by folding and ductile shear of a quasi-horizontal floor of a large crater, and attributed the distribution of metamorphism to this folding.

1.3.4 Chronology of events in the Sudbury - Cutler area and the Sudbury Basin

Table 2 shows the chronology of events in the Sudbury - Cutler area and the Sudbury Structure. The area was affected by an early deformation and low grade metamorphism, that happened after the intrusion of Murray and Creighton Plutons (2.33 b.y. ago) and before the intrusion of Nipissing Diabase (2.219 b.y. ago) (Card, 1978;

Events	Approximate Ages (Ga)
Grenville Orogeny	1.0 - 1.3
Olivine Diabase	1.47
Croker Complex	1.47
Deformation (part of Penokean Orogeny?)	
Cutler and Grenville Front Plutons	1.7
Penokean Orogeny (deformation and high grade metamorphism)	
Sudbury Event	1.85
Nipissing Diabase	2.219
Early deformation and low grade metamorphism	
Murray and Creighton Plutons	2.33
Deposition of Huronian Supergroup	2.5 - 2.21

Table 2: Chronology of events in the Sudbury - Cutler area and the Sudbury Basin

Jackson and Henderson, 1993). In the Huronian Supergroup, Card relates this early event to the formation of low grade minerals such as chlorite and muscovite, which define the layers in the McKim Formation that are later folded during the Penokean Orogeny.

The Sudbury Breccia in the McKim Formation and in the Murray and Creighton Plutons also shows evidence for an early deformation. One foliation observed only within the blocks is randomly oriented and is assumed to represent an early deformation that occurred before the brecciation; the main foliation cuts through both the blocks and the matrix with a consistent orientation and is assumed to represent the Penokean Orogeny (Brocoum and Dalziel, 1974, Card, 1978).

As further evidence for early deformation, Card (1978) observed that the Nipissing Diabase transects the axes of some major folds (McGregor Bay Anticline, Vernon Syncline) as well as the early foliation related to these folds, suggesting that the early foliation developed before the intrusion of the Nipissing Diabase (Card, 1978).

It is generally agreed (Brocoum and Dalziel, 1974; Card, 1978; Jackson and Henderson, 1993, Blonde, 1996) that the main metamorphism and deformation occurred after the intrusion of the Nipissing Diabase (2.219 b.y. ago) and before the intrusion of Olivine Diabase (1.46 b.y. ago). The timing of this major event with respect to the development of the Sudbury Structure is still a matter of debate.

Brocoum and Dalziel (1974) studied the deformation of the Sudbury Structure and they suggest that the Penokean Orogeny started shortly after the Sudbury Event. Fleet et al. (1987) studied the metamorphism of the Sudbury Igneous Complex and they proposed that the major metamorphism occurred after the intrusion of the Sudbury Igneous

Complex. The amphibolite grade, described by Fleet et al., indicates that the rocks of the Sudbury Igneous Complex now exposed at the surface were buried at considerable depth at the peak of metamorphism.

The Cutler and Grenville Front Plutons (1.7 b.y. ago) cut previously deformed Huronian rocks but the plutons are also deformed (Card, 1978). The deformation that affected the Cutler and Grenville Front Plutons is interpreted as the last phase of the Penokean Orogeny (Card, 1978), although the possibility cannot be ruled out that it is a separate and later event that followed the Penokean Orogeny.

The Croker Complex is not well exposed. Card (1965) suggests that it intruded after the major deformation and metamorphism (Penokean Orogeny).

The Olivine Diabase does not show any sign of deformation or metamorphism (Brocoum and Dalziel, 1974).

The last event affecting the area was the Grenville Orogeny (1.0 - 1.3 b.y. ago) involving deformation, high grade metamorphism and igneous activity south of the Grenville Front.

1.4 Geology of Drury and Lorne Townships

1.4.1 Stratigraphy

The oldest rocks in the area are granitic and metavolcanic rocks of the Archean Basement located in the northern part of Drury Township. To the south the contact with the other Huronian rocks is unconformable or faulted (Card, 1965).

Card (1965) and Ginn (1965) distinguish quartzite, pelite and conglomerate units.

Card (1965) correlated the quartzite with the Mississagi Formation, the pelitic unit with McKim Formation, and the conglomerate with Bruce and Ramsay Lake formations (see table 1). Ginn (1965) distinguishes lower, middle, and upper quartzite, as well as pelite and conglomerate units, but he did not correlate them with formations outside of the area. The quartzite consists of quartz-arenite, with some conglomerate and pelitic material, and abundant crossbedding in the upper part. The pelitic rocks lie conformably on the quartzite rocks. They consist of argillite, greywacke and subgreywacke. Usually they are thinly bedded, laminated, and show many other primary sedimentary structures such as crossbedding, ripple marks, grain gradation. The conglomerate contains pebbles and cobbles of granite, quartz, greenstone, and the matrix is composed of quartz, feldspar, and mica grains. The boundaries between metapelites and conglomerates, and metapelites and quartzites are gradational.

Gabbroic dikes of Nipissing Diabase and Olivine Diabase intrude the metasedimentary rocks. The Worthington Offset of the Sudbury Igneous Complex cuts through the southeast corner of Drury Township and the northern part of Lorne Township. In the northeast corner of Drury Township, the rocks of the Sudbury Igneous Complex are present.

1.4.2 Structural geology of the area

Card (1965) and Ginn (1965) described a series of folds trending northeast to east across the area. Generally the folds are open and gently plunging. Card (1965) divided the faults in Drury Township into three groups on the basis of their strike. Two groups trend

northeast, with small differences in orientation between them; the third group trends approximately north-south. The major faults of Drury Township trend northeast and dip vertically to steeply south.

Ginn (1965) also describes a set of faults in Lorne Township trending northwest and another trending north.

1.4.3 Metamorphism

Almost all the rocks of the area are metamorphosed. Generally the grade of metamorphism is higher in Drury Township. Card (1965) distinguished four metamorphic zones present in Drury Township: chlorite - biotite zone, garnet zone, chloritoid zone, and staurolite zone. The pelitic rocks show the greatest change during metamorphism. The major metamorphic event occurred after the emplacement of Nipissing Diabase, 2.219 b.y. ago, and before the intrusion of Olivine Diabase, 1.47 b.y. ago. Porphyroblasts of garnet, chloritoid, and staurolite are abundant in the pelitic rocks. Card (1978) described a prekinematic, synkinematic, and postkinematic growth of porphyroblasts; the pelitic rocks preserved their primary sedimentary structure but they show a strong foliation.

Card (1965) proposes a deformation and metamorphic history for the area through three events: 1. early "plastic" deformation, with major folds, and growth of low grade minerals such as chlorite and muscovite, 2. higher grade metamorphism causing the growth of biotite, garnet and staurolite, 3. "brittle" deformation and retrograde metamorphism; destroying higher grade minerals like garnet, biotite, staurolite.

CHAPTER 2: METAMORPHIC MAP OF THE WORTHINGTON AREA

Five metamorphic zones have been mapped in the Worthington area based on the mineral assemblages in the pelitic schists: chlorite - biotite zone, garnet zone, chloritoid zone, staurolite - chlorite zone and staurolite - biotite zone. The mineral assemblages based on petrographic study of the samples are summarized in table 3. The map is presented on figure 5.

2.1. Chlorite - biotite zone

The typical assemblage in the chlorite - biotite zone is quartz + plagioclase + muscovite + chlorite +/- biotite. Muscovite and sometimes chlorite define the foliation in this zone. The second generation of muscovite and chlorite and also biotite form porphyroblasts up to 1 mm in size. Chlorite is more abundant than biotite. The rocks display a foliation striking northeast - southwest and dipping steeply ($\sim 70^\circ$).

2.2. Garnet zone

In this zone the most common assemblage is quartz + plagioclase + muscovite + chlorite +/- biotite +/- garnet. In the map (figure 5) the garnet - in line represents the first appearance of garnet in the Worthington area, which is probably due to changes in the composition of the pelite. The garnet - containing samples are generally rich in quartz and coarser grained (average grainsize: 0.35 mm). Garnet forms porphyroblasts up to 5 mm in size and always appears with chlorite. Biotite is not always present and is often intergrown with chlorite that could be an alteration product after biotite. Garnet contains inclusions of quartz and opaque minerals such as pyrrhotite, ilmenite, chalcopyrite. Some of these

Zone	Assemblages
Chlorite - biotite zone	Qtz + pl + ms + chl
	Qtz + pl + ms + chl + bt
Garnet zone	Qtz + pl + ms + chl
	Qtz + pl + ms + chl + grt
	Qtz + pl + ms + chl + bt + grt
Chloritoid zone	Qtz + pl + ms + chl
	Qtz + pl + ms + chl + cld
	Qtz + pl + ms + chl + cld + st
	Qtz + pl + ms + chl + bt + grt
Staurolite - chlorite zone	Qtz + pl + ms + chl
	Qtz + pl + ms + chl + st
	Qtz + pl + ms + chl + bt + grt
Staurolite - biotite zone	Qtz + pl + ms + chl + st + bt

Table 3: Mineral assemblages in each metamorphic zone in Worthington area

Figure 5: Metamorphic zones and isograds in Worthington area

Legend of the map

Metamorphic zones

Isograds:

Isograds due to variations in composition.

Water

Reactions

- 1 Garnet - in reaction
- 2 Chloritoid - in reaction

Univariant reactions

- 3 Chloritoid = Garnet + Chlorite + Staurolite + H₂O
- 4 Garnet + Chlorite = Staurolite + Biotite + H₂O

Structural elements

Outcrop designation A., AE., G1 etc

inclusions are in equilibrium with garnet, but they are often located in the fractures of the garnet. Only one sample with garnet containing biotite inclusions was collected from this zone. Rocks in garnet zone are weakly to strongly deformed. The foliation, defined by muscovite, chlorite and sometimes biotite, strikes northeast - southwest and dips steeply.

2.3. Chloritoid zone

This zone is characterized by the presence of abundant chloritoid porphyroblasts that are less than 1 cm in size. Chloritoid appears in samples rich in muscovite (Al - rich) and is often situated in layers with chlorite (sample D-1, see figure 5). As the staurolite - chlorite zone is approached, staurolite and chloritoid appear together (outcrops N and O); in these samples the chloritoid porphyroblasts are 0.5 -1 cm in size, but the staurolite is not larger than 0.3 mm. Chloritoid bearing samples do not contain any biotite. Chlorite is sometimes an alteration product after chloritoid or staurolite. The matrix consists of quartz, plagioclase, muscovite, a small amount of tourmaline, apatite and opaque minerals such as pyrrhotite, ilmenite, chalcopyrite and Ti-oxides. The chloritoid grew after the formation of the compositional layering, suggested by the chloritoid in sample R1-3a (see photo 2a), containing inclusions that preserve this compositional layering. In the chloritoid zone most of the rocks are weakly (outcrops N and O) to moderately deformed (outcrops D, L, Z). Muscovite and sometimes chlorite define the foliation.

Samples from outcrop E1 are slightly different. They are also rich in muscovite, but contain, additionally to the common chloritoid bearing assemblage, clinozoisite and significant amount of tourmaline. Some of these samples are strongly deformed and the chloritoid is broken up and curved.

Garnet - bearing samples in the chloritoid zone are also richer in quartz and coarser grained than chloritoid bearing samples. These garnets contain abundant inclusions of biotite and they are armoured by biotite.

Andalusite was described in two samples by Fox (1971), but no andalusite was observed in this study.

2.4. Staurolite - chlorite zone

In the map the chloritoid - out reaction represents the lower boundary of the staurolite - chlorite zone:

Chloritoid = Garnet + Chlorite + Staurolite + H₂O,

which is a univariant in a six component system. Staurolite is abundant throughout the zone and forms porphyroblasts up to 2 cm in size. Chlorite also forms porphyroblasts, but in almost every sample appears with muscovite as an alteration product after staurolite. Some staurolites in this zone are texturally zoned with concentric zones defined by quartz inclusions. Staurolite appears in samples rich in Al (muscovite rich). Garnet containing samples are rich in quartz and often they do not contain any biotite. The size of garnets in the staurolite zone does not exceed 0.1 cm.

Rocks in the staurolite zone are moderately (central part of the area: outcrops: R, V, W) to strongly deformed (western part of the area, outcrops: AC, AD, AE). In the strongly deformed rocks staurolite is elongated in the foliation plane and quartz forms lenses also elongated in the foliation plane; these samples often display crenulation texture.

2.5. Staurolite - biotite zone

The univariant reaction:

marks the first appearance of the paragenesis of staurolite + biotite and the first appearance of biotite in Al rich pelites. In the Worthington area the biotite appears with staurolite in the western side of outcrop A (see figure. 5). The size of the biotite does not exceed 0.1 mm in size and it was not possible to achieve good chemical analyses of any of these biotites, but some of them clearly exhibit the characteristics of biotite (pleochroism, "bird's eye" extinction).

2.6. Discussion

In the Worthington area the isograds and the main foliation appear to transect each other at a low angle, suggesting that the isograds are either syn- or postdeformational. The isograds seem to be folded, according to the location of the (st + bt) - in isograd represented by the univariant reaction

The (st + bt) assemblage was found on the eastern side of outcrop A (see figure 5); east of this location the (st + bt) assemblage is not present and the (grt + chl) assemblage is present (outcrops AE, F, G, H and K), suggesting a closure to the east. Therefore this isograd is folded and probably the chloritoid - out isograd is folded as well.

Card (1978) suggested that the higher grade metamorphism is generally associated with rocks displaying weaker foliation and lower grade metamorphic rocks are associated with strong foliation. He concluded that the metamorphism and deformation were relatively independent of one another in detail. The field observations and petrographic study, however, do not agree with the conclusion of Card. In the Worthington area rocks

in staurolite - chlorite zone display the strongest foliation and rocks in garnet and chloritoid zone display weakly to moderately developed foliation. This observation also suggests that the main deformation and high grade metamorphism overlapped in time.

On the map (figure 5) the chloritoid - out isograd represents the disappearance of chloritoid, which might be due to variations in the composition of the pelites (richer in Mg). However, the chloritoid - out isograd must be located between the line representing the disappearance of chloritoid and the (st + bt) - in isograd. In the metamorphic grids (see chapter 5 for the detailed description of the metamorphic grids) for pelites in a prograde reaction sequence the chloritoid zone, represented by assemblages (cld + st + chl) and (grt + chl + bt), is followed by the breakdown of chloritoid to staurolite, chlorite and garnet and then the appearance of the assemblage (st + bt). During this fieldwork the (st + chl + grt) assemblage was not found, but Fox (1971) reported this assemblage from the north shore of Agnew Lake.

In the western side of the area the line representing the disappearance of chloritoid is located very close to the (st + bt) isograd and since the chloritoid - out reaction must be located between these two lines, it is assumed that the disappearance of chloritoid represents the chloritoid - out isograd.

CHAPTER 3: PETROGRAPHY AND GEOCHEMISTRY

3.1. McKim pelites in the Worthington area

Seventy - four samples of McKim pelites from High Falls Road-Agnew Lake area were used for petrography. The mineralogy of each metamorphic zone is summarized in table 3 and each sample in table 4. The character in front of the number represents the outcrop (see figure 5) where the sample was collected. Since almost all of the samples contain the same accessory minerals and more or less the same opaque minerals, these minerals are not included in table 4.

3.1.1. Deformation and metamorphism

Major regional scale faults do not transect the Worthington area. The field observations and petrography suggest that in the Worthington area, the true sequence of the isograds is preserved.

Almost all of the pelite samples in the High Falls Road-Agnew Lake area display a compositional layering, defined by alternating lighter and darker layers. The size of the layers ranges typically between 1 cm and 1-2 m. The darker layers are rich in muscovite and chlorite and the lighter layers are rich in quartz. This layering is likely to be primary sedimentary feature, because in the Drury and Lorne Townships the primary sedimentary structures are often observed.

According to Card (1964, 1978), Morris (1977) and Van Schmus (1976) the Sudbury - Espanola area was affected by an early deformation and low grade metamorphism before the intrusion of Nipissing Diabase. The evidence for such a

	Q	Pl	Kf	Ms	Chl	Bt	Grt	Cld	St
Chlorite-Biotite zone									
A1-1	X	X	X	X (ser)	X				
A1-3	X	X		X	X				
A1-4A	X	X		X	X	X			
Garnet zone									
B-3	X	X		X					
B1-2	X	X		X	X				
F-1	X	X		X	X	X	X		
F-2	X	X		X (ser)	X	X	X		
F-3	X	X		X	X	X	X		
G-1	X	X		X	X				
G-3	X	X		X	X				
G1-3	X	X		X	X				
G1-4	X	X		X	X	X	X		
G1-6	X	X		X	X				
H-1	X	X		X	X	X	X		
H-2	X	X		X	X	X	X		
H-3	X	X		X	X	X	X		
H-4	X	X		X	X	X	X		
I-1	X	X		X	X		X		
J-1	X	X		X	X		X		
K-1	X	X		X	X				
K-2	X	X		X	X		X		
K-3	X	X		X	X		X		
M-1	X	X		X	X				
Chloritoid zone									
AA-2	X	X		X	X				
AA-6	X	X		X	X				
D-1	X	X		X	X			X	
E1-3	X	X		X				X	
E1-3A	X	X		X				X	
E1-4	X	X		X				X	
E1-10	X	X		X		X			
L-1	X	X		X	X			X	
L-2	X	X		X	X			X	
N-0	X	X		X				X	X
N-1	X	X		X	X			X	X
N-2	X	X		X	X			X	X
N-3	X	X		X	X			X	X
N-6	X	X		X	X	X	X		
N-8	X	X		X	X	X	X		
O-2	X	X		X	X				X
O-3	X	X		X	X	X	X		
R1-3	X	X		X	X			X	
R1-3A	X	X		X	X			X	
R1-4	X	X		X	X			X	X
Z-1	X	X		X	X			X	
Z-2	X	X		X	X			X	
Z-12	X	X		X	X			X	
Staurolite zone									
A-1	X	X	X	X	X				X
A-1A	X	X		X	X				X
A-2	X	X	X	X	X				X
A-5	X	X		X	X				X
A-6	X	X		X	X				X
AB-2	X	X		X	X				X
AC-1	X	X		X	X				X
AD	X	X	X	X	X				X
AD-1	X	X	X	X	X				X
AE-1	X	X		X	X		X		
AE-2	X	X		X	X	X	X		
AE-2B	X	X		X		X			
AE-3	X	X		X		X			
AE-4	X	X		X	X				X
D1-1	X	X		X	X				X
E-1	X	X		X	X				X
P-3	X	X		X					X
Q-4	X	X		X	X				X
Q-8	X	X		X	X				X
Q-9	X	X		X	X				X
R-4	X	X		X	X				X
S-V	X	X		X	X	X			X
T-B	X	X		X	X				X
V-3	X	X		X	X	X			X
W-5	X	X		X	X				X
W-7	X	X		X	X				X
X-1	X	X	X	X	X				X
Z-9	X	X		X	X				X

Table 4: Mineralogy of the samples used for petrography in Worthington area

metamorphic event in the Worthington area is ambiguous. Some thin sections contain two generations of chlorite and/or muscovite. The first generation defines the foliation and the size of these muscovite and chlorite grains does not exceed 0.1 mm. The second generation forms porphyroblasts up to 5 mm in size. The second generation definitely formed later, but the length of time difference cannot be determined; the two generations might have formed during the same deformational event. Therefore there is no certain evidence for an early, pre - Penokean deformation and accompanying low grade metamorphism.

Most of the rocks in the Worthington area display a main foliation striking northeast - southwest. This foliation is defined by muscovite, chlorite and sometimes biotite. Staurolite is elongated in the foliation plane in the northwestern part of the area, where the foliation is strongly developed. In other areas the external fabric deflects around staurolite and also chloritoid porphyroblasts (photo 1a, 1b, 1c and 1d; 2a, 2b and 2c). These porphyroblasts might be prekinematic, in which case the foliation formed later and wrapped around the chloritoid and staurolite; or the porphyroblasts might have grown during flattening (synkinematic). However, in sample Z-2 (photo 1c and 1d) the chloritoid is clearly affected by deformation during its growth, because one chloritoid crystal is curved around the other one, which is slightly curved as well. Therefore it seems reasonable to conclude that the chloritoid is synkinematic and since the staurolite is in equilibrium with chloritoid (chloritoid zone), the staurolite is probably synkinematic as well.

One garnet sample contains a slightly curved inclusion of biotite, which suggests synkinematic growth. Some of the garnets in the area seem to have grown across the

Photo 1. a. Chloritoid porphyroblast exhibiting hourglass structure defined by quartz inclusions, simple twinning and strong pleochroism. The fine grained matrix consists of quartz, plagioclase, muscovite and chlorite. (Sample R1-3a)

b. Same as the previous photo under crossed polars.

c. Abundant chloritoid porphyroblasts in metapelites in the Worthington area. The chloritoids have been deformed and curved probably during the growth of the porphyroblasts, suggesting synkinematic growth. (Sample Z-2)

d. Same as the previous photo under crossed polars.

The scale bar represents 1 mm.

- Photo 2. a. Abundant staurolite porphyroblasts in the Worthington area. Staurolites are more or less elongated in the foliation plane and the foliation is deflected around them, suggesting pre- or synkinematic crystal growth. The matrix consists of quartz, plagioclase, chlorite and muscovite. (Sample W-5)
- b. Muscovite and chlorite forming pseudomorph after staurolite (in the core) in the staurolite zone. (Sample R-4)
- c. Staurolite porphyroblasts elongated in the foliation plane. (Sample W-5)

The scale bar represents 1 mm.

foliation, suggesting postkinematic growth. Also the foliation is deflected around some garnets, suggesting either pre- or synkinematic crystal growth (photo 1c and 1d). Summarizing all of the evidence, the growth of the garnets could have started before the main deformation, continued during deformation, and might have continued after the main deformation.

3.1.2. AFM diagrams

Figures 6, 7, 8 and 9 show the AFM diagrams for the garnet, chloritoid, staurolite - chlorite and staurolite - biotite zones. As seen in the diagrams, there are two distinct bulk compositions in the Worthington area. One is rich in Al and contains staurolite and chloritoid. The other composition is poorer in Al, rich in Si and contains biotite, garnet and chlorite. The Al rich pelites have a narrow range of bulk composition and contain only staurolite and chlorite with neither aluminum silicate nor garnet. In the staurolite - biotite zone the size of the biotite is very small (< 0.1 mm) and it was impossible to obtain Scanning Electron Microprobe analyses of this biotite. Therefore the AFM diagram for this zone is constructed using biotite composition from the staurolite - chlorite zone.

Figure 10 shows schematically the AFM diagrams for each zone with the reactions that separate the zones, in order to facilitate the comparison of this area with metamorphic grids and other metamorphic areas. The reactions separating the zones are described in more detail in the next chapter.

3.2. Sudbury Breccia in McKim pelites

Sudbury Breccia in McKim pelites was found in the NE part of the area, in outcrop N (photo 3a and 3b). These samples contain 3 mm idiomorphic chlorite porphyroblasts. In

Figure 6: Composition of the minerals in garnet zone represented on an AFM diagram (Worthington area)

Figure 7: Composition of the minerals in chloritoid zone represented on an AFM diagram (Worthington area)

Figure 8: Composition of the minerals in staurolite zone represented on an AFM diagram (Worthington area)

Figure 9: The appearance of the staurolite - biotite assemblage

Figure 10: Sequence of the reactions and assemblages in the Worthington area represented on AFM diagrams. The star and diamond shape symbols represent the bulk compositions found in the Worthington area.

Photo 3. a. Sudbury Breccia in Worthington area containing chlorite porphyroblasts that crosscut the boundary of the matrix and clast of the Sudbury Breccia. The matrix of the pelite consists of quartz, plagioclase, muscovite and biotite in both the clasts and the matrix of the breccia.

b. Same as the previous photo.

c. Garnet porphyroblast in the chloritoid zone armoured in biotite and chlorite, containing inclusions of biotite, quartz and opaque minerals such as pyrrhotite, chalcopyrite and ilmenite. (Sample N-8)

d. Garnet porphyroblast in the garnet zone with inclusions of quartz and opaque minerals. The matrix consists of quartz, plagioclase, muscovite and chlorite. (Sample H-1)

The scale bar represents 1 mm.

the same outcrop the pelitic fragments contain porphyroblasts of chlorite, chloritoid, biotite, garnet and staurolite of 2-4 mm in size. There is no textural evidence, including grain size, to suggest that chlorite in the matrix is not contemporaneous with the chlorite and other minerals in the fragments. All of the minerals appear to have grown during the same metamorphic event.

The following petrographic observations have been made:

1. Some porphyroblasts grow across the boundary of the matrix and clasts (photo 3a and 3b), which would not be possible if the brecciation happened after the growth of the porphyroblasts.
2. The size of the porphyroblasts is the same in the matrix and the clasts (2 - 4 mm)
3. The porphyroblasts prefer to grow at the boundary of the matrix and clasts (better seen in hand specimens), suggesting that the porphyroblasts grew when the boundaries were already present and these boundaries represented areas in the rock where the interfacial energy was higher.

These observations suggest that the brecciation happened before the growth of chlorite porphyroblasts.

3.3. Sudbury Structure

3.3.1. Onwatin Formation

Four samples of Onwatin Formation were used for petrography. They contain a significant amount of carbon and are very fine grained. The minerals present are quartz, muscovite, chlorite and biotite. The Vermilion Member additionally contains carbonate

minerals (calcite and dolomite). All of the samples of Onwatin Formation from South Range display a strong foliation defined by muscovite.

3.3.2. Onaping Formation

Six samples of breccia from the Onaping Formation were analysed. The clasts of the breccia are very heterogeneous. The minerals found in these samples are quartz, plagioclase, muscovite, chlorite, biotite, garnet, amphibole. The compositions of these minerals are shown in the Appendix 6. All of the samples from South Range display a foliation, which in most cases is defined by elongated amphiboles. The North Range Onaping samples do not display any distinctive foliation. Two samples contain garnet and they seem to be either pre- or syn-kinematic, as suggested by photos 4a and 4b; the finer grained amphiboles grow around the garnets. The amphibole is rich in Ca and less than 0.1 mm in size; the garnet is euhedral, very rich in Mn and Ca and less than 1 mm in size. The compositions of garnet, amphibole and biotite are consistent throughout the thin section as determined by electron microprobe analyses.

3.4. Calc - silicate samples of the Espanola Formation northeast of the Sudbury

Structure

The Espanola Formation consists of alternating calcareous and siliceous units. Samples ESP-1, ESP-2 and ESP-3 are from a quarry northeast of the Sudbury Structure (figure 1), where the Espanola Formation is very rich in carbonates and is metamorphosed. Table 5 shows the mineralogy of the three samples.

Sample ESP-1 is very rich in carbonates (calcite and dolomite) and talc (photo 4c); it also contains small amount of phlogopite and very small amount of quartz. The sample

Photo 4. a. and b. Euhedral garnet porphyroblasts in the Onaping Formation. The fine grained matrix consists of amphibole, plagioclase and quartz. The samples are strongly foliated. The amphiboles defining the foliation are deflected around the garnet, suggesting that the garnets grew either pre- or synkinematically. (Sample AV-605)

c. Tale and dolomite in siliceous marbles of Espanola Formation northeast of the Sudbury Structure. (Sample ESP-1)

d. Amphibole (Mg-rich actinolite) with calcite in the siliceous marbles of Espanola Formation northeast of the Sudbury Structure. (Sample ESP-2)

The scale bar represents 1 mm.

	Cal	Dol	Tlc	Act	Qtz	Phl	Chl
Sample							
ESP 1	X	X	X		X	X	
ESP 2	X			X	X	X	X
ESP-3	X			X	X		

Table 5: Mineralogy of the calc-silicate samples of Espanola Formation

is generally fine grained with coarser grained areas in it. Samples ESP-2 and ESP-3 are more siliceous and they do not contain any dolomite, but 50 - 60 % of the rocks are made up of amphibole (Mg rich actinolite) and contain more quartz than ESP-1. Sample ESP-3 consists of only calcite, amphibole and quartz (photo 4d); sample ESP-2 contains a small amount of phlogopite and chlorite additionally to calcite, amphibole and quartz.

CHAPTER 4: THERMOBAROMETRY

4.1. Methods

Thermobarometry is used to determine the temperature and pressure of equilibration of mineral assemblages. The methods used in this thesis are described below.

The **TWEEQU** (Thermobarometry With Estimation of Equilibration) is a computer program that plots equilibria implied by a mineral assemblage, using a thermodynamic dataset for end-members of the minerals and their mixing properties (Berman, 1991). If the minerals in an assemblage equilibrated at the same T and p, then all of the independent equilibria must intersect at one point in p - T space. If the thermodynamic or compositional data are inaccurate or the assemblage is not in equilibrium, the equilibria do not meet at one point.

The **garnet - biotite geothermometer** uses the partitioning of Fe and Mg between coexisting biotite and garnet to estimate the temperature of equilibration. The garnet - biotite method is very sensitive to temperature, but not pressure. The exchange reaction is:

almandine phlogopite pyrope annite

The distribution coefficient of the reaction is:

$$K_D = ((\text{Fe} / \text{Mg})_{\text{bt}}) / ((\text{Fe} / \text{Mg})_{\text{grt}})$$

where grt = garnet and bt = biotite; and K_D is a function of temperature, pressure and phase composition. Many authors tried to find the relationship between K_D and the temperature using experimental methods (Ferry and Spear, 1978) and empirical methods

(Saxena, 1969; Thompson, 1975; Goldman and Albee, 1977). The formula used here was first suggested by Hodges and Spear (1982):

$$T (K) = (12454 + 0.047p(\text{bars}) + 3*3300*(X_{\text{grs}}^2 + X_{\text{alm}}*X_{\text{grs}} + X_{\text{grs}}*X_{\text{sps}} + X_{\text{prp}}*X_{\text{grs}})) /$$

$$(4.662 - 3*R*\ln((X_{\text{prp}}*X_{\text{ann}}) / (X_{\text{phl}}*X_{\text{alm}})) + 3*1.5*(X_{\text{grs}}^2 + X_{\text{alm}}*X_{\text{grs}} + X_{\text{grs}}*X_{\text{sps}} +$$

$$X_{\text{prp}}*X_{\text{grs}}))$$

where the mole fractions of compositions in garnet are defined as,

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

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

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

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

and in biotite,

$$X_{\text{ann}} = \text{Fe} / (\text{Fe} + \text{Mg} + \text{Ti} + \text{Al}^{\text{VI}})$$

$$X_{\text{phl}} = \text{Mg} / (\text{Fe} + \text{Mg} + \text{Ti} + \text{Al}^{\text{VI}}).$$

INVEQ (inverse chemical equilibrium) is a computer program developed by Terrence Gordon (1992). At a fixed T and p, the Gibbs free energy, G, of all possible compositions of a mineral can be represented as a surface in composition - free energy space (figure 11). The G of one particular composition is a point on the G surface, that can be defined by a tangent plane to the G surface. The partial molar free energies of the end-members are given by the intersection of the tangent plane with co-ordinate axes for the compositions of each end-member. At equilibrium, G of the system is at a minimum; therefore the partial molar free energies of all end-members lie on a single plane, tangent

Figure 11: Free energy surfaces of minerals represented in composition - free energy space

Figure 12: Partial molar free energies of the end-members of two minerals in equilibrium

Figure 13: A single equilibrium (boundary curve in p-T space) that corresponds to a single pair of intersecting tie lines in the equilibrium tangent plane

Figure 14: The "best fit" plane to partial molar free energies of the end-members

Figure 15: The misfit of each individual end-member

to the free energy surface of all coexisting phases; all lines joining the values of their partial molar free energies intersect (figure 12). A single equilibrium (boundary curve in p - T space) corresponds to a single pair of intersecting tie-lines on the equilibrium tangent plane (figure 13). When the partial molar free energies of the end-members are coplanar, the T and p values define a curve in T - p space. In reality the partial molar free energies of the end-members might not lie within a single plane due to analytical error and possible disequilibrium effects due, for example, to re-equilibration. INVEQ finds the "best fit" plane to the free energy balances (figure 14). In this way it is possible to measure the misfit for each individual end-member (figure 15) and to give an estimate in the uncertainty of the p and T determination.

4.2. Results

4.2.1 Worthington area

In the Worthington area the samples used for thermobarometry have the assemblage, garnet + biotite + chlorite + muscovite + quartz + plagioclase. The compositions of the largest garnets are shown in table 6. The pressure and temperature results are shown in table 7. Samples used for the calculations (H-1, H-4, N-8 and AE-2) were selected in the basis of petrography. Samples H-1 and H-4 belong to the garnet zone. In sample H-1 all of the garnets are smaller than 2 mm. Towards the rim the Fe, Mg and Ca content of the garnet increases and the Mn content decreases. Since there is no petrographic evidence for disequilibrium, it is assumed that the garnet and biotite are in equilibrium.

Sample #		X alm	X prp	X sps	X grs	X ann	X phi
H-1	grt rim	0.752	0.075	0.086	0.086	0.457	0.365
	grt core	0.732	0.064	0.132	0.072	0.457	0.365
H-3	grt rim	0.769	0.063	0.083	0.085	0.432	0.365
	grt core	0.731	0.078	0.107	0.085	0.452	0.355
H-4	grt rim	0.765	0.079	0.071	0.084	0.441	0.37
	grt halfway	0.739	0.072	0.108	0.081	0.449	0.362
	grt core	0.735	0.064	0.112	0.088	0.454	0.371
N-8	grt rim	0.778	0.08	0.08	0.061	0.447	0.373
	grt inner rim	0.777	0.088	0.073	0.062	0.44	0.39
	grt core	0.782	0.103	0.055	0.061	0.44	0.39
AE-2	grt rim	0.703	0.072	0.126	0.099	0.421	0.415
	grt core	0.723	0.08	0.112	0.085	0.431	0.409

Table 6: Composition of the phases in Worthington area

Pressure and temperature data with different methods						
		grt - bt	TWEEQU	INVEQ		
		p (bars)		T (C)		
H-1	grt rim	511	4222	520	3882	512
	grt core	496	2815	474	2463	465
H-3	grt rim	487	3074	457	2634	443
	grt core	520	4111	514	3720	509
H-4	grt rim	509	4000	526	3683	515
	grt halfway	507	3519	503	3198	495
	grt core	496	3259	474	2942	469
N-8	grt rim	506	4074	503	3702	497
	grt inner rim	510	4630	531	4292	526
	grt core	527	3593	571	3262	562
AE-2	grt rim	495	3593	474	3307	469
	grt core	504	3593	491	3306	483

Table 7: Pressure and temperature results estimated by samples from Worthington area

Sample H-4 is very similar to sample H-1, except the largest garnet is 0.9 mm. The zonation of the garnets shows the same trend as the garnet in sample H-1. Sample N-8 is richer in quartz than H-1 and H-4, and belongs to the chloritoid zone. The largest garnet is 2.0 mm. The rim of this garnet is depleted in Fe and richer in Mn; the temperatures calculated by the three methods are lower for the rim than the core (table 7). Also the garnets in this sample are surrounded by biotite and contain inclusions of biotite. One of the garnets contains an elongated, curved inclusion of biotite, suggesting that during the growth of the garnet there was still some deformation in progress. This biotite is in textural equilibrium with the garnet beside it. In calculating the temperatures, the core of the garnet is assumed to be in equilibrium with the core of the adjacent biotite grains. The rim of the garnet is assumed to be in equilibrium with biotite in contact with garnet either as adjacent grains or as grains within the garnet. The composition of the biotite remains nearly consistent throughout the sample.

Sample AE-2 is in the staurolite zone. The garnet is only 0.5 mm, subhedral - anhedral. The rim of the garnet is poorer in Fe and Mg, and richer in Mn, the same trend as the garnet in sample N-8 (table 6).

Figures 16, 17, 18 and 19 show the TWEEQU plot for the rims of samples H-1, H-4 and the cores of samples N-8 and AE-2. Although three curves intersect at a point on these figures, only two of the curves are independent. It is the consistency of results from sample to sample rather than the coincidence of curves that indicates the attainment of equilibrium.

Figure 16: TWEEQU plot of sample H-1 from Worthington area

Figure 17: TWEEQU plot of sample H-4 from Worthington area

Figure 18: TWEEQU plot of sample N-8 from Worthington area

Figure 19: TWEEQU plot of sample AE-2 from Worthington area

Figure 20 represents the location of the samples in Worthington area used for geothermobarometry.

4.2.2 Samples of the Onaping Formation and from the Lindsley, Vermilion and Copper Cliff South Mine

The Onaping samples used for thermometry contain the assemblage garnet + biotite + chlorite + amphibole + quartz + plagioclase. Samples from the Lindsley, Vermilion and Copper Cliff South mines contain the assemblage garnet + biotite + chlorite + quartz + plagioclase + / - muscovite. These samples were used only for garnet - biotite thermometry and the results are represented in table 8.

Garnets from the Onaping Formation, Vermilion and Lindsley mines are enriched in Mn and Ca (table 9). Garnets from the Copper Cliff South mine are rich only in Ca, but not Mn. The large amount of Ca and Mn in the samples might influence the temperature results. The calculated temperature depends on the Fe / Mg ratio in the garnet and biotite. If it is assumed that the Fe / Mg ratio in these minerals is not significantly changed by Ca and Mn, then temperature of equilibration can be calculated. The resulting temperatures are assigned a larger error limit of $\pm 100^{\circ}\text{C}$.

4.3. Discussion of the results

In thermobarometry the possible sources of error include (Spear, 1993):

1. Analytical imprecision in microprobe analysis and uncertainty of electron microprobe standard compositions and correction factors
2. Accuracy of the thermobarometry method
3. Uncertainties in mineral activity models

Figure 20: Temperature and pressure results in Worthington area

Legend of the map

Metamorphic zones:

- Biotite zone
- Garnet zone
- Chloritoid zone
- Staurolite - chlorite zone
- Staurolite - biotite zone

Diabase

Pelite in chloritoid or
staurolite - chlorite zone

Isograds:

- Known
- Assumed
- Inferred

Isograds due to variations in composition:

- Known
- Assumed
- Inferred

Road

Water

Reactions

1 Garnet - in reaction

2 Chloritoid - in reaction

Univariant reactions

3 Chloritoid = Garnet + Chlorite + Staurolite + H₂O

4 Garnet + Chlorite = Staurolite + Biotite + H₂O

Structural elements:

Folds

Foliation

Faults

Outcrop designation: A, AE, G1 etc

Sample #		p=500b	p=2000b	p=4000b	p=5000b	p=6000b	p=8000b	p=10000b
L-04 (lind)		464	465	465	466	467	467	469
		487	488	488	490	490	491	492
		442	443	443	444	445	445	446
		448	448	449	450	451	451	452
ver 93-02		519	520	521	522	523	524	525
AV605	rim	491	492	493	494	494	496	497
	halfway	517	518	520	521	521	523	524
	core	352	352	353	353	353	354	354
AV604	rim	499	500	502	502	503	504	506
	outer rim	466	467	468	469	469	470	472
	core	499	500	502	502	503	504	506
	rim	351	351	352	352	352	353	353
	halfway	489	490	491	492	492	494	495
	core	469	470	471	472	472	473	475
CCS96-3	rim	439	440	441	442	442	444	445
	halfway	442	443	444	445	446	447	448
	core	448	449	450	451	451	453	454

Table 8: Temperature results estimated by samples of the Sudbury Structure

Sample #		X alm	X prp	X sps	X grs	X ann	X phl
L-04 (lind)		0.342	0.005	0.353	0.3	0.715	0.2
		0.319	0.006	0.348	0.327	0.694	0.2
		0.299	0.003	0.412	0.281	0.715	0.2
		0.345	0.004	0.383	0.268	0.715	0.2
		0.329	0.003	0.344	0.324	0.715	0.2
ver 93-02		0.628	0.011	0.125	0.236	0.56	0.087
AV605	rim	0.281	0.019	0.39	0.309	0.457	0.425
	halfway	0.252	0.023	0.408	0.317	0.457	0.425
	core	0.246	0.0001	0.426	0.328	0.457	0.425
AV604	rim	0.271	0.02	0.391	0.318	0.459	0.424
	outer rim	0.274	0.013	0.413	0.3	0.459	0.424
	core	0.266	0.02	0.407	0.307	0.459	0.424
	rim	0.273	0.0001	0.407	0.323	0.452	0.413
	halfway	0.268	0.017	0.394	0.321	0.452	0.413
	core	0.259	0.012	0.394	0.334	0.452	0.413
CCS96-3	rim	0.872	0.033	0.055	0.039	0.520	0.368
	halfway	0.898	0.037	0.032	0.033	0.520	0.368
	core	0.901	0.041	0.022	0.036	0.520	0.368

Table 9: Composition of the garnets and biotites in the samples of the Sudbury Structure

4. "Geological uncertainties" arising from compositional heterogeneities in minerals.

The uncertainty ranges of the geothermobarometry methods are ± 1 kbar and ± 50 °C, assuming that the correct mineral compositions were chosen (Spear, 1993). For the Mn and / or Ca rich samples the error limit is larger (~ 100 °C).

The results produced with different methods are in fairly good agreement with one another. Generally the TWEEQU method gives the highest temperatures and pressures for a given composition. The core composition of sample N-8 shows the largest difference in temperatures and pressure between different methods. The garnet-biotite thermometer produces significantly lower temperature than the other two methods, but taking into consideration the error limit, the results overlap.

4.4. Estimation of temperature from the Espanola Formation samples northeast of the Sudbury Structure

The assemblages present in the Espanola Formation are: calcite + dolomite + talc + quartz $\pm$ phlogopite $\pm$ chlorite and calcite + amphibole + quartz $\pm$ phlogopite $\pm$ chlorite. Figure 21 shows the grid for siliceous marbles calculated by Carmichael (1991). According to the grid the first appearance of amphibole in siliceous marbles that do not contain antigorite is above 400 °C (if $p > 0.5$ kbar). The temperature depends on the composition of the fluids as indicated on figure 21 and if the fluids are richer in H₂O, the temperature is probably above 500 °C. In the area northeast of the Sudbury Structure the calc - silicate rocks occupy a small area (< 1 km²); therefore the fluids affecting the rocks are not likely to contain significant amount of CO₂, which suggests temperatures above 500 °C (amphibolite facies).

Figure 21: The reaction $Tc + Qtz + Cal = Tr + Dol$ in the $CaO - MgO - SiO_2 - H_2O - CO_2$ system. Tremolite is stable on the high temperature side of the reaction. The numbers along the reaction represent the mole fraction of CO_2 in the fluid phase. All assemblages include $H_2O - CO_2$ vapour.

There is not enough data for the estimation of the pressure in the quarry, but the samples do not show significant deformation. Only one of the samples containing talc displays a weak foliation defined by talc.

CHAPTER 5: COMPARISON OF THE WORTHINGTON AREA TO METAMORPHIC GRIDS FOR PELITES

In the past many scientists have tried to construct a metamorphic grid for pelites. The first approaches were based entirely on field observations: Albee (1965, 1972), Kepezhinskias and Khlestov (1977) and Harte and Hudson (1979). Subsequently, thermodynamic data of the minerals became available through experiments. The second generation of scientists tried to produce a grid that fit both thermodynamically and petrologically: Spear and Cheney (1989), Wang and Spear (1991), and Stuwe and Ehlers (1997). Powell and Holland (1990) based their grid entirely on thermodynamic data.

The major difference between these grids is in the location of the boundary curves involving the phases garnet, staurolite, biotite, chlorite, chloritoid, muscovite, quartz and hydrous fluids. There are five possible reactions involving these minerals in excess of muscovite, water and fluids:

- (1) $\text{Grt} + \text{Chl} = \text{Cld} + \text{Bt}$
- (2) $\text{Cld} + \text{Chl} = \text{Bt} + \text{St}$
- (3) $\text{Cld} = \text{Grt} + \text{Bt} + \text{St}$
- (4) $\text{Cld} = \text{Grt} + \text{St} + \text{Chl}$
- (5) $\text{Grt} + \text{Chl} = \text{St} + \text{Bt}$

In the KFMASH system these reactions intersect at the [Als, Cd] invariant point (these reactions do not involve the phases Als and Cd) (figure 22). The sequence of the reactions around the [Als, Cd] invariant point must always be the same: 1, 2, 3, 5 and 4, according to the AFM diagram (see figure 22). The slope of the reactions is, however, a matter of

Figure 22: The sequence of the reactions in the KFMASH system involving the phases garnet, chlorite, biotite, staurolite, chloritoid, muscovite, quartz and hydrous fluids

debate and that changes the sequence of the reactions in a prograde terrane (increasing temperature). The difference can be highlighted with the location of the boundary for the reaction (1) and therefore the stability field of the assemblages (Grt + Chl) and (Cld + Bt).

Aluminous rocks at Worthington contain all of these minerals and provide an opportunity to test the published p - T grids against a well preserved field occurrence. Figure 23 represents the sequence of the assemblages and reactions in the Worthington area, according to petrography and thermobarometry. In order to compare the metamorphism in Worthington area to the existing grids there are three important facts emphasized here.

1. In the whole area (Cld + Bt) assemblage was not found, but the (Grt + Chl) assemblage is common.

2. The sequence of the isograds in the Worthington area is (see figure 23):

3. The pressure is generally low ($p < 4.8$ kbar) as indicated by thermobarometry.

In the Albee (1965, 1972) grid the sequence of the reactions in a prograde terrane is either 1, 2 and 3 or 4 and 5 (figure 24); therefore the (Cld + Bt) field, which is not observed at Worthington, is located either below or above the [Als, Cd] invariant point, depending on the $p_{\text{H}_2\text{O}}$ (vapour pressure) and p_s (total lithostatic). When $p_{\text{H}_2\text{O}} = p_s$ the (Cld + Bt) field is located at low pressures (figure 24a), below the [Als, Cd] invariant point, and when $dp_{\text{H}_2\text{O}} < dp_s$ the (Cld + Bt) field is located at high pressures (figure 24b), above

Figure 23: Sequence of the assemblages and reactions in the Worthington area plotted in p - T diagram. Curves defining the stability field of aluminosilicates are also shown.

Figure 24: The Albee (1965, 1972) grid
 a. $\text{pH}_2\text{O} = \text{pS}$, and b. $\text{pH}_2\text{O} < \text{pS}$

Figure 25: The Kepezhinskas and Khlestov (1977) (a) and the Harte and Hudson (1979) (b) grids

the [Als, Cd] invariant point (Albee, 1965, 1972). This grid was based on field observations in Lincoln Mountain (Vermont, USA) (1965) and 14 other areas (1972).

The Albee (1965, 1972) grid is only qualitative; therefore the Worthington area could support either grid, depending on the location of [Als, Cd] invariant point.

The grids constructed by **Kepezhinskias and Khlestov (1977)** and **Harte and Hudson (1979)** are very similar (figure 25 a and b). In both grids the (Cld + Bt) field has a very narrow temperature range. In the Kepezhinskias and Khlestov grid reactions 1, 2 and 3 are located above the [Als, Cd] invariant point and the (Cld + Bt) field extends to higher pressures, above the invariant point (similar to the grid of Albee, when $p_{H_2O} < p_s$). In the Harte and Hudson grid the reactions 1, 2 and 3 are located below the [Als, Cd] invariant point and the (Cld + Bt) field extends to lower pressures (similar to Albee's grid, when $p_{H_2O} = p_s$). Harte and Hudson (1979) based their grid entirely on field observations in the eastern Scottish Dalradian. Kepezhinskias and Khlestov (1977) calculated their grid taking into consideration their field observations in the Chulyshman Anticlinorium (Gorny Altai) and other work (Albee, 1972; Halferdahl, 1961; Osberg, 1971).

These grids are both qualitative as well. Therefore, for the same reason as described above for the Albee grid, the Worthington area could support either of the grids depending on the location of the [Als, Cd] invariant point in p - T coordinates.

In the **Spear and Cheney (1989)** and **Wang and Spear (1991)** grids the slope of the reaction (1) changes; therefore the sequence of the reactions with increasing temperature is either 1, 4 and 5 or 2 and 3, depending on the pressure (figure 26). Also, reaction (1) moves to the left with chloritoid and biotite forming the low grade assemblage

Figure 26: The grid of Spear and Cheney (1989) and Wang and Spear (1991). Symbols indicate the assemblages in Worthington area. Contours indicate the mole fraction of spessartine in the garnet.

and reacting to chlorite and garnet. In the Spear and Cheney grid the (Grt + Chl) assemblage in a Mn-free rock is restricted to a narrow field below the [Als, Cd] invariant point and the (Cld + Bt) assemblage has a large field extending to lower temperatures from the reaction (1).

In the grid of Wang and Spear (1991), not shown on figure 26, the sequence of the reactions is the same, but there are two [Als, Cd] invariant points and the (Grt + Chl) field is located between these two invariant points at pressures above 5 kbars. Below the low pressure [Als, Cd] invariant point (~5 kbars) there is no (Grt + Chl) assemblage present.

This arrangement is not consistent with the field observations at Worthington, because the (Grt + Chl) assemblage is very common and the (Cld + Bt) assemblage is not observed in rocks that equilibrated below 5 kilobars. Wang and Spear (1991) explained the limited stability of (Grt + Chl) with the effect of Mn, which increases the stability field of (Grt + Chl) (figure 26). Eventually, if the Mn content is high enough ($Mn / (Mn + Mg + Fe) > 3$) the (Cld + Bt) field disappears at lower pressures.

In the Spear and Cheney (1989) and Wang and Spear (1991) grids in order for the (Cld + Bt) field to disappear the $Mn / (Mn + Mg + Fe)$ ratio in the garnet should be between 0.3 and 0.4. In the Worthington area this ratio in the garnets ranges between 0.06 and 0.2, but the (Cld + Bt) assemblage is still not present. Therefore these grids are not consistent with field data from the Worthington area.

Powell and Holland (1990) constructed their grid based entirely on thermodynamic data (figure 27). In the KFMASH system the [Als, Cd] invariant point is not stable, there is no reaction (1) and there is no (Cld + Bt) field either. They tried to

Figure 27: The Powell and Holland (1990) grid

adjust the grid to the field observations by including a significant mixing energy for Fe^{3+} in biotite and chloritoid. Figure 27 shows the grid when the biotite contains 15% Fe^{3+} and the chloritoid contains 10% Fe^{3+} . A new [Als, Cd] invariant point is created, which stabilizes the (Cld + Bt) field at pressures below the [Als, Cd] point. In this way the grid becomes very similar to the Albee (1965, 1972) and the Harte and Hudson (1979) grids. The reaction (1) moves to the right and the (Bt + Cld) assemblage has a narrow field below the [Als, Cd] invariant point, and the (Grt + Chl) assemblage is stable at temperatures below the (Cld + Bt) field.

The presence and the size of the (Cld + Bt) assemblage in the Powell and Holland (1990) grid depends on the Fe^{3+} content of chloritoid and biotite. The sequence of the reactions in the Worthington area is 4, followed by 5, which in the Powell and Holland grid are located above the [Als, Cd] invariant point. The pressure in Worthington area is below 4.8 kbar. According to the Powell and Holland grid, the location of the [Als, Cd] invariant point depends on the amount of Fe^{3+} in biotite and chloritoid. The pressure at which the invariant point is located increases with increasing amount of Fe^{3+} in the minerals. Therefore, the rocks in the Worthington area could be consistent with this grid if these minerals do not contain significant amount of Fe^{3+} .

Stuwe and Ehlers (1997) calculated a grid using the computer software Thermocalc (Powell and Holland, 1988) and an updated version of the thermodynamic dataset of Holland and Powell (1990) (Holland and Powell, 1995) (figure 28). Reaction (1) is not present and there is no (Cld + Bt) field. The grid is consistent with their field observations in Broken Hill, Australia.

Figure 28: The grid of Stuwe and Ehlers (1997). The symbols represent the assemblages in Worthington area.

In the Stuwe and Ehlers (1997) grid the (Cld + Bt) field does not appear, which does not explain the presence of this assemblage in many other areas. But regardless of this problem the data from the Worthington area are consistent with the grid, since the (Cld + Bt) assemblage was not found here.

CHAPTER 6: TEMPORAL RELATIONSHIP OF THE PENOKEAN OROGENY AND THE SUDBURY EVENT

The Penokean Orogeny affected the rocks of the Southern Province after the intrusion of Nipissing Diabase and before the intrusion of the Sudbury Diabase Swarm (Brocoum and Dalziel, 1974, Card, 1978). It is still a matter of debate, however, whether the Penokean Orogeny started before or after the Sudbury Event. The present study approaches this problem in two ways.

1. Petrographic study of the Sudbury Breccia.
2. Deformation and metamorphism of the rocks inside the Sudbury Basin.

6.1. Sudbury Breccia

The Sudbury Breccia originated by brittle fracturing and comminution of Footwall rocks in an explosive event followed instantaneously by the intrusion of the Sudbury Igneous Complex (Dressler, 1984). Therefore, the Sudbury Breccia represents the exact time of the Sudbury Event.

Sudbury Breccia was found in the chloritoid zone of the Worthington area (outcrop N, see figure 5). The Breccia contains chlorite porphyroblasts, that represent the metamorphism (Penokean) in the area. The detailed description of these samples is included in chapter 3. The petrographic study shows that the brecciation of these rocks occurred before the growth of chlorite porphyroblasts. Therefore, the Penokean metamorphism must postdate the Sudbury Event.

6.2. Rocks of the Sudbury Basin

Samples of Onwatin and Onaping Formations from the South Range were studied in more detail. All of these rocks display a weakly to strongly developed foliation striking approximately northeast - southwest and dipping steeply. The attitude of the foliation inside and south of the Sudbury Structure is the same.

Samples of the Onwatin Formation contain the assemblage quartz + plagioclase + muscovite +/- chlorite +/- biotite. The highest grade of metamorphism is represented by samples containing chlorite and biotite, that is middle to upper greenschist facies.

The highest grade of metamorphism in the Onaping Formation is represented by samples containing chlorite, biotite and garnet, suggesting at least middle to upper greenschist, possibly amphibolite facies metamorphism, depending on the composition of the garnet. Fe and Mn rich garnet might appear at grades lower than amphibolite facies (Rousell, 1975, Spear, 1993). Garnet containing samples were used for garnet - biotite thermometry and the calculated temperature ranges between 352 and 520 °C (at 4 kilobar).

Regardless of the composition of the garnets in Onaping Formation, the samples from both the Onwatin and Onaping Formations suggest that the grade of metamorphism in the South Range is at least as high as middle to upper greenschist, which is comparable to the metamorphic grade just south of the Sudbury Structure.

Both the metamorphism and deformation of the Sudbury Basin suggest that the Southern Province and The Sudbury Basin were affected by the same event (Penokean Orogeny to the same extent).

6.3. Discussion

The conclusion of the present study is that the Penokean Orogeny started after the Sudbury Event, represented by the brecciation of the Footwall rocks, deposition of the Whitewater Group and intrusion of the Sudbury Igneous Complex.

This conclusion is not in agreement with Card (1978) who proposed an abrupt change in the grade of metamorphism at the boundary of the Sudbury Structure and the Southern Province and suggested that the Penokean Orogeny started and culminated before the Sudbury Event.

The present study supports the conclusion of Brocoum and Dalziel (1974), Rousell (1975), Fleet et al. (1987), Cowan and Schwerdtner (1994) and Easton (1996).

Figure 29 summarizes data about the metamorphism and deformation of the Sudbury Structure and the Southern Province known at the present time. The isograds in the Southern Province south and southwest of the Sudbury Structure are drawn according to Card (1978) and data from the present study.

The metamorphism of the Sudbury Igneous Complex was studied in more detail by Fleet et al. (1987), who mapped the amphibolite isograd in the Sudbury Igneous Complex in the South Range and found that this isograd is the continuation of the amphibolite isograd just south of the Sudbury Structure, suggested by Card (1978). In the North Range the Sudbury Igneous Complex contains samples suggesting middle to upper greenschist facies (Fleet et al., 1987).

The deformation and metamorphism of the Sudbury Basin were studied by Rousell (1975), who was the first scientist to map the biotite - in isograd inside the Basin. The

Figure 29: Metamorphism and deformation of the Sudbury Structure and the rocks of the Southern Province adjacent to the Sudbury Structure

Legend of the map

Sudbury Igneous Complex

Offset Dykes

Metamorphic Facies

A Amphibolite

G2 Middle to Upper Greenschist

G1 Lower Greenschist

Isograds

1 Biotite - in

2 Garnet - in

Structural Elements

Fault

Foliation

Worthington area

Location of the samples used for thermometry

Mines:

1 McCreedy West

2 Craig

3 Fraser

4 Stratchona

5 Barnett

6 Whistle

7 Victor

8 Lindsay

9 Little Stobie

10 Copper Cliff South

11 Copper Cliff North

12 Creighton

13 Crean Hill

14 Vermilion

15 Worthington

structural data (foliation and faults) shown on the map in figure 29 are mainly from the work of Rouseil (1975) and partly from the present study.

Easton (1996) also defined the biotite - in isograd inside the Basin and the garnet - in isograd as well. The location of the biotite - in isograd is the same as the one proposed by Rouseil (1975).

Northeast of the Sudbury Structure the siliceous marbles contain the assemblage calcite + amphibole, which suggests a minimum temperature of 400 °C, possibly 500 °C, according to the grid of Carmichael (1991); these have equilibrated at temperatures comparable to amphibolite grade rocks south of the Sudbury Basin. According to Dressler (1984) the contact effect of the Sudbury Igneous Complex cannot be recognized further than 1.2 km from the Sudbury Igneous Complex. The siliceous marble samples are located 6 km from the Sudbury Igneous Complex; this distance is too far to be considered contact metamorphism. There is an Offset Dyke close to the siliceous marbles, but such a dyke does not carry sufficient heat to cause metamorphic effects more than a few meters from the contact. Therefore the metamorphism is assumed to be the regional metamorphism that affected the Southern Province south of the Sudbury Structure and the whole Sudbury Structure.

The isograds in the North Range and adjacent to it are drawn according to the data of Fleet et al. (1987), who propose middle to upper greenschist facies metamorphism in the Sudbury Igneous Complex in the North Range and according to the amphibolite facies metamorphism, suggested by the siliceous marble samples just northeast of the Sudbury Structure. Due to the lack of more data the location of these isograds is approximate.

The map shows that the isograds in the Sudbury Structure are the continuation of the isograds in the Southern Province. The small differences are probably due to the different lithologies of these rocks. In the South Range the highest grade of metamorphism is south of the Sudbury Structure. Another higher grade terrane occurs southwest of the Sudbury Structure and includes the Worthington area.

The grade of metamorphism decreases to lower greenschist facies towards the centre of the Sudbury Basin, then increases to middle to upper greenschist facies in the North Range and possibly higher northeast of the Sudbury Structure.

The distribution of metamorphism suggests that all the rocks of the Sudbury Structure and the Southern Province were metamorphosed during the Penokean Orogeny.

The present study is consistent with the work of Cowan and Schwerdtner (1994), who suggested that the geometry of the Sudbury Structure originated by folding and ductile shear of a quasi - horizontal floor of a large, complex impact crater due to a push from southeast.

CHAPTER 7: CONCLUSIONS

1. In the area near Worthington five metamorphic zones can be mapped: chlorite - biotite, garnet, chloritoid, staurolite - chlorite and staurolite - biotite zones.
2. The peak temperature in Worthington area ranges between 443 and 571 °C, and pressure ranges between 2463 and 4630 bars. The p and T results calculated using the two thermobarometry methods (TWEEQU, INVEQ) and the T calculated with the garnet - biotite thermometer are consistent and within the error limit (± 50 C) or overlap.
3. The metamorphism in the Worthington area supports the grid of Albee (1965, 1972), Kepezhinskis and Khlestov (1977), Harte and Hudson (1979) and Stuwe and Ehlers (1996), although the latter grid is not consistent with many other areas due to the absence of (Cld + Bt) assemblage. The Worthington area does not support the grid of Spear and Cheney (1989) and Wang and Spear (1991), because in these grids the (Cld + Bt) assemblage has a large field extending to lower temperatures from the reaction (1) and in order for the (Cld + Bt) field to disappear the $Mn / (Mn + Mg + Fe)$ ratio in the garnet should be between 0.3 and 0.4. In the Worthington area this ratio does not exceed 0.2 in the garnets, but the (Cld + Bt) assemblage is still not present.
4. In the Worthington area, the metamorphism was synkinematic, but some of the porphyroblasts might have started to grow before the deformation and continued growing after the deformation.
5. The rocks of the Sudbury Structure and the Southern Province were metamorphosed during the Penokean Orogeny. The strongest evidence of this conclusion is given by the

petrography of the Sudbury Breccia samples from Worthington area. Chlorite porphyroblasts grow across the matrix - clast boundary within the breccia.

6. In the South Range the grade of metamorphism decreases from amphibolite (in the Sudbury Igneous Complex and just south and southwest of the Sudbury Structure) to lower greenschist toward the middle of the Basin, then increases again to middle to upper greenschist facies (in the Sudbury Igneous Complex in the North Range) and possibly amphibolite facies northeast of the Sudbury Structure.

REFERENCES

- Albee, A.L., 1965: A petrogenetic grid for the Fe-Mg silicates of pelitic schists. *American Journal of Science*, vol. 263, p. 512-536.
- Albee, A.L., 1972: Metamorphism of Pelitic Schists: Reaction Relations of Chloritoid and Staurolite. *Geological Society of America Bulletin*, vol. 83, p. 3249-3268.
- Benett, G., Dressler, B.O., and Robertson, J.A., 1991: The Huronian Supergroup and Associated Intrusive Rocks, *in* *Geology of Ontario*, O.G.S. Special Volume 4, p.549-591.
- Berman, R.G., 1988: Internally-consistent thermodynamic data for stoichiometric minerals in the system Na₂O-K₂O-CaO-MgO-FeO-Fe₂O₃-Al₂O₃-SiO₂-TiO₂-H₂O-CO₂. *Journal of Petrology*, vol. 29, p. 445-522.
- Berman, R.G., 1990: Mixing properties of Ca-Mg-Fe-Mn garnets. *The American Mineralogist*, vol. 75, p. 328-344.
- Berman, R.G., 1991: Thermobarometry Using Multi-Equilibrium Calculations: A New Technique with Petrological Applications. *Canadian Mineralogist*, vol. 29, p. 833-855.
- Berman, R.G. and Brown, T.H., 1984: A thermodynamic model for multicomponent melts, with application to the system CaO-Al₂O₃-SiO₂. *Geochimica et Cosmochimica Acta*, vol. 48, p. 661-678.
- Berman, R.G. and Koziol, A.M., 1991: Ternary excess properties of grossular-pyrope-almandine garnets and their influence in geothermobarometry. *American Mineralogist*, vol. 76, p. 1223-1231.
- Blonde, J.A., 1996: Petrology and Metamorphism of Nipissing Diabase of May Township, Ontario. Unpublished M.Sc. Thesis.
- Brocoum, S.J., and 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, p. 1571-1580.
- Card, K.D., 1964: Metamorphism in the Agnew Lake Area, Sudbury District, Ontario, Canada. *Geological Association of America Bulletin*, vol. 75, p. 1011-1030.
- Card, K.D., 1965: Hyman and Drury Townships. Ontario Department of Mines, Geological Report, No. 34.

- Card, K.D., 1971a: Panache Lake area (west part): Ontario Department of Mines Preliminary Map, p. 668.
- Card, K.D., 1971b: Panache Lake area (east part): Ontario Department of Mines Preliminary Map, p. 669.
- Card, K.D., 1978: Metamorphism of the Middle Precambrian (Aphebian) Rocks of the Eastern Southern Province, *in* Metamorphism in the Canadian Shield, G.S.C. Paper 78-10, p. 269-282.
- 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, p. 335-380.
- Carmichael, D.M., 1991: Univariant mixed-volatile reactions: pressure-temperature phase diagrams and reaction isograds. *Canadian Mineralogist*, vol. 29, p. 741-754.
- Chatterjee, N.D. and Froese, E.F., 1975: A thermodynamic study of the pseudobinary join muscovite-paragonite in the system $\text{KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_8\text{-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. *American Mineralogist*, vol. 60, p. 985-993.
- Collins, W.H., 1925: North shore of Lake Huron. Geological Survey of Canada, Memoire 143.
- Corfu, F., and Andrews, A.J., 1986: A U-Pb age for mineralized Nipissing Diabase, owganda, Ontario. *Canadian Journal of Earth Sciences*, vol. 23, p. 107-109.
- Cowan, E.J., and Schwerdtner, W.M., 1991: Fold Origin of the Sudbury Basin, *in* Proceedings of the Sudbury-Norilsk Symposium, Ontario Geological Survey Special Volume 5, p. 45-56.
- Dressler, B.O., Gupta, V.K., and Muir, T.L., 1984: The Sudbury Structure, *in* Geology of Ontario, Ontario Geological Survey Special Volume 4, part 1, p. 593-627.
- Easton, R.M., 1992: The Grenville Province, *in* Ontario Geological Survey, Special Volume 4, part 2, p. 713-904.
- Easton, R.M., 1996: Project Unit 94-07. Metamorphic Map for Ontario. Abstract. Ontario Geological Survey, Precambrian Geoscience Section, p. 28-32.
- Fairbairn, H.W., Hurley, P.M., Card, K.D. and 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, p. 489-497.

- Ferry, J.M., and Spear, F.S., 1978: Experimental Calibration of the Partitioning of Fe and Mg Between Biotite and Garnet. *Contributions to Mineralogy and Petrology*, vol. 66, p. 113-117.
- Fleet, M.E., Barnett, R.L., and Morris, W.A., 1987: Prograde metamorphism of the Sudbury Igneous Complex. *Canadian Mineralogist*, vol. 25, p. 499-514.
- Fox, J.S., 1971: Coexisting chloritoid and staurolite and the staurolite-chloritoid isograd from the Agnew Lake area, Ontario, Canada. *Geological Magazine*, vol. 108, p. 205-219.
- Fuhrman, M.L. and Lindsley, D.H., 1988: Ternary-feldspar modeling and thermometry. *American Mineralogist*, vol. 73, p. 201-216.
- Gibbins, W.A., and McNutt, R.H., 1975a: The Age of the Sudbury Nickel Irruptive and the Murray Granite. *Canadian Journal of Earth Sciences*, vol. 12, p. 1970-1989.
- Ginn, R.M., 1965: Geology of Nairn and Lorne Townships, District of Sudbury. Ontario Department of Mines, Geological Report, No. 35.
- Goldman, D.S. and Albee, A.L., 1977: Correlation of Mg/Fe partitioning between garnet and biotite with O18/O16 partitioning between quartz and magnetite. *American Journal of Science*, vol. 277, p. 750-761.
- Gordon, T.M., 1992: Generalized thermobarometry: Solution of the inverse chemical equilibrium problem using data for individual species. *Geochimica et Cosmochimica Acta*, vol. 56, p. 1793-1800.
- Gordon, T.M., Aranovich, L.Ya, and Fed'kin, V.V., 1994: Exploratory data analysis in thermobarometry: an example from the Kisseynew Sedimentary Gneiss Belt, Manitoba, Canada. *American Mineralogist*, vol. 79, p. 973-982.
- Halferdahl, L.B., 1961: Chloritoid: Its composition, X-ray and Optical properties, stability, and occurrence. *Journal of Petrology*, vol. 2, p. 49-135.
- Harte, B., and Hudson, N.F.C., 1979: Pelite facies series and the temperatures and pressures of Dalradian metamorphism in eastern Scotland, *in* Harris, A.L., Holland, C.H., and Leake, B.E., editors, *The Caledonides of the British Isles: Reviewed*. Geological Society special Publication 8, 323-337.
- Hodges, K.V., and Spear, F.S., 1982: Geothermometry, geobarometry and the Al₂SiO₅ triple point at Mt. Moosilauke, New Hampshire. *American Mineralogist*, vol. 67, p. 1118-1134.

- Holland, T.J.B. and Powell, R., 1990: An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: the system K_2O - Na_2O - CaO - MgO - MnO - FeO - Fe_2O_3 - Al_2O_3 - TiO_2 - SiO_2 - C - H_2 - O_2 . *Journal of Metamorphic Geology*, vol. 8, p. 89-124.
- 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, p. 46-50.
- Kepezhinskas, K.B., and Khlestov, V.V., 1977: The Petrogenetic Grid and Subfacies for Middle-temperature Metapelites. *Journal of Petrology*, vol. 18, part 1, p. 114-143.
- Knight, C.J., 1967: Rubidium - strontium isochron ages of volcanic rocks of the north shore of Lake Huron, Ontario, Canada. *Geological Association of America Bulletin*, vol. 80, p. 1725-1736.
- Kretz, R., 1983: Symbols for rock-forming minerals. *American Mineralogist*, vol. 68, p. 277-279.
- McMullin, D., Berman, R.G., and 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, p. 889-908.
- 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, p. 137-140.
- Morris, W.A., 1984: Paleomagnetic Constraints on the Magmatic, Tectonic, and Metamorphic History of the Sudbury Basin Region, *in* The Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey Special Volume 1, p. 411-430.
- Powell, R. and Holland, T.J.B., 1988: An internally consistent thermodynamic dataset with uncertainties and correlations: 3. Application to geobarometry worked examples and a computer program. *Journal of Metamorphic Geology*, vol. 6, p. 173-204.
- Powell, R. and Holland, T.J.B., 1990: Calculated mineral equilibria in the pelite system, KFMASH (K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O). *American Mineralogist*, vol. 75, p. 367-380.

- Robertson, J.A., Frarey, M.J. and Card, K.D., 1969: The Federal - Provincial Committee on Huronian Stratigraphy Progress Report. Canadian Journal of Earth Sciences, vol. 6, number 2, p. 335-336.
- Roscoe, S.M., 1969: Huronian rocks and uraniferous conglomerates in the Canadian Shield. Geological Survey of Canada, Paper 68-40.
- Rousell, D.H., 1972: The Chelmsford Formation of the Sudbury Basin - a Precambrian turbidite, *in* New Developments in Sudbury Geology, Geological Association of Canada, Special Paper 10, p. 79-91.
- Rousell, D.H., 1975: The Origin of Foliation and Lineation in the Onaping Formation and the Deformation of the Sudbury Basin. Canadian Journal of Earth Sciences, vol. 12, p. 1379-1395.
- Rousell, D.H., 1984a: Structural geology of the Sudbury Basin, *in* The Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey Special Volume 1, p. 83-95.
- Rousell, D.H., 1984b: Onwatin and Chelmsford Formations, *in* The Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey Special Volume 1, p. 211-219.
- Saxena, S.K., 1969: Silicate solid solution and geothermobarometry: 3. Distribution of Fe and Mg between coexisting garnet and biotite. Contributions to Mineralogy and Petrology, vol. 22, p. 259-267.
- Spear, F.S., 1993: Metamorphic phase equilibria and pressure-temperature-time paths. Mineralogical Society of America Monograph 1: 798 p.
- Spear, F.S. and Cheney, J.T., 1989: A petrogenetic grid for pelitic schists in the system $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-FeO-MgO-K}_2\text{O-H}_2\text{O}$. Contributions to Mineralogy and Petrology, vol. 101, p. 149-164.
- Stuwe, K., and Ehlers, K., 1997: Multiple Metamorphic Events at Broken Hill, Australia Evidence from Chloritoid-bearing Parageneses in the Nine-Mile Mine Region. Journal of Petrology, vol. 38, number 9, p. 1167-1186.
- Thompson, A.B., 1975: Mineral reactions in pelitic rocks: II. Calculation of some P-T-X(Fe-Mg) phase relations. American Journal of Science, vol. 276, p. 425-454.
- Van Schmus, W.R., 1976: Early and Middle Proterozoic History of the Great Lakes Area, North America. Royal Society of London Philosophical Transactions, vol. 280, p. 605-628.

- Wang, P. and Spear, F.S., 1991: A field and theoretical analysis of garnet + chlorite + chloritoid + biotite assemblages from the tri - state (MA, CT, NY) area, USA. *Contributions to Mineralogy and Petrology*, vol. 106, p. 217-235.
- Zolnai, A.I., Price R.A., and Helmstaedt, H., 1984: Regional cross section of the Southern Province adjacent to Lake Huron, Ontario: implication for the tectonic significance of the Murray Fault Zone. *Canadian Journal of Earth Sciences*, 21, p. 447-456.

APPENDIX 1: DESCRIPTION OF THE MINERALS IN THE WORTHINGTON AREA

Quartz

Quartz is the most common mineral in the pelites; it is anhedral granular and has undulatory extinction, characteristic of metamorphic quartz. In some samples the quartz forms lenses, suggesting stronger deformation.

Plagioclase

Plagioclase is also common in every zone; it is difficult to distinguish from the quartz with undulatory extinction when it is not strongly zoned. In some samples the plagioclase shows strong zonation. The anorthite (An) content of the plagioclase ranges between 25 and 60 %, but generally is around 40 % as determined by electron microprobe analyses (Appendix 4). The An content usually increases towards the rim, but strongly zoned plagioclase crystals show the opposite trend with An decreasing towards the rim.

K-feldspar

K-feldspar is present only in a few samples; it is usually very altered. It is found even in higher grade rocks, but it seems to be related to veins, suggesting a secondary process.

Muscovite

Muscovite is very common in pelites, but some of the samples in this area contain only sericite. Two generations of muscovite can be distinguished. The first generation defines the main foliation. The size of this muscovite does not exceed 0.1 mm. The second

generation of muscovite is generally larger (approximately 5 mm). The importance of these two generations is described at the beginning of the chapter.

The composition of muscovite does not vary significantly in the whole area, in addition to the major elements, it contains small amount of Ti, Cr, Fe, Ba and Na as determined by electron microprobe analyses (Appendix 5).

Chlorite

Chlorite is found in every metamorphic zone in the area. In plane polarized light the chlorite is slightly pleochroic (pale green - yellowish green); between crossed polars it has an anomalous purplish interference colour. The chlorite always has abundant pleochroic halos, caused by zircon or titanite. Two generations of chlorite are recognizable. The first generation is less than 0.2 mm. The second generation forms porphyroblasts up to 1 cm in size. These two generations have the same significance as described at the beginning of this chapter for the two generations of muscovite present in metapelites. The chlorite also appears as an alteration product of staurolite with muscovite. It forms pseudomorphs after staurolite.

The chemistry of the chlorite is shown in Appendix 6. The $\text{Fe} / (\text{Fe} + \text{Mg})$ ranges between 0.5 and 0.6. The Mg content increases with increasing grade of metamorphism.

Biotite

The presence of biotite depends on the composition of the pelite. In lower grade samples, only the quartz rich samples contain biotite. Biotite forms elongated, dark brown - light brown, tabular crystals, up to 5 mm in size. It contains abundant pleochroic halos.

Appendix 7 shows the composition of biotite. The $\text{Fe} / (\text{Fe} + \text{Mg})$ ratio in the biotite is always higher than in the chlorite when both of them are present.

Garnet

Garnet is the most abundant in the garnet zone, but there are garnet bearing assemblages in higher grade samples too. The garnet forms euhedral - subhedral porphyroblasts up to 2 mm in size; it contains inclusions of quartz and opaque minerals such as pyrrhotite, ilmenite, chalcopyrite and Ti-oxides. In higher grades garnet contains inclusions of biotite and is mantled by biotite (photos 1c and 1d).

The composition of garnet is represented in Appendix 8; it is very almandine rich and the $\text{Fe} / (\text{Fe} + \text{Mg})$ ratio decreases towards the rim of the garnet, except in the higher grade samples where the outer rim shows an increase of the $\text{Fe} / (\text{Fe} + \text{Mg})$ ratio.

Chloritoid

Chloritoid is found only in the chloritoid zone, where it is abundant (> 30 %). The chloritoid forms elongated, euhedral porphyroblasts, up to 5 mm in size. It is slightly to strongly pleochroic (green - yellow), often twinned on elongation plane and exhibits an hourglass pattern defined by quartz inclusions (photos 2a, 2b, 2c and 2d).

Appendix 9 shows the composition of chloritoid; it is very rich in Fe.

Staurolite

Staurolite is fairly common in chloritoid zone and abundant in staurolite zone (> 40 %) (photos 3a and 3c). In the chloritoid zone the staurolite is not larger than 2 mm; in the staurolite zone the maximum size of the staurolite is up to 2 cm. The staurolite in both zones is strongly pleochroic, often twinned and contains abundant inclusions of quartz. In

the higher grade samples, it alters to chlorite and muscovite that form pseudomorphs after staurolite (photo 3b).

The composition of staurolite is represented in Appendix 10; the mineral often contains Mn, Zn and Ti in small amounts.

Accessory minerals

Tourmaline is almost always present in very small amount; it forms euhedral - subhedral pleochroic crystals.

Titanite forms pleochroic halos in biotite and chlorite; it is barely recognizable, but the larger ones have diamond shape and are brown.

Zircon also forms pleochroic halos in mafic minerals (biotite and chlorite).

Opaque minerals

Almost every sample in the area contains opaque minerals, which are pyrrhotite, ilmenite, chalcopyrite and a mixture of Ti-oxides. The Ti-oxide is an alteration product after ilmenite.

APPENDIX 2: DESCRIPTION OF THE MINERALS IN THE ESPANOLA FORMATION

Calcite

In these samples calcite is abundant; it looks clear, colourless with high interference colours. The size of the calcite crystals ranges between 0.1 and 5 mm. In sample ESP-1 the calcite forms small veins, < 1mm wide. The calcite contains only small amount of Fe in addition to Ca.

Dolomite

Dolomite is only present in sample ESP-1; it is similar to calcite, except that it contains small inclusions of opaque and other minerals that make it cloudy.

Talc

Talc is also present only in sample ESP-1. It forms large (3 - 5 mm) crystals, sometimes radiating, and has high interference colours (photo 4c).

Amphibole

Amphibole forms elongated, acicular crystals, up to 5 mm in size (photo 4d). The amphibole is colourless or slightly coloured in plane polarized light, has first or second order interference colours and small extinction angle ($0 - 15^{\circ}$). The composition of the amphibole is shown in Appendix 11. The Fe / (Fe + Mg) ratio ranges between 0.80 and 0.85.

Quartz

Quartz is not abundant in these samples, samples ESP-2 and ESP-3 contain more quartz (~ 10 %). The size of the quartz is usually less than 0.5 mm.

Chlorite

Chlorite forms crystals maximum 3 mm in size. It is light green and weakly pleochroic in plane polarized light and has first order gray interference colour. The chlorite in these samples is very Mg rich, the Mg / Fe ratio is close to 3:1.

Biotite

Biotite is present as small (<3 mm) crystals; it is brown and pleochroic. The Mg / Fe ratio in the biotite is around 4:1, which makes it phlogopite.

Plagioclase

Only a small amount of plagioclase is present in sample ESP-2. It is almost pure albite.

APPENDIX 3: ACTIVITY OF CHLORITE

The structure of the chlorite consists of regularly alternating "talc-like" $Y_6Z_8O_{20}(OH)_4$ and "brucite-like" $Y_6(OH)_{12}$ sheets, where the octahedral site (Y) is usually occupied by Mg, Al and Fe, and the tetrahedral site (Z) is occupied by Si and Al. In this structure the Al can substitute on both octahedral and tetrahedral sites. In order to keep the charge balance the (Si, Al) substitution is coupled with substitution of Al and Fe^{3+} on the octahedral site, but it is not known how much exactly is coupled and whether Al is randomly distributed on the tetrahedral site or preferentially incorporated into certain sites.

Also chlorite may be intergrown with another sheet silicates such as smectite, illite, biotite, muscovite or other mica. In this case the chemical composition does not represent the chlorite completely. Chlorite may also have excess or missing "brucite-like" layers, when the chlorite analysis does not make sense stoichiometrically.

Some of these problems may be avoided by analyzing the chlorite with X-ray diffraction or TEM (Transmission Electron Microscope), but it is difficult and time-consuming to determine the exact composition of chlorite, and therefore the thermodynamic properties and activities of chlorite end-members. Some of the attempts for calculating the activity of chlorite end-members are described below and tested with TWEEQU.

Calculating a simple activity model of a solid solution there are two principles that have to be satisfied (Skippen and Carmichael, 1990).

1. The activity $a = X^s$, where s is given by the stoichiometry of the component and X is the molar proportion.

2. A coupled substitution has to be treated as a single unit when calculating the activity of a component.

A simple activity model for chlorite, that satisfies the two principles, is:

$$a_{chl} = (Mg/5)^5 * (Si/3)^3.$$

Holland and Powell (1990) suggested an activity model using three chlorite end-members.

clinochlore (clin): $Mg_4(Mg, Al)Si_2(Si, Al)O_{10}(OH)_8$

$$a_{clin} = 16 * (1 - x_{chl})^5 * (1 - y_{chl})^2 * y_{chl}^2$$

daphnite (daph): $Fe_4(Fe, Al)Si_2(Si, Al)O_{10}(OH)_8$

$$a_{daph} = 16 * x_{chl}^5 * (1 - y_{chl})^2 * y_{chl}^2$$

amesite (ames): $Mg_4Al_2Si_2Al_2O_{10}(OH)_8$

$$a_{ames} = (1 - x_{chl})^4 * y_{chl}^4$$

where $x_{chl} = Fe / (Fe + Mg)$ and $y_{chl} = x_{Al M2}$.

The results for sample (N-8), plotted with TWEEQU method and using different activity models, are represented on figures 30, 31 and 32. Figure 18 shows the p and T data for the same sample ignoring the chlorite. The p and T values are much higher when chlorite is not ignored, but these p and T results are not consistent with other methods (grt-bt). Also if amesite is included in the mineral assemblage, the TWEEQU becomes very chaotic. These results suggest that either the thermodynamic properties or the mixing properties (activities) of chlorite are not reliable, especially for amesite. Therefore, estimating the p and T in the area, the chlorite is ignored in the calculation.

Figure 30 : TWEEQU plot of sample N-8, using Berman (1991) database and a simple activity model for chlorite:
 $a(\text{chl}) = (\text{Mg}/5)^5 \cdot (\text{Si}/3)^3$

Figure 31: TWEEQU plot of sample N-8, using Holland and Powell (1990) database with two chlorite end-members (clinochlore and daphnite). The activities of the end-members are calculated using the Holland and Powell (1990) activity

Figure 32: TWEEQU plot of sample N-8, using Holland and Powell (1990) database and three chlorite end-members (clinochlore, daphnite and amesite). The activities are calculated with the Holland and Powell (1990) activity model.

APPENDIX 4
Plagioclase Analyses in the Worthington Area

SAMPLE	SiO2	Al2O3	K2O	CaO	Na2O	BAO	FEO	TOTAL
Garnet Zone								
F-1	61.34	24.48	0	6.28	7.94	0	0	100.04
F-1	60.72	24.06	0.06	5.82	8.7	0	0	99.36
F-2	60.2	25.04	0.16	6.49	8.07	0	0.18	100.14
F-2	59.45	25.93	0	7.54	7.51	0	0.19	100.62
F-3	64.4	18.16	15.85	0	0	1.25	0.16	99.82
F-3	59.29	24.2	0.45	5.83	7.55	0	0.37	97.69
F-3	59.23	26.21	0	7.96	7.39	0	0.17	100.96
G1-4	63.47	23.25	0	4.53	9	0	0	100.25
G1-4	64.62	22.56	0	3.44	9.74	0	0.13	100.49
H-1	59.74	25.66	0	7.37	7.8	0	0	100.57
H-1	59.21	25.58	0	7.37	7.57	0	0.13	99.86
H-2	59.28	25.78	0	7.56	7.11	0	0.14	99.87
H-2	58.59	26.68	0	8.22	6.99	0	0	100.48
H-3	59.25	26.02	0	7.75	7.73	0	0.23	100.98
H-3	60.15	26.38	0	7.54	7.56	0	0.17	101.8
H-4	58.62	25.73	0	7.75	7.06	0	0	99.16
H-4	59.57	26.55	0	8.16	7.04	0	0.18	101.5
Chloritoid Zone								
N-6	53.25	29.24	0.23	10.67	5.97	0	0.59	99.95
N-6	52.95	28.69	0.18	10.72	5.39	0	0.63	98.56
N-6	60.53	24.62	0.07	5.82	8.47	0	0.32	99.83
N-7	57.42	26.91	0	8.9	6.07	0	0.12	99.42
N-7	59.13	25.54	0	7.45	7.28	0	0	99.4
N-7	56.01	28.13	0	10.65	5.66	0	0.14	100.59
N-7	51.91	30.29	0.1	12.96	4.06	0	0.38	99.7
N-7	57.83	27.33	0	8.98	6.43	0	0.23	100.8
N-7	57.69	26.91	0.1	8.97	6.49	0	0.38	100.54
N-8	55.61	28.56	0.08	10.48	5.7	0	0.18	100.61
N-8	62.08	24.48	0	5.65	9.3	0	0	101.51

SAMPLE	SiO2	Al2O3	K2O	CaO	Na2O	BAO	FEO	TOTAL
O-3	58.2	25.62	0	7.87	7.16	0	0	98.85
O-3	59.44	25.66	0	7.36	7.44	0	0	99.9
Staurolite Zone								
A-1	65.22	18.92	17.1	0	0	0	0	101.24
AE-2	58.57	26.59	0	8.07	6.94	0	0	100.17
AE-2	58.33	26.4	0.06	8.54	6.82	0	0.12	100.27
AE-4	60.16	25.04	0	6.48	8.22	0	0	99.9
AE-4	60.73	25.12	0	6.42	8.05	0	0	100.32
S-V	57.11	28.85	0.09	10.06	6.1	0	0.2	102.41
S-V	55.68	28.86	0.07	10.81	5.73	0	0.3	101.45
S-V	62.16	25	0	5.87	8.58	0	0	101.61
T-B	59.46	25.51	0	6.78	7.9	0	0	99.65
T-B	59.73	26.14	0	6.95	8.33	0	0	101.15
W-7	60.75	25.44	0	6.9	7.3	0	0.11	100.5
W-7	61.08	25.66	0	7.02	7.66	0	0.14	101.56
W-7	60.91	25.45	0	6.85	8.06	0	0.17	101.44
X-1	64.8	22.81	0.11	3.59	9.9	0	0	101.21
X-1	64.47	23.11	0	4.04	9.59	0	0	101.21

Plagioclase Analyses in the Onwatin Formation

ONW-V	61.33	19.52	14.54	0	0	4.55	1.18	101.12
ONW-V	63.94	18.33	17	0	0	0	1.31	100.58

Plagioclase Analysis in the Espanola Formation

ESP-2	67.51	19.02	0	0.51	11.15	0	0	98.19
-------	-------	-------	---	------	-------	---	---	-------

APPENDIX 5
Muscovite Analyses in the Worthington Area

SAMPL	SiO2	Al2O3	TiO2	CR2O	FEO	MNO	MGO	CAO	K2O	NA2O	BAO	CL	TOTAL
Garnet Zone													
F-1	45.6	35.16	0.18	0.15	0.95	0	0.43	0	9.6	1.12	0.4	0	93.59
F-3	46.72	30.95	0.66	0	2.51	0	2.08	0	9.73	0	1.14	0	93.79
h-1	45.66	35.13	0.3	0	1.05	0	0.63	0	10.42	0.75	0.43	0	94.37
h-2	46.19	34.98	0.39	0	1.07	0	0.65	0	9.94	0.86	0.34	0	94.42
h-3	49.15	32.14	0.28	0.11	0.98	0	0.62	0	9.38	0.82	0.26	0	93.74
H-4	46.61	35.65	0.33	0.1	1.07	0	0.76	0	9.83	0.48	0.28	0	95.11
Chloritoid Zone													
D-1	45.34	37.18	0.24	0	1.69	0	0.3	0	8.64	1.91	0	0	95.3
D-1	45.35	37.63	0.34	0	0.67	0	0	0	8.68	2.02	0	0	94.69
E1-3A	46.31	32.86	0.15	0.13	0.66	0	1.74	0	10.86	0	0.48	0	93.19
E1-4	47.12	34.04	0.47	0.19	0.59	0	1.04	0	10.37	0	0.64	0	94.46
N-1	46.68	37.25	0.21	0.15	0.7	0	0.35	0	8.89	1.49	0	0	95.72
N-6	45.52	36.71	0.26	0	1.14	0	0.4	0	9.8	1.27	0	0	95.1
N-8	45.59	36.19	0.14	0	1.21	0	0.5	0	9.88	1.46	0.2	0	95.17
O-3	45.67	35.37	0.68	0	1.1	0	0.3	0	9.48	1.28	0	0	93.88
Staurolite Zone													
A-1	44.21	36.81	0.35	0	1.29	0	0.55	0	8.29	1.65	0	0	93.15
AE-2	45.58	34.47	0.25	0	1.17	0	0.93	0	10.61	0	0.21	0	93.22
AE-4	45.18	36.25	0	0	0.73	0	0.24	0	7.72	2.07	0.21	0	92.4
W-7	46.1	37	0.24	0	0.69	0	0	0	8.66	2.01	0.38	0	95.08
X-1	46.6	36.35	0.43	0.12	0.48	0	0.63	0	9.38	1.23	0.93	0	96.15

APPENDIX 6
Chlorite Analyses in the Worthington Area

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MNO	MGO	K2O	CAO	CL	TOTAL
Garnet Zone											
F-1	24.7	22.35	0	0	26.83	0.21	12.23	0	0.07	0	86.39
F-1	24.87	22.19	0	0	25.91	0.24	12.95	0	0	0	86.16
F-2	24.8	22.93	0	0	26.5	0.12	13.91	0	0	0	88.26
F-3	25.2	20.18	0	0	27.73	0	12.91	0.07	0	0	86.09
G1-3	23.57	22.42	0	0.11	28.11	0.19	12.03	0	0	0	86.43
G1-3	23.29	22.69	0	0	27.93	0.27	11.7	0	0	0	85.88
G1-4	24.73	21.65	0.15	0.11	27.65	0.29	13.15	0	0	0	87.73
G1-4	24.73	21.49	0	0	27.69	0.2	12.99	0	0	0.06	87.16
H-1	24.19	22.44	0	0	27.19	0.15	12.54	0.08	0	0	86.59
H-2	23.89	23.39	0	0	26.46	0	12.94	0	0	0	86.68
H-2	23.91	22.81	0	0	26.76	0	12.71	0	0.12	0	86.31
H-3	24.27	22.89	0	0	26.32	0.18	13	0	0	0	86.66
H-4	24.18	21.97	0.16	0	26.42	0.11	12.49	0.07	0	0	85.4
H-4	23.89	22.24	0	0	26.61	0	12.52	0	0	0	85.26
M-1	23.65	23.33	0	0	29.29	0.27	11.63	0	0	0	88.17
M-1	24.01	23.51	0	0	29.42	0.31	11.48	0	0	0	88.73
Chloritoid Zone											
D-1	23.27	23.4	0	0	28.82	0.2	11.11	0	0	0	86.8
D-1	24.05	24.17	0	0	28.83	0.13	11.97	0	0	0	89.15
E1-4	27.14	22.62	0	0	13.08	0	23.05	0	0	0	85.89
N-1	24.52	23.52	0	0	26.24	0	13.4	0	0	0	87.68
N-1	23.79	22.68	0	0.11	26.18	0.12	13.2	0	0	0	86.08
N-2	24.61	23.98	0	0.12	25.55	0	14.2	0	0	0.06	88.52
N-2	24.36	23.72	0	0	26.11	0.12	13.19	0	0	0	87.5
N-6	24.24	22.58	0	0	26.17	0.2	13.44	0	0	0	86.63
N-6	24.56	23.27	0	0	26.54	0.23	13.29	0	0	0	87.89
N-7	26.24	21	0	0	21.45	0.14	17.69	0	0	0	86.52
N-8	24.62	22.36	0	0	25.53	0.17	14.14	0	0	0	86.82
N-8	24.7	22.64	0	0	25.66	0	14.45	0	0	0	87.45

SAMPLE	SIO2	AL2O3	TIO2	CR2O3	FEO	MNO	MGO	K2O	CAO	CL	TOTAL
O-2	23.69	22.82	0	0	27.09	0.26	11.98	0	0	0	85.84
O-3	25.02	22.83	0	0.14	25.66	0	13.28	0.07	0	0	87
O-3	23.83	21.34	0	0	26.28	0	12.8	0	0	0	84.25
R1-3	24.27	23.77	0	0	26.69	0.14	12.76	0	0	0	87.63
Z-2	23.86	22.83	0	0	28.77	0.17	11.94	0	0	0	87.57
Staurolite Zone											
A-1	23.73	23.33	0	0	28.01	0.2	12.06	0	0	0	87.33
A-1	23.69	23.78	0	0	27.47	0.19	11.05	0	0.08	0	86.26
AB-2	24.06	23.42	0	0	27.86	0.16	12.74	0	0	0	88.24
AE-2	24.96	22.02	0	0	25.01	0.22	15.08	0	0	0	87.29
AE-2	24.59	21.92	0	0	25.29	0.22	14.83	0	0	0	86.85
AE-4	24.19	23.15	0	0	26.29	0.15	12.94	0	0	0	86.72
D1-1	24.6	23.01	0	0	28.5	0.18	12.39	0	0	0	88.68
D1-1	24.1	22.78	0	0	27.36	0.22	13.05	0	0	0	87.51
R-4	24.03	22.85	0	0	28.79	0	12.18	0	0	0	87.85
S-V	27.35	21.09	0	0	17.95	0.22	21.05	0	0	0	87.66
T-B	23.31	23.47	0	0.12	26.4	0.2	12.4	0	0	0	85.9
T-B	23.87	23.72	0	0	26.96	0.18	12.36	0	0	0	87.09
V-3	23.83	23.15	0.11	0	27.54	0.18	12.77	0	0	0	87.58
W-5	24.21	23.71	0.11	0	26.67	0.21	13.7	0	0	0	88.61
W-5	24.33	24.09	0	0	27.15	0.17	12.5	0	0	0	88.42
X-1	26.26	23.31	0	0	15.08	0	22.23	0	0	0	86.88
X-1	26.51	23.64	0	0.14	14.91	0	22.06	0	0	0	87.26

Chlorite Analyses in the Sudbury Breccia

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MnO	MgO	K2O	CaO	CL	TOTAL
NB-1 1	25.33	22.09	0.1	0	23.4	0.17	16.47	0	0	0	87.56
NB-1 4	24.93	22.07	0	0	21.98	0.21	16.49	0	0	0	85.68
NB-1 5	24.95	22.38	0	0.11	22.08	0.15	16.49	0	0	0	86.16
NB-1 6	25.38	22.44	0	0	21.87	0.16	16.77	0	0	0	86.62
NB-1 8	25.36	22.32	0	0.16	21.95	0.17	16.62	0.09	0.1	0	86.77
NB-1 9	25.68	22.24	0	0	21.33	0.23	17.51	0	0	0	86.99

Chlorite Analyses in the Onwatin Formation

ONW-V 1	22.32	20.12	0	0	38.2	0.27	5.56	0	0	0	86.47
ONW-V 2	22.21	20.57	0	0	38.36	0.43	5.41	0	0.22	0	87.2

Chlorite Analyses in the Onaping Formation

AV605 5	26.22	20.2	0	0.17	25.38	1.11	14.34	0.19	0.11	0	87.72
AV60512	25.96	19.91	0	0	25.54	1.04	14.07	0	0.08	0	86.6
AV60520	25.56	20.54	0	0.1	24.28	1.03	15.29	0.07	0.07	0	86.94

Chlorite Analyses in the Espanola Formation

ESP-2 3	27.84	19.14	0	0	14.22	0	23.24	0	0	0	84.44
ESP-2 3	27.88	19.07	0	0	13.98	0	23.01	0	0.08	0	84.02

APPENDIX 7

Biotite Analyses in the Worthington area

SAMPLE	SIO2	AL2O3	TIO2	CR2O3	FEO	MNO	MGO	K2O	CAO	NA2O	CL	TOTAL
Garnet Zone												
F-1	36.1	18.86	1.73	0.16	20.09	0.15	9.16	9.72	0	0	0	95.97
F-1	35.76	18.43	1.72	0	19.72	0.12	8.91	9.8	0	0	0	94.46
F-2	29.26	20.07	0.59	0.15	24.97	0	12.45	2.86	0	0	0	90.35
F-3	35.44	18.48	1.69	0.17	20.49	0	8.72	9.68	0	0	0	94.67
F-3	35.7	18.69	1.7	0	20.29	0	9.25	9.7	0	0	0	95.33
G1-4	35.4	18.15	1.81	0.16	21.39	0.12	8.89	9.69	0	0	0	95.61
G1-4	35.56	17.88	1.87	0.13	21.52	0.14	9.09	9.62	0	0	0	95.81
H-1	36.18	19.15	1.76	0.12	20.84	0	9.35	9.61	0	0	0	97.01
H-4	35.86	18.98	1.57	0	19.77	0	9.32	9.11	0	0	0	94.61
H-4	35.47	18.44	1.58	0	19.74	0.11	8.93	9.17	0	0	0	93.44
H-4	35.34	18.68	1.65	0.13	20.49	0	9.38	8.64	0	0	0	94.31
Chloritoid Zone												
N-6	34.67	19.62	1.6	0	19.92	0	8.7	9.68	0	0	0	94.19
N-6	35	19.42	1.46	0	19.99	0	8.98	10.02	0	0	0	94.87
N-7	36.93		1.77	0.12	17.58	0	12.03	9.76	0	0	0.05	95.02
N-7	36.69	17.07	1.71	0	17.82	0	11.81	9.66	0	0	0	94.76
N-7	37	16.75	1.66	0.12	17.22	0	12.06	9.64	0	0	0	94.45
N-7	38.07	16.56	1.45	0	15.92	0	13.31	9.59	0	0	0	94.9
N-8	35.6	18.62	1.65	0	19.78	0	9.25	10.12	0	0	0	95.02
N-8	35.86	18.67	1.67	0	19.46	0	9.69	9.98	0	0.95	0	96.28
O-3	33.03	19	1.77	0	22.18	0	8.82	7.84	0	0	0.1	92.74
O-3	30.66	18.77	1.68	0	23.61	0	9.55	5.91	0	0	0.14	90.32
O-3	33.23	18.64	1.91	0	22.26	0	8.99	7.71	0	0	0.16	92.9
O-3	33.48	18.66	1.85	0	22.01	0	8.97	7.95	0	0	0.12	93.04
Staurolite Zone												
AE-2	36.4	17.83	1.73	0	19.01	0.16	10.5	9.73	0	0	0.06	95.42
AE-2	35.96	17.94	1.68	0	19.46	0.14	10.35	9.67	0	0	0	95.2
AE-2B	35.47	17.76	1.91	0	19.52	0.19	9.86	10.08	0	0	0	94.79

Biotite Analyses in the Sudbury Breccia

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MnO	MgO	K2O	CaO	Na2O	CL	TOTAL
NB-1	36.02	18.25	1.67	0	17.59	0	11.56	9.46	0	0	0.05	94.6
NB-1	36.12	17.66	1.64	0	16.87	0.12	11.59	9.44	0	0	0.06	93.5
NB-1	37.4	18.48	1.73	0	17.44	0.13	11.51	9.57	0	0	0	96.26
NB-1	36.32	18.09	1.67	0	16.78	0.15	11.72	9.46	0	0	0	94.19
NB-1	34.66	18.39	1.52	0	18.35	0.15	12.4	8.15	0	0	0.06	93.68
NB-1	36.04	18.48	1.66	0	16.83	0	11	9.54	0.1	0	0	93.65

Biotite Analyses in the Onaping Formation

AV604	35.31	15.73	1.16	0	19.98	0.58	10.36	9.21	0	0	0	92.33
AV604	36.46	16.06	0.94	0	19.59	0.56	10.13	9.76	0	0	0	93.5
AV604	36.27	16.52	1.25	0	20	0.55	10.26	9.5	0	0	0	94.35
AV604	36.23	16.06	1.45	0	19.84	0.46	10.21	9.4	0	0	0.06	93.71
AV605	36.24	16.62	1.04	0	20.79	0.59	10.85	9.18	0	0	0	95.31
AV605	35.49	16.34	1.16	0	19.94	0.58	10.54	9.27	0	0	0.07	93.39

Biotite Analysis in the Espanola Formation

ESP-2	41.28	12.06	0.52	0	9.17	0	20.44	9.71	0	0	0	93.18
-------	-------	-------	------	---	------	---	-------	------	---	---	---	-------

APPENDIX 8

Garnet Analyses in the Worthington Area

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MnO	MgO	CaO	TOTAL
Garnet Zone									
F-1 core	37.11	20.4	0	0	31.6	6.34	1.32	2.22	98.99
F-1 rim	37.96	20.84	0	0	31.41	6.7	1.59	2.06	100.56
F-2 rim	37	20.69	0	0	32.05	5.05	1.47	3.32	99.58
F-2 core	36.98	20.89	0	0	31.12	7.41	1.9	2.32	100.62
F-3 rim	36.67	20.6	0	0	31.77	5.87	1.48	3.27	99.66
F-3 core	36.94	20.83	0	0	31.66	7.26	1.69	2.18	100.56
H-1 rim	36.95	20.91	0	0	34.14	3.87	1.91	3.06	100.84
H-1 core	36.67	20.64	0	0	32.73	5.84	1.62	2.5	100
H-2 rim	36.51	20.91	0	0	34.24	3.65	1.7	2.83	99.84
H-2 core	36.27	20.74	0	0	32.58	5.29	1.73	2.75	99.36
H-3 rim	36.7	20.57	0	0	34.17	3.62	1.58	2.95	99.59
H-3 core	37.06	21.13	0	0	32.91	4.74	1.96	2.97	100.77
H-4 core	36.76	20.4	0	0	32.12	4.86	1.57	3.01	98.72
H-4 halfway	36.84	20.54	0	0	32.23	4.65	1.76	2.77	98.79
H-4 rim	36.78	20.16	0	0	33.55	3.09	1.95	2.88	98.41
K-3 rim	37	20.73	0	0	34.28	4.34	1.64	2.77	100.76
K-3 core	37.11	21.09	0	0	33.76	5.47	2.15	2.25	101.83
Chloritoid Zone									
N-6 core	36.72	21.37	0.18	0	32.96	6.04	1.47	2.66	101.4
N-6 halfway	36.87	20.99	0	0	32.08	6.43	1.64	2.23	100.24
N-6 rim	36.52	21.74	0	0	31	8.28	1.33	1.98	100.85
N-8 rim	36.45	20.16	0.33	0	34.74	3.52	2.01	2.14	99.35
N-8 halfway	36.18	20.41	0.36	0.14	34.83	3.23	2.2	2.17	99.52
N-8 core	36.48	20.4	0.42	0	34.99	2.41	2.59	2.11	99.4
O-3 core	37.3	20.55	0.55	0	33.49	2.07	3.35	2.23	99.54
O-3 halfway	37.39	20.65	0.42	0.14	32.11	0.79	4.89	2.39	98.78
O-3 rim	36.72	20.02	0	0	34.13	3.18	1.97	2.15	98.17

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MNO	MGO	CAO	TOTAL
Staurolite Zone									
AE-2 core	37.17	20.87	0	0	32.46	4.95	2.01	2.97	100.43
AE-2 rim	37.57	21.03	0	0	31.65	5.58	1.82	3.48	101.13
Garnet Analyses in the Onaping Formation									
AV604 rim	36.95	20.35	0.21	0	12.3	17.55	0.51	11.28	99.15
AV604 outer rim	37.08	20.53	0	0	12.21	18.18	0.33	10.44	98.77
AV604 core	36.91	20.39	0.25	0	12	18.17	0.51	10.84	99.07
AV604 rim	36.85	20.12	0.16	0	12.14	17.69	0	11.24	98.2
AV604 halfway	36.88	20.34	0.21	0	12.19	17.7	0.44	11.41	99.17
AV604 core	36.8	20.17	0.22	0	11.6	17.41	0.31	11.68	98.19
AV605 core	37.36	21.23	0.18	0	10.77	18.4	0	11.2	99.14
AV605 halfway	37.34	21.1	0.22	0	11.32	18.08	0.58	11.12	99.76
AV605 rim	37.05	21.11	0.16	0	12.56	17.21	0.48	10.77	99.34
AV605 core	36.78	20.92	0.3	0	10.5	18.5	0.44	11.56	99
AV605 halfway	37.66	21.07	0.22	0	11.49	18.2	0.6	11.07	100.31
AV605 rim	36.92	21.26	0.23	0	12.36	16.57	0.66	11.34	99.34
AV605 core	37	21.13	0.18	0	11.14	18.3	0.39	11.48	99.62
AV605 halfway	37.56	20.95	0.23	0	12.09	17.51	0.6	11.08	100.02
AV605 rim	36.96	21.15	0.13	0	12.36	17.35	0.33	10.94	99.22

APPENDIX 9
Chloritoid Analyses in the Worthington Area

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MnO	MgO	CL	TOTAL
Chloritoid Zone									
AE-4	27.54	54.28	0.57	0	12.67	0.3	1.18	0	96.54
AE-4	27.53	54.75	0.63	0	12.32	0.26	1.12	0	96.61
D-1	24.03	41.16	0	0	24.55	0.56	2.12	0	92.42
D-1	24.34	41.24	0	0.11	24.37	0.52	2.34	0	92.92
L-1	24.06	39.71	0	0	24.2	0.33	2.76	0	91.06
L-1	24.08	40.36	0	0	24.08	0.38	3.1	0	92
N-O	24.26	41.22	0	0	23.62	0.4	3.2	0	92.7
N-O	24.32	41.47	0	0	23.73	0.39	2.92	0	92.83
N-1	24.58	40.59	0	0	23.51	0.3	2.88	0	91.86
N-1	24.68	40.69	0	0.12	23.01	0.41	2.76	0	91.67
N-2	24.2	40.54	0	0	23.07	0.43	2.88	0	91.12
N-3	24.34	40.28	0	0	23.97	0.37	3.03	0	91.99
N-3	24.36	40.41	0	0	23.65	0.52	3.09	0	92.03
R1-3	24.56	40.37	0	0	23.71	0.47	3.17	0	92.28
R1-3	24.6	40.42	0	0	24.1	0.42	3.04	0	92.58
Z-2	24.28	39.87	0	0	24.35	0.44	2.83	0	91.77
Z-2	24.33	40.33	0	0	24.56	0.43	2.49	0	92.14

APPENDIX 10
Staurolite Analyses in the Worthington Area

SAMPLE	SiO2	TiO2	Al2O3	FeO	MnO	MgO	ZnO	TOTAL
Chloritoid Zone								
N-O	27.95	0.46	55.55	12.96	0.24	1.25	0.38	98.79
N-1	27.67	0.3	54.91	13.02	0.28	1.07	0.27	97.52
N-1	27.8	0.26	54.65	12.45	0.23	1.01	0.25	96.65
N-2	28.06	0.49	55.38	12.45	0.25	0.9	0.29	97.82
O-2	27.93	0.27	54.74	10.53	0.37	1.1	2.34	97.28
O-2	27.67	0.32	54.81	10.94	0.31	1.04	1.95	97.04
Staurolite Zone								
AB-2	27.77	0.5	54.83	11.94	0.38	1.23	1.28	97.93
AB-2	27.79	0.51	54.64	12.2	0.41	1.28	0.78	97.61
D1-1	26.93	0.49	54.17	12.07	0.33	0.97	0.65	95.61
D1-1	27.93	0.52	54.69	12.84	0.33	1.06	0.54	97.91
D2-1	27.85	0.55	54.06	13.14	0.3	1.2	0.52	97.62
D2-1	27.86	0.49	54.65	13.12	0.27	1.25	0.48	98.12
R-4	27.12	0.52	54.58	11.89	0.27	1.11	1.89	97.38
R-4	27.24	0.35	55.09	12.06	0.3	1.03	1.8	97.87
T-B	26.97	0.51	55.6	12.92	0.22	1.03	0.41	97.66
T-B	26.37	0.48	55.43	13.14	0.26	0.91	0	96.59
V-3	27.8	0.54	53.41	12.58	0.37	1.07	0.74	96.51
V-3	27.83	0.53	53.8	13.06	0.21	1.44	0.52	97.39
W-5	27.63	0.5	54.53	13.27	0.34	1.15	0.38	97.8
W-7	27.78	0.4	52.86	12.45	0.26	0.83	0.39	94.97
W-7	27.47	0.38	53.46	12.98	0.24	1.22	0.38	96.13

APPENDIX 11
Amphibole Analyses in the Onaping Formation

SAMPLE	SiO2	Al2O3	TiO2	CR2O3	FeO	MnO	MgO	K2O	CaO	Na2O	CL	TOTAL
AV60513	55.25	2.44	0	0	11.57	0.69	14.47	0.87	11.05	0	0	96.34
AV60516	51.19	4.09	0	0	13.55	0.66	14.96	0.14	9.68	0	0	94.27

Amphibole Analyses in the Espanola Formation

ESP-3 1	55.98	1.21	0	0	7.36	0	18.72	0	12.99	0	0	96.26
ESP-3 3	56.03	0.9	0	0	7.2	0	18.95	0	12.83	0	0	95.91
ESP-3 4	55.23	1.22	0	0	7.79	0	18.02	0.11	12.65	0	0	95.02
ESP-2 2	57.25	1.33	0	0	6.46	0	20.22	0	13.29	0	0	98.55
ESP-2 6	55.81	1.44	0	0	8.29	0	18.81	0	12.68	0.9	0	97.93

IMAGE EVALUATION TEST TARGET (QA-3)

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved