

Investigation of transpressive deformation zones in the North Caribou greenstone belt (NW Superior) and relationships with regional metamorphism: Implications for the tectonothermal evolution during Archean cratonization

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Abstract

The Archean North Caribou greenstone belt (NCGB) possesses abundant transpressive deformation zones on its northern margins, which appear to have formed under amphibolite facies conditions. Protracted deformation and regional metamorphism are coeval with widespread magmatism and accretion events in the Superior Province, yet the importance of these shear zones in the tectonic evolution of the NCGB is equivocal. Structural analyses support a transpressive system that strongly implicates horizontal tectonism. This is partly in contrast with some currently proposed models for Archean greenstone belts suggesting synchronous vertical and horizontal movements. Geochemical and microstructural analyses from shear zones indicate heterogeneous deformation/fluids conditions on a km-scale. Monazite and mica geochronological ages indicate metamorphism and deformation occurring during the amalgamation of the Superior craton from ca. 2.75 to 2.4 Ga. The high metamorphic grade background may obscure tectonic signatures, yet some structural and geochemical characteristics remain consistent with other greenstone belts where vertical and horizontal displacement are recorded.

Key words: Superior Province, shear zones, metamorphism, transpression, geochronology

Word count: ~ 21 400 words (without figure captions and references)

Caractérisation de zones de déformation transpressives dans la ceinture de roches vertes North Caribou (Province Supérieure NO) et leur association avec le métamorphisme régional : Implications pour l'évolution tectonothermale pendant la cratonisation Archéenne.

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Résumé

La ceinture de roches vertes Archéenne North Caribou (NCGB) possède d'abondantes zones de déformations transpressives, qui semblent s'être formées sous conditions dans le faciès amphibolite. La déformation prolongée et le métamorphisme régional sont contemporains avec un magmatisme et des périodes d'accrétions répandus à travers la Province Supérieure. L'importance de ses zones de cisaillement dans l'évolution tectonique du NCGB est sous questionnement, cependant des analyses structurales supportent un système transpressif. Ceci implique un mode de tectonisme horizontal, qui est partiellement en contraste avec certains modèles proposés pour les ceintures des roches vertes Archéennes qui suggèrent des mouvements horizontaux et verticaux. Des analyses géochimiques et microstructurales provenant de zones de cisaillement montrent la nature hétérogène des conditions de déformation/fluides. La géochronologie de monazite et micas correspondents des périodes de métamorphisme et déformation causées par l'amalgamation du craton Supérieur de ca. 2,75 à 2,4 Ga. Le métamorphisme élevé peut couvrir certaines signatures tectoniques, cependant certaines caractéristiques structurales et géochimiques sont consistantes avec d'autres ceintures de roches vertes qui montrent un tectonisme vertical et horizontal.

Table of Contents

Abstract/Résumé	ii
Table of contents	iv
List of figures	vii
List of tables.....	viii
List of appendices.....	viii
Aknowledgements	x
Introduction.....	xi
Research objectives.....	xi
Summary of activities	xiii
Part I.....	1
Abstract.....	2
1. Introduction	3
2. Geological setting	6
2.1. Archean tectonics of the western Superior Province	6
2.2. North Caribou greenstone belt	8
3. Regional metamorphism.....	11
4. NCGB shear zones	12
5. Dinnick Lake shear zone	17
5.1. Whole rock geochemistry methods	18
5.2. Whole rock geochemistry results	19
5.3. EBSD methods	23
5.3.1.Pole figures	24
5.3.2.Grain boundary misorientation study	24
5.4. EBSD results	26
5.4.1.Pole figures	26

5.4.2. Grain boundary misorientation	28
6. Discussion.....	31
6.1. Synchronous metamorphism and deformation in the NCGB.....	32
6.2. Dinnick Lake shear zone.....	34
6.3. Transpression in shear zones of the NCGB, implications for horizontal tectonism.....	39
7. Summary	41
Part II	43
Abstract.....	44
1. Introduction	45
2. Geological setting	48
2.1. Archean tectonics of the western Superior Province	48
2.2. Geology of the North Caribou greenstone belt.....	51
3. Metamorphism of the NCGB	54
4. Mineral chemistry of phyllosilicate, amphibole and garnet.....	61
4.1. Fabric forming minerals.....	61
4.2. Amphiboles	65
4.3. Garnet	66
4.3.1. Metamorphic garnet	71
4.3.2. Hydrothermal garnet	72
5. Geochronology.....	73
5.1. K-Ar ages of fabric forming minerals.....	73
5.1.1. Results	79
5.2. In situ monazite U-Th-total Pb geochronology	80
5.2.1. Results	81
6. Discussion.....	85
6.1. Metamorphic patterns	85

6.2. Timeline of the NCGB.....	87
6.2.1.Abukuma-type regional metamorphism and hydrothermal alteration (2.75-2.71 Ga)	88
6.2.2.Retrograde metamorphism and hydrothermal alteration (2.60-2.56 Ga).....	90
6.2.3.Progressive metamorphism and hydrothermal alteration (2.50-2.44 Ga).....	92
6.2.4.Tectonic implications	94
7. Summary	95
References	97
Resume	113
Appendices	115

List of figures

Part I: Microstructural analyses of shear zones

Figure 1.1: Location and geological map of the NCGB

Figure 1.2: Photos of metamorphic assemblages and textures

Figure 1.3: Photos and geological map of Dinnick Lake shear zone

Figure 1.4: Whole rock geochemistry of basalts in the DSZ

Figure 1.5: Whole rock geochemistry of granites in the DSZ

Figure 1.6: Quartz pole figures

Figure 1.7: Representative feldspar and hornblende pole figures

Figure 1.8: Quartz grain boundary misorientation histograms

Figure 1.9: Strain/temperature gradient model for the DSZ

Part II: Characteristics and timing of deformation

Figure 2.1: Location and geological map of the NCGB with sample locations

Figure 2.2: Metamorphic map

Figure 2.3: Photos of metamorphic assemblages

Figure 2.4: Geochemistry of phyllosilicates, amphibole and garnet

Figure 2.5: Garnet x-ray maps

Figure 2.6: Monazite photos

Figure 2.7: Monazite ages

Figure 2.8: Robustness of monazite ages

Figure 2.9: Age map and timeline of the NCGB

List of tables

Part I

All tables are in appendices (listed below)

Part II

Table 2.1: K-Ar ages

All other tables are in appendices (listed below)

List of appendices

Appendix A: Whole rock geochemistry of the Dinnick Lake area

Appendix B: Analytical parameters for EBSD analyses

Appendix C: EBSD data rotation and thin section/pole figure orientation schematics

Figure C1.1: Schematic of thin section/pole figure orientation and rotation of EBSD data

Appendix D: Methodology for Kolmogorov-Smirnov statistical test

Appendix E: All feldspar and hornblende pole figures

Figure E1.1: All feldspar pole figures

Figure E1.2: All hornblende pole figures

Appendix F: Feldspar and hornblende grain boundary misorientation histograms

Figure F1.1: Feldspar grain boundary misorientation histograms

Figure F1.2: Hornblende grain boundary misorientation histograms

Appendix G: Sample descriptions

Table G1: Sample locations

Appendix H: Major element EMPA and x-ray mapping methodologies

Appendix I: Major element EMPA results

Table I1: Major element EMPA of biotite

Table I2: Major element EMPA of white mica

Table I3: Major element EMPA of chlorite

Table I4a: Major element EMPA of garnet (conducted by Gagnon)

Table I4b: Major element EMPA of garnet cores and rims (conducted by Kalbfleisch)

Table I5: Major element EMPA of amphibole

Appendix J: Methodology and results of U-Th-total Pb geochronology

Table J1: EMPA U-Th-total Pb data of monazite

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Introduction

Research objectives

Archean cratons represent the oldest remnants of crustal material found on Earth and are important to study in terms of a variety of characteristics. The Superior Province, one of the largest and best preserved Archean cratons, has been the source of many discussions on the nature of tectonism during the Archean (vertical versus horizontal tectonics), orogenic gold systems and the relationships between extensive deformation and fluid channeling. The goals of this research were: (1) to characterize the mode and amount of deformation during cratonization of the Superior between 3.0-2.4 Ga, using crustal-scale shear zones in the North Caribou greenstone belt (NCGB). Most models for Archean tectonics focus on crustal-scale shear zones since most of the deformation is accommodated there (e.g. Chen et al. 2001, Lin and Beakhouse 2013), therefore our investigations were focused on shear zones in the NCGB that are found in abundance particularly on the northern margins of the belt. Several analytical techniques were employed to investigate and quantify deformation mechanisms and crustal conditions in these shear zones. On a more regional scale, field observations and petrography were conducted on a variety of samples collected across the entire length of the greenstone belt, with an emphasis on textures and microstructures (e.g. shear sense indicators, evidence for dynamic recrystallization, mineralogy, etc). On a more localized scale, electron backscatter diffraction (EBSD) analysis was conducted on a ~1 km transect across a major shear zone (Dinnick Lake shear zone) that is along strike with the Musselwhite gold deposit. EBSD is an SEM-based method of calculating the crystallographic preferred orientation (CPO) of a rock, therefore providing information on deformation mechanisms, temperature estimates and recrystallization of major rock-forming minerals.

(2) The importance of these major crustal-scale shear zones in orogenic gold systems is still under questioning. In the NCGB, many of these are found on margins of the belt at granite-greenstone contacts, yet these were only previously studied in terms of dominant kinematics and size (Breaks et al. 2001). They are also important in the tectonothermal evolution of greenstone belts, therefore a variety of analytical techniques were used to characterize their relationships with regional metamorphism or tectonic

events (e.g. suture zones, conduits for fluids, reactivated structures). A regional metamorphic study was conducted on the belt to complement a previous study conducted in the 1980's that included only the northern arm of the NCGB (Break et al. 2001). To determine metamorphic grades, simple petrography on samples across the belt was conducted to determine peak metamorphic assemblages. Additional major element EMPA geochemistry was conducted on major minerals to further constraint metamorphic facies. Amphiboles and garnet chemistry can be used to infer a metamorphic grade as they are often index minerals. Fabric-forming minerals such as white micas, biotite and chlorite were investigated to complement an already existing compilation of chemistry across the entire belt. Lastly, cratonization of the Superior implicated many magmatism, deformation and metamorphic episodes which surely produced fluids that were circulated in crustal-scale structures. The Musselwhite mine is on evidence of this fluid circulation, yet very little information on fluid channeling in shear zones of the NCGB was previously obtained. In order to detect evidence of fluid channeling in shear zones, mineral textures (e.g. zoning, grain shapes, etc) and macroscopic structures (e.g. veining, alteration minerals, etc) were investigated, as well as whole rock geochemistry in the Dinnick Lake area.

(3) Many geochronological data was acquired in the NCGB from various studies, yet a clear tectonic evolution is still equivocal. Many ages can be difficult to interpret as the high metamorphic background and hydrothermal alterations are hard to distinguish. U-Th-total Pb geochronology of monazite from high strain zones (conducted by Kalbfleisch 2012) was included in this study in order to build a more robust interpretation. Additional K-Ar dating of fabric-forming white mica and biotite was performed to add to this database. Therefore with a compilation of available geochronological data and results obtained through various textural and microstructural investigations described above, we were able to produce a general timeline representing the tectonothermal evolution of the NCGB in a Superior Province context, which spans from 3.0 Ga to 2.4 Ga.

Summary of research activities

Research material presented in this document is divided into two parts. The first portion of the thesis discusses microstructural observations of shear zones in an Archean tectonics context and was submitted to Tectonophysics special issue on "Tectonics of oblique plate boundary settings" in March 2015. The second portion of the thesis highlights the timing of deformation and regional metamorphism of the North Caribou greenstone belt and will be submitted to Canadian Journal of Earth Sciences in the spring of 2015. Additionally, this work was presented at several conferences in the form of posters or short talks, such as PDAC minerals colloquium 2013 (poster), SEG Whistler 2013 (poster), GSA Vancouver 2014 (oral presentation) and AGU GAC-MAC 2015 (poster).

During the course of this research project, the field observations and laboratory data, reported in this document, were acquired by the author as well as Tash Kalbfleisch during completion of her University of Ottawa MSc thesis (Kalbfleisch, 2012). Compilation of these two datasets was necessary in order to build a meaningful tectonic interpretation of the area and best cover the geographic extent of the belt. Presented here is a brief summary of the provenance of each data set.

- Samples were collected by Gagnon over the summers of 2012 and 2013 (with the assistance of Colter Kelly and Marie-Ève Lajoie), as well as by Kalbfleisch (with the assistance of Élise Cossette, Amanda Van Lankvelt and Jason Duff) in 2010 and 2011.
- Field observations of shear zones located in the southern portion of the North Caribou greenstone belt (provided in part one of the thesis) are by Kalbfleisch. These unpublished data were combined with Gagnon's field observations for the central and western portions of the belt.
- All petrographic analyses were conducted by Gagnon in order to produce a metamorphic map and select strategic samples for further analyses.
- Electron backscatter diffraction analyses, data processing and structural analyses of the central portion of the belt were conducted by Gagnon.

- Whole rock geochemistry was completed by Gagnon on samples from two traverses in the central portion of the belt. Sample preparation (crushing, pulverizing) was performed by Gagnon before sending the material to Activation Laboratories (Lancaster ON). Additional geochemical data was provided by John Biczok from the Musselwhite mine in addition to the dataset.
- Major element EMPA analyses of phyllosilicates, amphibole and garnet from samples JAC XX, NCB12-XX and 13NCGB-XX, as well as samples NCTK10-16B and -44 were performed by Gagnon. Major element electron microprobe analysis (EMPA) analyses of the same minerals from samples named NCTK10-XX (excluding NCTK10-16B and -44) and NCB11-XX were performed by Kalbfleisch. Methodology, figures, and data tables are inclusive to reflect this grouping of data.
- Additionally, X-ray maps for samples JAC11 and 13NCGB-1 were acquired by Gagnon, whereas X-ray maps of sample NCTK10-26 were acquired by Kalbfleisch.
- K-Ar geochronology of muscovite and biotite was conducted by Gagnon.
- *In situ* U-total Pb monazite dating was conducted by Kalbfleisch. Therefore the text presented in part two of the thesis includes modified material written by Kalbfleisch; methodology, results and part of the discussion regarding monazite geochronology. The interpretation is that of Gagnon.

Part I

Characterization of transpressive deformation in shear zones of the Archean North Caribou greenstone belt (NW Superior Province) and the relationship with regional metamorphism

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Abstract

The 3.0-2.7 Ga North Caribou greenstone belt (NCGB), host to the Musselwhite BIF-hosted Au deposit, possesses abundant crustal-scale shear zones on its northern margins, which appear to have formed under amphibolite facies conditions. Protracted deformation and regional metamorphism are coeval with widespread magmatism and accretion events during cratonization of the western Superior Province, and are responsible for folding the ore-hosting BIF and channeling fluids. The importance of these shear zones in the tectonic evolution of the NCGB and their relationship with metamorphism is equivocal, yet higher-grade metamorphic minerals seem to correlate with loci of higher strain. Structural analyses support transpressive collision that produced steeply-dipping planar and shallow-plunging linear fabrics with dominant dextral kinematics, that trend broadly parallel to the doubly arcuate shape of the belt. Electron backscatter diffraction analyses were conducted on strategic samples across one shear zone in order to characterize crustal conditions during transpressive deformation. The Dinnick Lake shear zone cuts through mafic metavolcanic rocks and, at its core, a sheared granite composed of recrystallized quartz. Whole rock geochemistry shows little variation in Ca, Na, Mg and K (often used as indicators of hydrothermal alteration) from surrounding less deformed units, suggesting deformation in a dry environment. Microstructural analysis show subgrain rotation recrystallization and deformation by prism a- and c-slip in quartz, as well as aligned hornblende that together suggest deformation temperatures above 500°C. Quartz in mafic rocks along the margins of the shear zone also show a basal a-slip component, indicating slightly lower strain or temperature. Although the NCGB exhibits some evidence of vertical tectonism (dome and keel structures), the dominant strain record within the marginal shear zones is that of horizontal (transpressive) displacement. This is in agreement with other greenstone belts in the Western

Superior (e.g. Hemlo greenstone belt) where vertical and horizontal tectonism were coeval during late stages of cratonization.

1. Introduction

The Archean North Caribou greenstone belt (NCGB) in northwestern Ontario is part of the nucleus of Canada's western Superior Province (termed North Caribou Superterrane, NCS), which is characterized by east-west trending belts that represent remnants of microcontinents and oceanic basins (Percival et al. 1994, Biczok et al. 2012; **Fig. 1.1A**). The NCGB comprises 3.0-2.7 Ga metavolcanic-metasedimentary assemblages and is host to the Musselwhite lode gold deposit (**Fig. 1.1B**). The ore occurs in middle amphibolite metamorphic facies banded iron formation units, along highly strained, near-vertical limbs of isoclinal folds and within adjacent fold hinges. The margins of the NCGB are defined by discrete deformation zones, which were likely reactivated throughout the amalgamation of the western Superior Province during the Neoproterozoic Uchian orogeny (Percival et al. 1994, Breaks et al. 2001, Percival et al. 2006, Kalbfleisch 2012). Percival et al. (2006) among others suggested growth of the Superior Province is a consequence of horizontal tectonism, in contrast with models proposing vertical tectonism to explain the formation of arcuate greenstone belts typical of the Western Superior and other Archean granite-greenstone terrains (e.g. Lin and Jiang 2001, Lin and Beakhouse 2013). Significant vertical displacement has been documented in several other western Superior greenstone belts such as Hemlo and Cross Lake, supporting a dome and keel model that would result in sagduction of greenstone belts between rising granitoid domes (Lin 2005, Parmenter et al. 2006, Lin and Beakhouse 2013). A dominant vertical component is proposed to have been synchronous with a subordinate horizontal component, focused along crustal-scale shear zones at

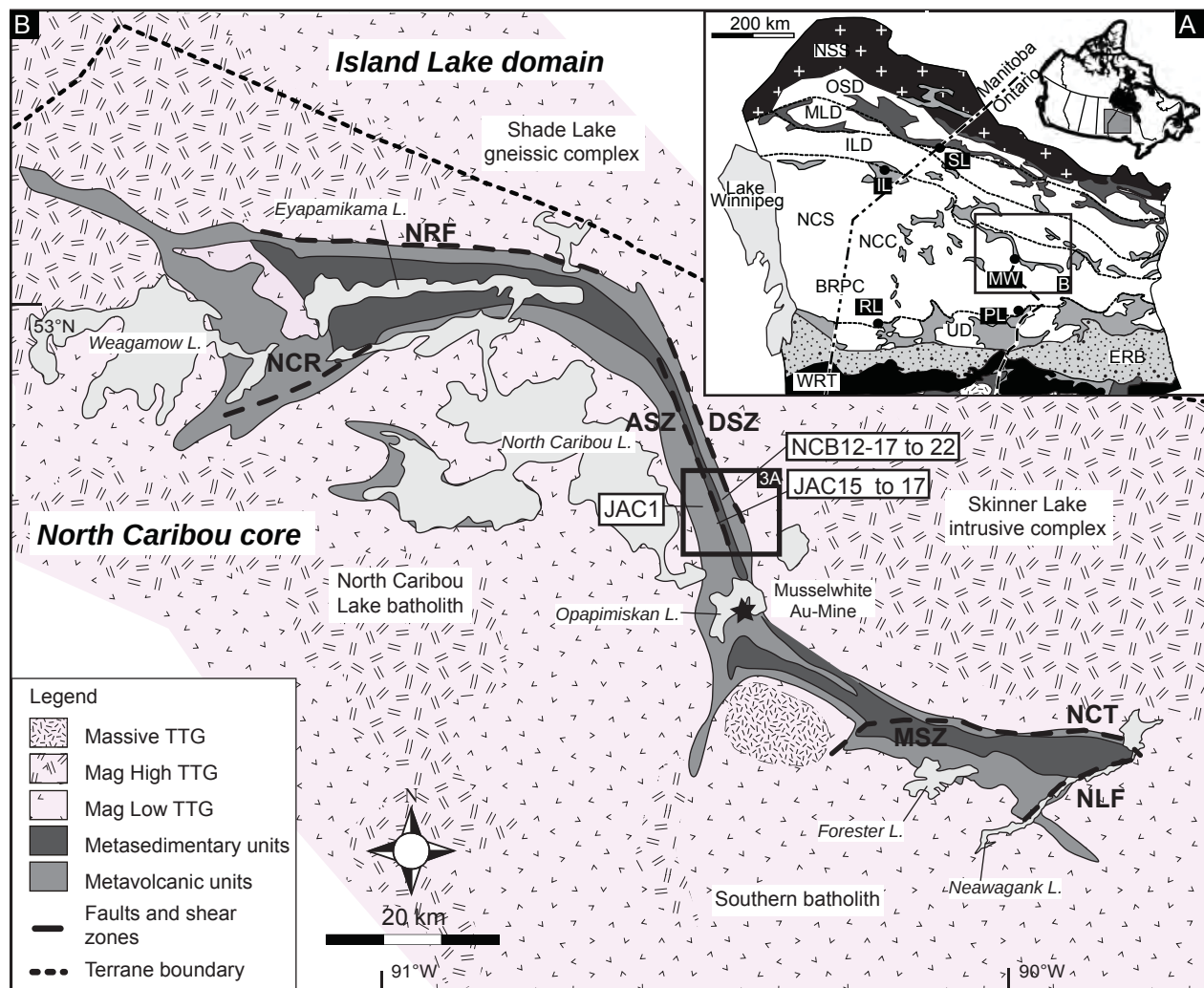


Figure 1.1: Location and regional geological map of the North Caribou greenstone belt in Northwestern Ontario. A) Modified from Percival et al. 2006. Location of the NCGB in the Western Superior Province. Black box shows map area of figure 3A. NSS, Northern Superior superterrane; NCS, North Caribou superterrane; OSD, Oxford-Stull domain; MLD, Munroe Lake domain; ILD, Island Lake domain; NCC, North Caribou core; BRPC, Berens River plutonic complex; UD, Uchi domain; SL, Stull Lake; IL, Island Lake; MW, Musselwhite; RL, Red Lake; PL, Pickel Lake; WRT: Winnipeg River terrane; ERB: English River basin. B) Modified from Breaks et al. 2001. Regional geological map of the NCGB surrounded by TTG granitoids classified by their aeromagnetic signatures. Sample locations used for analyses are shown in white boxes. Musselwhite mine is represented by the yellow star. ASZ, Akow Lake shear zone; DSZ, Dinnick Lake shear zone; MSZ, Markop Lake shear zone; NCT, North Caribou-Totogan deformation zone; NCR, North Caribou River fault; NLF, Neawagank Lake fault; NRF, North Rim fault zone.

granite-greenstone contacts with a potential for channeling fluids and ore deposition. Yet studies of other Archean greenstone belts (e.g. Yilgarn craton, Western Australia) indicate more complex systems with transpression-related shortening and shearing processes in the formation of shear zones and arcuate greenstone belts (e.g. Chen et al. 2001, Zibra et al. 2014). Shear zones on northern margins of the NCGB separate the Island Lake Domain (ILD) in the north from the North Caribou superterrane to the south, and are interpreted as a suture (Percival et al. 2006). Understanding the nature of tectonism at this important boundary will provide insights into Archean geodynamics and the evolution of the western Superior Province, as well as on the potential for structurally-controlled orogenic gold deposits that are thought to originate from collisional systems during the Archean (Biczok et al. 2012).

The metamorphic grade of the host rock at the Musselwhite mine and the overall conditions of metamorphism are notable from the typical greenschist facies often observed in other greenstone belts of the Superior Province. Abukuma-type regional metamorphism in the NCBG is thought to have occurred at 2.75-2.69 Ga, reaching middle amphibolite facies conditions (Breaks et al. 1991; Kalbfleisch 2012; Biczok et al. 2012; Kelly et al. 2013; Kelly and Schneider 2015). Protracted tectonism in the belt created the complex metamorphic map pattern and consequent metamorphic veil, making it difficult to distinguish between metamorphic and ore-bearing hydrothermal signatures. Although deformation has important implications for mineralization in the NCGB (e.g. dilatant zones, fracture network for veining, tectonic pumping, etc.), little attention has been given to understanding the major shear zones within this portion of the western Superior Province. These shear zones have only been documented in terms of their orientation, size and dominant kinematics (Breaks et al. 2001).

We have conducted extensive sampling in order to further document the deformation and metamorphic assemblages in the NCBG. This was coupled to a detailed microstructural and textural investigation using electron backscatter diffraction (EBSD) analysis on one major shear zone, the Dinnick Lake shear zone (DSZ), that is located on the northern margin of the NCBG and is along strike from the Musselwhite deposit (**Fig. 1.1B**). Samples from the Akow Lake (ASZ), Markop Lake (MSZ) and North Caribou-Totogan (NCT) shear zones were studied for structural and petrographical comparison. The main objectives of resolving the tectonometamorphic relationships are to better understand the nature and tectonic evolution of the NCBG within a Superior Province context, and provide insight into Archean geodynamics. Our results strongly support transpressive, horizontal deformation that was focused in major deformation zones formed under mid-crustal conditions.

2. Geological setting

2.1. Archean tectonics of the western Superior Province

The Superior Province is one of the best-preserved and largest Archean terranes, and possesses numerous economically viable metallic ore deposits, including many large structurally controlled gold deposits. This vast craton represents the core of the Canadian Shield and is characterized by E-W to NW-SE trending subprovinces separated by large-scale boundary faults (Percival et al. 2006 and references herein). Geochronology, isotopic work and aeromagnetic surveys across the province have permitted the reclassification of these subprovinces into a series of terranes and superterranes, which are thought to represent fragments of ancient crust material that were fragmented and amalgamated during orogeny (Percival et al. 2006). The accretion of microcontinents during the Neoarchean Uchian orogeny created a pattern of scattered and narrow

greenstone belts interpreted to represent relicts of oceanic basins between older continental crust terranes (Percival et al. 2006). Orogeny was protracted, with up to five accretionary events, and closely associated with widespread magmatism, regional metamorphism and deformation (Percival et al. 2006 and references therein).

The nucleus of the western Superior Province is thought to be the 3.0 Ga North Caribou superterrane (NCS) to which younger microcontinents and island arcs accreted both from the north and the south (Williams 1990, Thurston et al. 1991, Percival et al. 2006). The northern margin of the NCS represents a purported suture zone of an ancient southward-directed subduction zone that led to the docking of the ca. 3.7 Ga Northern Superior Superterrane (oldest Eoarchean microcontinent in the western Superior, Böhm et al. 2000, 2003, Skulski et al. 2000, Percival et al. 2006). Convergence is evinced by the presence of south-over-north shear zone kinematics (Lin et al. 2006) and the identification of magmatic arc activity between 2.775 and 2.733 Ga across the Island Lake, Munroe Lake, and Oxford-Stull domains (**Fig. 1.1A**, Corkery et al. 2000, Skulski et al. 2000, Parks et al. 2006). The southern margin of the NCS likewise records ca. 2.75-2.71 Ga arc magmatism across the Berens River plutonic complex and Uchi domain (Corfu et al. 1995), which has been interpreted as northward subduction that led to the docking of the ca. 3.4 Ga Winnipeg River Terrane (**Fig. 1.1A**, Percival et al. 2006).

This study is focused on the North Caribou greenstone belt located within the NCS (**Fig. 1.1B**). The NCS is a Mesoarchean microcontinent characterized by ca. 3.0 Ga juvenile crust overlain by ca. 2.9-2.86 Ga sedimentary and mafic to ultramafic units. The latter assemblage is thought to represent platformal or rift-type sequences (Thurston and Chivers 1990, Thurston et al. 1991). It has been proposed that this arcuate greenstone belt trapped between granitoid domes could have originated as a product of vertical tectonism, permitting sagduction of heavier

greenstones during domal ascent of granitoids (e.g. Goodwin and Smith 1980, Gorman et al. 1978, Chardon et al. 1996, 1998, Lin 2005, Parmenter et al. 2006, François et al. 2012). However, other recent studies have revealed the complexity of tectonism during the Archean and several other models have been proposed. Lin et al. (2013) proposed synchronous vertical and horizontal tectonism during the formation of the Hemlo greenstone belt, with channeling of ore-bearing fluids in shear zones at granite-greenstone contacts. Chen et al. (2001) presented a transpressional model implicating horizontal motions for the formation of shear zones and the formation of arcuate greenstone belts, whereas Zibra et al. (2014) invoked an inclined transpressive system in which shear zones developed during progressive pluton emplacement. Deformation zones bounding the northern margins of the NCGB are of particular interest in this question as they preserve a record of deformation and may be conduits for metal-bearing fluids responsible for the mineralization across the belt.

2.2. North Caribou greenstone belt

The NCGB is a 3.0-2.7 Ga metavolcanic-metasedimentary belt located in the North Caribou Superterrane. The greenstone belt is surrounded by slightly younger granitoid and gneiss domes, which define a doubly arcuate geometry with two E-W trending arms and a central NNW-SSE portion. The oldest dated supracrustal unit is a thin felsic metavolcanic unit found west of Opapimiskan Lake and recently dated at 3053.1 ± 0.8 Ma (V. McNicoll pers. comm.). This is overlain by the South Rim metavolcanic assemblage dated at ca. 2981 Ma, which itself is unconformably overlain by the ca. 2967-2980 Ma Opapimiskan-Markop package of clastic and chemical metasedimentary and komatiite-rich metavolcanic rocks (U-Pb zircon, deKemp 1987, Davis and Stott 2001, Biczok et al. 2012). The northern flank of the belt is occupied by the ca.

2868 Ma North Rim assemblage, which is separated from the South Rim assemblage by apparently younger metasedimentary rocks along the central axis of the belt which comprise ~50% of the belt (Thurston et al. 1991, Breaks et al. 2001, Davis and Stott 2001, Biczok et al. 2012). The stratigraphically youngest sedimentary rocks are interpreted as submarine turbidite fan deposits and include cobble- to pebble-quartz conglomerates grading upward to quartz-rich wackes and are ideal for determining peak metamorphic conditions as they often contain index minerals (**Fig. 1.2A-E**; Breaks et al. 2001 and references therein, Biczok et al. 2012, Kelly et al. 2013). Supracrustal assemblages of the NCGB are surrounded by contemporaneous 2.9-2.7 Ga granitoid suites, including the Shade Lake gneissic complex to the east and north, the North Caribou Lake batholith to the south and west, and the Southern batholith to the north (**Fig. 1.1B**; Breaks et al. 2001, Biczok et al. 2012, Van Lankvelt 2013).

The NCGB is host to the >5.9 M oz Musselwhite lode gold deposit, with multiple sulfidized and quartz flooded/veined ore zones contained in a moderately metamorphosed banded iron formation that is tightly folded and historically has averaged 6-7 g/t Au (Biczok et al. 2012). Gold mostly resides in highly strained fold limbs and adjacent hinges (Biczok et al. 2012). Although the deposit lies at the boundary between two crustal domains, there is no evidence that the deposit is controlled by a major crustal-scale shear zone (Biczok et al. 2012). Gold was deposited under amphibolite facies conditions (540-600°C) and the sources for mineralizing fluids are still equivocal, but are thought to be a mix of magmatic- and metamorphic-derived fluids that circulated through shear/high strain zones (Otto 2002, Isaac 2008, Biczok et al. 2012, Kalbfleisch 2012, Duff 2014). Mineralization is located in a garnet-grunerite silicate facies of the iron formation and is characterized by pyrrhotite veinlets in the host rock as well as fracture-filling in garnet. Mineralization-related alteration is identified by

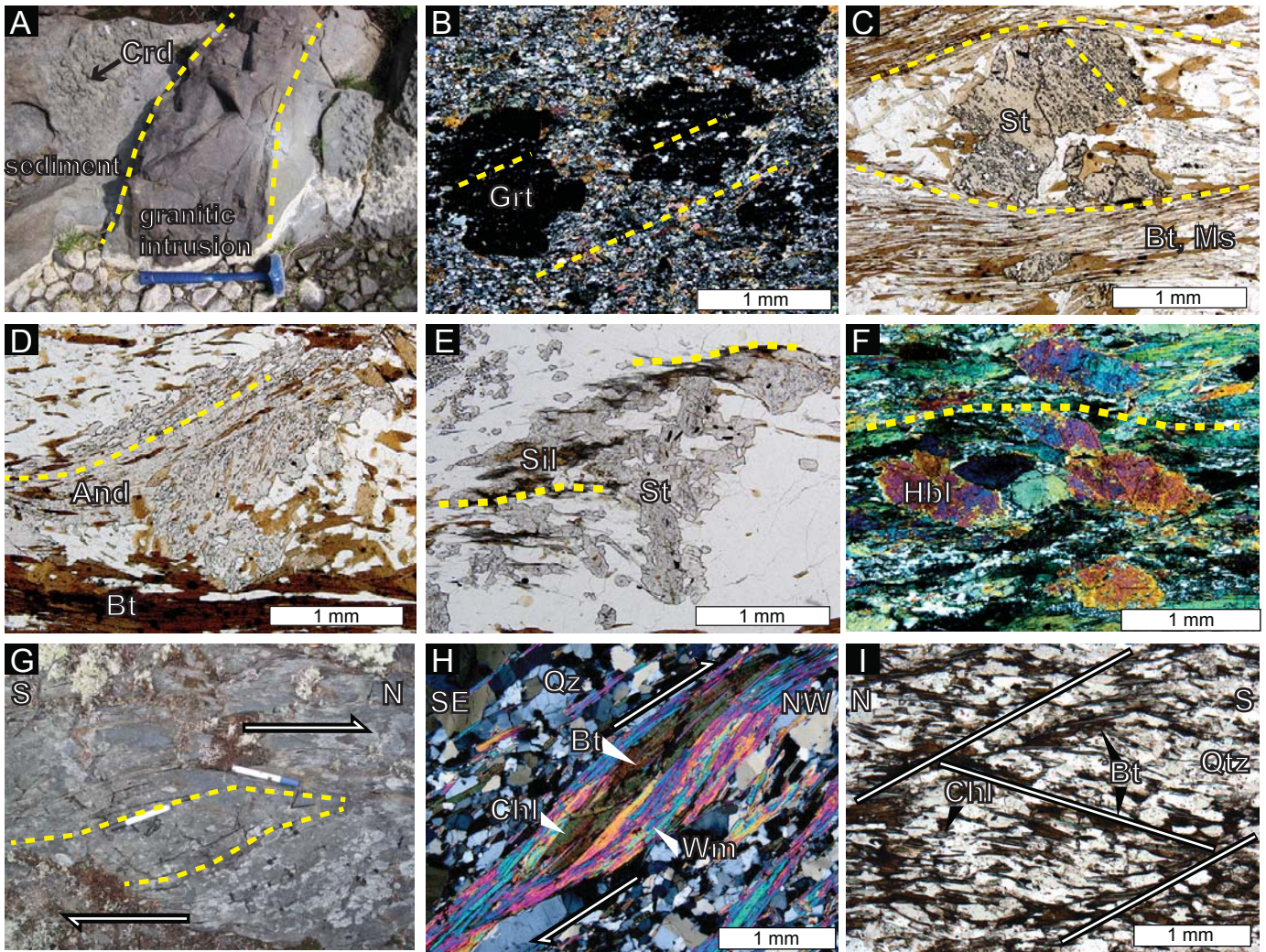


Figure 1.2: Field photos and photomicrographs of representative metamorphic and structural textures in the NCGB. A) Porphyroblastic cordierite in a metasediment adjacent to the felsic intrusion on east Eyapamikama Lake. B) Photomicrographs of syn- to post-tectonic garnets (Grt) from metasedimentary rocks in the Castor-Pollux (13NCGB-2). C)-D)-E) Plane-polarized light photos of peak metamorphic mineral assemblages in metasedimentary rocks from the Akow Lake area showing syn-tectonic staurolite (St), andalusite (And), and sillimanite (Sil). Commonly, the staurolite and andalusite are poikiloblastic and corroded; Sillimanite is generally found growing on andalusite. Note the inclusion trails within the refractory index minerals, which are oblique to the main rock structure. F) Cross-polarized light photo of hornblende (Hbl) porphyroblasts in foliated mafic volcanic rocks from the Akow Lake shear zone showing sinistral shearing. Finer Hbl define a finer foliation surrounding the larger porphyroblasts. G) Mafic volcanics on the western edge of the DSZ showing steeply dipping foliation with dextral kinematics. H) Cross-polarized photo of a sigmoidal bundle of white mica, biotite, and chlorite surrounded by dynamically recrystallized quartz in a two-mica schist from the transition of the NCT and MSZ. I) Plane-light image of SC-fabric in a biotite-schist from the ALFZ.

green amphibole replacing grunerite, quartz veining, chlorite patches and the growth of hydrothermal garnet (Biczok et al. 2012). Additionally, chlorite replacing garnet, green amphibole and grunerite indicate a retrograde metamorphic path at 210-250°C in high strain zones (Otto 2002, Biczok et al. 2012). The age of mineralization has broadly been reported at ca. 2717-2660 Ma, with a preferred age of 2690 Ma, based on Sm-Nd whole rock-garnet ages at the mine (Biczok et al. 2012), and across the belt at ca. 2765-2700 Ma based on U-Pb zircon depth profiling analyses on zircon (Kelly and Schneider, 2015).

3. Regional metamorphism

Metamorphic patterns in the NCGB were previously studied by Breaks et al. (2001) and limited to a simple isograd map of the N-S trending portion and northwestern arm of the belt. Two main trends were identified based on mineral assemblages in the different lithologies. The first being an increase of metamorphic grade from the northwest, dominated by chlorite + biotite, to the mine area discerned with the presence of garnet + staurolite + grunerite ± sillimanite (Breaks et al. 2001, Kelly et al. 2013). This trend was interpreted as being evidence for hotter conditions or exposure of deeper crustal levels in the mine area. The second trend is a zonal increase in grade to the north in the Eyapamikama Lake area, the northwestern arm of the belt. This increase is noted by the presence of biotite + chlorite near the southern rim of the belt that locally grades into garnet + staurolite + andalusite + sillimanite at the northern rim (Breaks et al. 2001, Kelly et al. 2013). Another metamorphic feature was identified as nodal, localized contact metamorphism represented by the growth of cordierite porphyroblasts in proximity to small intrusions (**Fig. 1.2A**, Kelly et al. 2013). Metamorphic patterns are broadly parallel to the doubly arcuate shape of the belt; this curved geometry has been interpreted as being induced by the

domal emplacement of the North Caribou Lake batholith (2870 Ma; Breaks et al. 2001, Stott and Biczok 2010), intruding into an already metamorphosed terrane, evinced by a thin contact aureole adjacent to the batholith (not observed in this study; Breaks et al. 2001). The southern arm of the greenstone belt was not investigated in this original metamorphic study due to limited occurrences of index minerals. There is also an abundance of shear zones cross-cutting through the belt, which have disturbed the background metamorphic patterns, making it more difficult to resolve the metamorphic grade.

The variations in metamorphic grade were defined petrologically by identifying specific mineral assemblages in metasedimentary and mafic metavolcanic units. Lowest temperature conditions are represented mostly by fabric forming minerals such as muscovite and chlorite, whereas higher-grade conditions are represented by a variety of porphyroblastic phases (e.g. garnet, staurolite, and andalusite). The relationships of these porphyroblasts with structural fabrics such as garnet with inclusion trails parallel to main foliation, andalusite and sillimanite aligned with foliation, rotated staurolite, and hornblende L-tectonites indicate a dominant syn- to post-tectonic growth (**Fig. 1.2A-F**, described in section 4). Breaks and Bartlett (1991) also recorded several occurrences of kyanite in the Miskeesik Lake area and possibly in the Markop Lake area, pointing to higher pressure conditions in certain parts of the belt. Although kyanite-bearing assemblages were not observed in our sampling, we cannot exclude the possibility of these conditions occurring in some areas.

4. NCGB shear zones

Several deformation zones define the northern margins of the NCGB and their importance in the regional tectonometamorphic history is unclear. Shear zones discussed here,

from north to south, include the North Rim fault (NRF), the Akow Lake shear zone (ASZ), the Dinnick Lake shear zone (DSZ), the Markop Lake shear zone (MSZ) and the North Caribou-Totogan shear zone (NCT). Strike length varies from 10-40 km, and the width of the shear zones is generally 200-300 m (**Fig. 1.1B**). The Markop Lake shear zone is not as discrete, as it may be as wide as 1500 m, and it may represent the westward termination of the extensive Totogan shear zone.

Regional rock structure is pervasive and nearly all units exhibit a moderate to steep planar foliation that is generally parallel to the main trend of the belt and that varies in intensity, spacing or homogeneity. Structure is mainly defined by segregation of quartz/feldspar-rich microlithons from phyllosilicate-rich foliation planes in metasedimentary/felsic metavolcanic units, and by the alignment of hornblende in mafic metavolcanic units (**Fig. 1.2C, F, H**). Rock fabric increases towards narrow shear zones and in some cases their cores display dynamically recrystallized and lineated units (e.g., mylonite and L-tectonite). In addition, some ductile shear zones have been brittlely reactivated and display fault breccia or pseudotachylite with fragments of mylonitic material at their core (Breaks et al. 2001). Most high metamorphic grade minerals such as andalusite, sillimanite and staurolite are found in proximity to these high strain zones and preserve syn- to post-tectonic porphyroblast textures (Breaks et al. 2001, Kelly et al. 2013). White mica and biotite wrap around porphyroblasts when present, otherwise they are found intergrown with chlorite in sinuous bundles. Less common are coarse blocky mica and chlorite grains that are randomly oriented and cross-cut the main foliation, suggesting a secondary paragenesis formed under low strain. Shear sense can be determined in several locations based on S-C fabric and shear bands (e.g. ASZ and DSZ respectively, **Fig. 1.2G, I**) that illustrate dominant dextral displacement, consistent with other studies (Breaks et al. 2001). Hornblende is

found mostly in mafic metavolcanic units, but can be seen in some metasedimentary rocks in proximity to contacts with mafic units (e.g. NRF area). Most amphibole are elongated and define the main fabric; a few porphyroclasts are seen in the DSZ and ASZ, which are coarser and appear more corroded. Amphibole are present as augen-shaped pods or boudins surrounded by recrystallized quartz and appear as fish structures (**Fig. 1.2F**). Their sigmoidal shape may indicate strain kinematics. In the DSZ and ASZ, amphibole displays mostly dextral kinematics, but it is not uncommon to observe sinistral shear sense, as well. Other porphyroblasts such as staurolite and andalusite are abundant in the ASZ and MDZ. Often poikiloblastic and flattened with respect to the fabric (**Fig. 1.2A-E**), their relationship with the rock structure illustrates peak metamorphic conditions that were syn- to post-tectonic. Garnet in deformation zones is relatively undeformed but can be flattened or fractured with regard to the fabric. Most garnets contain inclusion trails that are parallel or inclined relative to the main fabric and commonly are present in cm-scale dilation zones or clusters surrounded by chlorite and biotite, which may suggest a hydrothermal origin (e.g. MSZ, NRF).

Quartz also allows for an estimation of strain intensity which is reflected in the degree at which it underwent recrystallization or recovery. Thin section study revealed that undulose extinction is pervasive in proximity to high strain zones. Recrystallized domains are generally segregated from other phases, and in some cases segregated into polycrystalline ribbons separated from finer grained quartz crystals. The internal structure of ribbons comprises elongated crystals displaying interlobate to polygonal boundaries with well-developed undulose extinction. Grain bulging leading to the formation of subgrains, which are rotated in alignment with the fabric, are common recrystallization textures throughout units. Grain boundary migration, which represents the first stage of quartz recovery, can be observed in the most

strained material which is often at the cores of shear zones or, at a smaller-scale, in quartz ribbons (**Fig. 1.3**). In high strain zones, elongate quartz and plagioclase grains show a preferred growth direction parallel to the main foliation and locally at a $>45^\circ$ angle from foliation (e.g. DSZ, **Fig. 1.3**). The intensity of strain is also well represented in metaconglomerates cut by the MSZ where WSW-ENE 3:1 stretching of tonalitic cobbles is visible (Kalbfleish 2012).

Localized deformation has important implications in the NCGB. The belt is bordered to the north by many crustal-scale deformation zones, which are a feature often observed in greenstone belts of the NW Superior (e.g. Chen et al. 2001, Parmenter et al. 2006, Lin et al. 2013). Three distinct ductile deformation events can be discerned with the presence of folding, pervasive steep planar fabrics and shallow linear fabrics forming tectonite or mylonitic textures (cf. Breaks et al. 2001, Biczok et al. 2012). Late ductile-brittle events were also recorded in a few fault zones suggesting a reactivation of pre-existing ductile structures at shallower depths, evinced by fragmented mylonitic or tectonitic (representing the earlier ductile conditions) blocks at their core (Breaks et al. 2001). The main deformation event that produced the pervasive fabrics in the belt is also responsible for the formation of crustal-scale shear zones as well as lineations, boudinage and mesoscopic folds (Breaks et al. 2001, Biczok et al. 2012). Most of the other deformation events are often difficult to recognize as they are more localized or overprinted by later events. The distribution of strain intensity in the belt is irregular and varies spatially from weak to very strong, with the northern arm of the belt exhibiting generally weaker deformation than the southern arm, which has abundant shear zones.

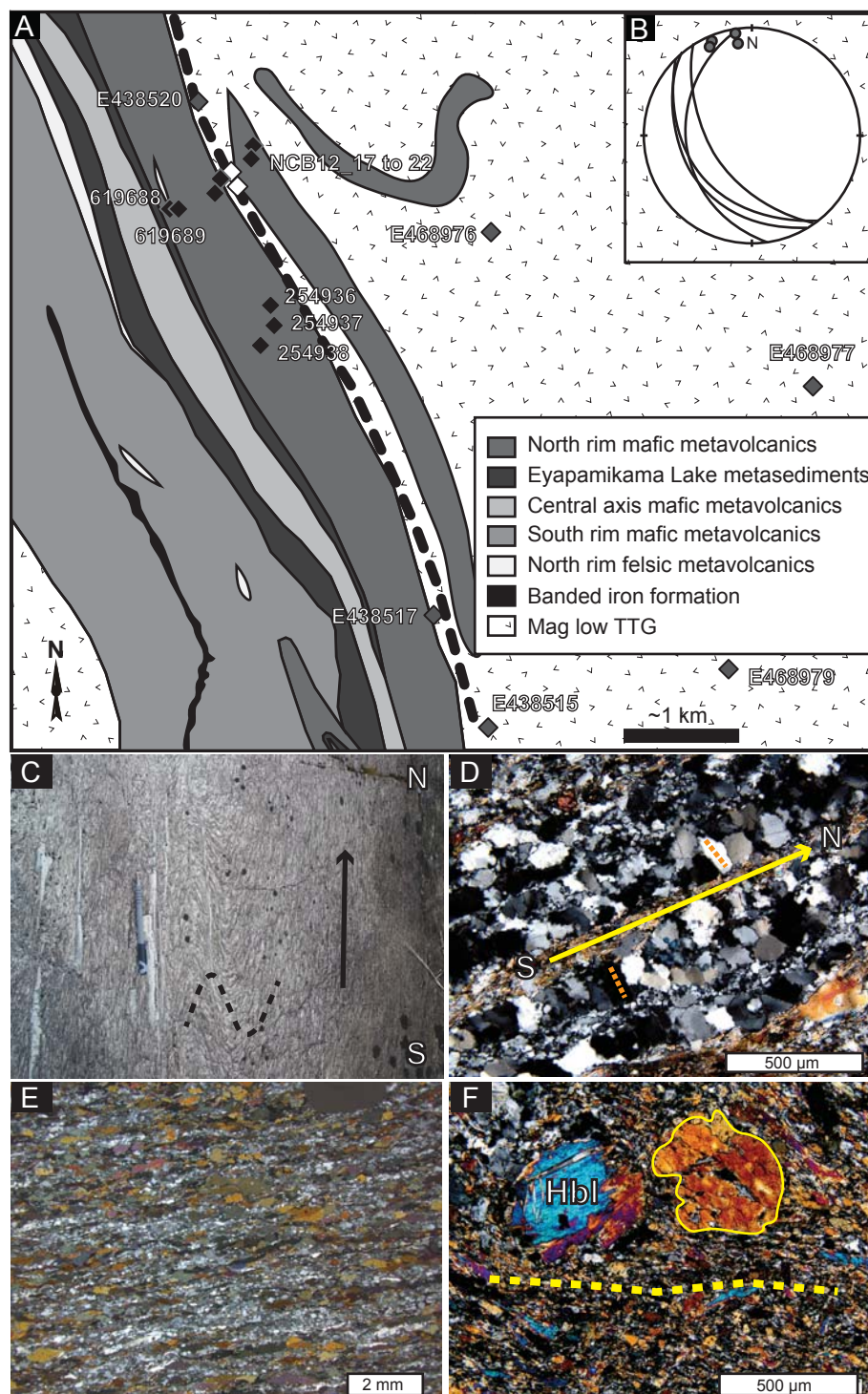


Figure 1.3: Geological map and photos of representative textures across the Dinnick Lake shear zone. A) Geological map of the Dinnick Lake area with sample location (See figure 1B for precise location in the NCBG). Black diamonds represent mafic metavolcanic samples of the North Rim volcanics, dark grey diamonds represent granite samples and white diamonds represent the L-tectonite (note that symbols correspond to whole rock geochemistry figures). B) Structural measurements of lineation (dark grey circles) and foliation (black lines) from the sampled transect. C) Field photograph of the sheared granite (L-tectonite) at the core of the shear zone. Arrow shows the shallow plunging lineations, whereas dotted line shows a localized fold. D) Polarized light photomicrograph of the L-tectonite showing segregation of recrystallized Qz and feldspars. Note that alteration minerals such as Wm + Bt are more concentrated in Fsp-rich domains. Some Qz crystal are elongated at a $>45^\circ$ angle from main fabric. E)-F) Polarized light photomicrographs of mafic metavolcanic units either side of the L-tectonite. Fabric is defined by elongated Hbl and Qz + Pl domains. Older Hbl prophyroclasts are also present and seem more strained, corroded and altered.

5. Dinnick Lake shear zone

The Dinnick Lake shear zone (DSZ) was selected for a detailed study with the goal of characterizing the nature of deformation on a microstructural scale. We chose the DSZ because it represented an understudied area in the belt and might offer important implications in the mineralization process as it is a crustal-scale shear zone which, if projecting along strike to the southeast, would trace close to the Musselwhite mine lode gold deposit. In addition to field observations, we performed whole rock geochemistry to assess the degree of chemical alteration of these deformed rocks. To empirically evaluate the nature and deformation mechanisms of the shear zone, we conducted electron back-scatter diffraction (EBSD) analysis on strategic samples across the shear zone. This was done to quantitatively determine the mode and amount of deformation accommodated in crystal lattices of quartz, feldspars and hornblende, and will provide estimates of crustal conditions during the deformation event.

The DSZ deforms mafic metavolcanic and granitic units (**Fig. 1.3A**), and possesses fewer lithotypes than most other shear zones that intercalate several metasedimentary, mafic and felsic units, therefore optimizing consistency in microstructural data. As with other shear zones of the North Caribou belt, it is characterized by dominantly steep planar fabrics ($>45^\circ$) and shallow linear fabrics that trend NNW-SSE (**Fig. 1.3B**). At the core of the shear zone is a sheared granitoid with a well-developed L-tectonite exhibited by segregation of recrystallized quartz and feldspar-rich domains. Lineations are shallow plunging, display a $<15^\circ$ northward plunge, and are locally folded on a cm-scale as open folds. Petrographically, elongated quartz crystals are mainly subparallel to the foliation, but in higher strain areas, the shape preferred orientation of quartz crystals can be at a $>45^\circ$ angle with respect to the main foliation/lineation. Other minerals include potassium feldspar and plagioclase with accessory titanite and epidote, and muscovite

and biotite as alteration phases. Note that alteration minerals are more concentrated in feldspar-rich domains (**Fig. 1.3C-D**). On either side of the L-tectonite granitoid, lies a strongly foliated mafic metavolcanic sequence of the North Rim volcanics assemblage, containing amphibole (hornblende), plagioclase, and quartz. The NRV is characterized by mostly tholeiitic massive to pillowed mafic volcanic units that tectonically overly metasediments of the Keeyask assemblage (Thurston et al. 1991, Biczok et al. 2012). The well-developed, steeply dipping planar fabric is defined by elongated amphibole crystals separated by recrystallized quartz (and plagioclase) ribbons; quartz exhibits strong undulose extinction and subgrain development. Other amphibole grains are present as larger, corroded porphyroclasts that show fracturing and undulose extinction (**Fig. 1.3E-F**). A few sigmoidal-shaped augens composed of highly strained quartz ($\pm$ plagioclase) indicate both dextral and sinistral displacement and represent strain focusing during deformation.

5.1. Whole rock geochemistry methods

Six samples from the DSZ (NCB12-17 to 22) were analyzed for whole rock geochemistry at Activation Laboratories Ltd. (Ancaster, Canada). Rocks were crushed and pulverized at the University of Ottawa until 95% of the material passed through a 200 mesh (74 μ m) sieve. Minor, major and trace elements were analyzed using fusion inductively coupled plasma mass spectrometry (FU ICP-MS) where each sample is fused into a glass bead before being dissolved and analyzed. Details about the analysis can be found from Hoffman (1992) or on their website (actlabs.com). Additionally, whole rock geochemistry data from a similar traverse across the Akow Lake shear zone located 3 kilometers west (JAC1, 15, 16, 17; **Fig. 1.1B**) and samples collected over the past ten years by geologists from the Musselwhite mine were added to our

results for the purpose of better identifying trends between highly strained and less deformed material in the Dinnick Lake area (**Fig. 1.3A**). These include samples representing the NRV south and north of our Dinnick Lake traverse, as well as surrounding undeformed granitoids in the area for comparison with the L-tectonite. Results are presented in **Appendix A, tables A1-2**.

5.2 Whole rock geochemistry results

The whole rock geochemistry of mafic volcanic units plotted on a standard TiO_2 vs. Zr plot reveal two dominant trends: high and low TiO_2 trends (**Fig. 1.4A**). The low to intermediate trend corresponds to the South Rim volcanic basalts, which is truncated along the south rim and the central axis of the belt (**Fig. 1.3A**) by metasediments in the ASZ/DSZ area, whereas the high trend is mainly representative of the North Rim basalts. Since our work is focused on the Dinnick Lake shear zone along the margin of the North Rim volcanics, we have more closely examined the eight samples collected in the area which belong to the North Rim volcanics sequence. The Rb/Sr and absolute Rb values, which typically indicate potassic alteration, are relatively low and consistent (<3 ppm Rb; **Table A1**) suggesting there has been little alteration and hydrothermal flow through this zone. On the K/Zr vs. Al/Zr, K/Al vs. K_2O and Rb vs. K_2O Pearce element ratio (PER) plots, all the samples fall on tight trend lines or groups, further supporting the absence of potassic alteration (**Fig. 1.4B-D**). There are similar trends for other elements such as Ca, Na, and Mg, where there are no signs of deviation from the common trend lines and therefore little indication of hydrothermal alteration (**Fig. 1.4E-H**). These plots were used simply to demonstrate the tight trends or clusters of compositions which suggest little fluid circulation in the DSZ, since the opposite would have resulted in scattered and more random distributions. Samples NCB12-17B and 619689 are exceptions since they possess different

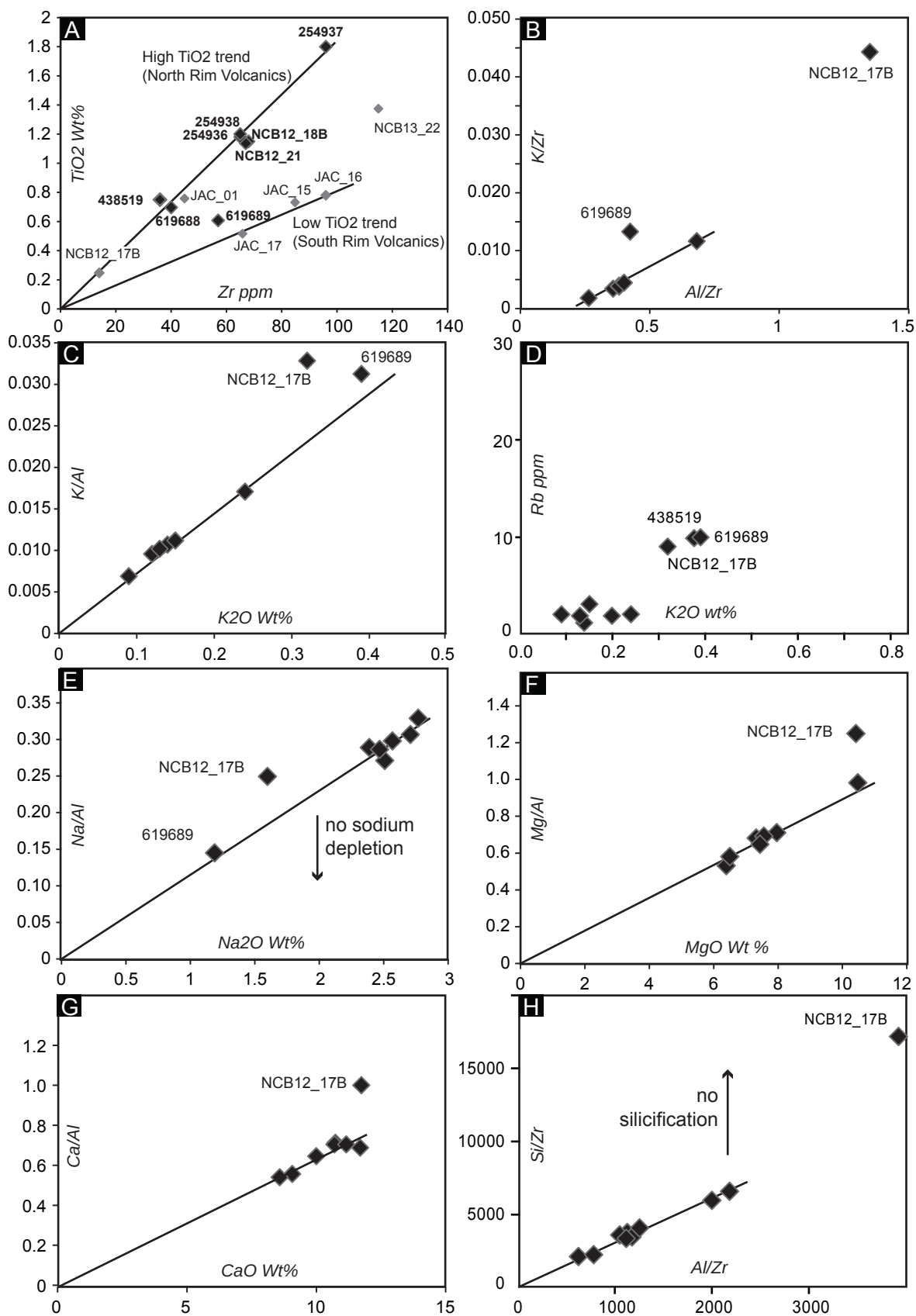


Figure 1.4: Whole rock geochemistry of mafic metavolcanic units in the DSZ area. A) TiO₂ (Wt%) and Zr (ppm) diagram showing different trends between mafic volcanic units. Black diamonds represent samples of the NRV discussed in the DSZ geochemistry section and used in the following diagrams. Grey diamonds represent samples of the SRV that were not focused on in this study. B) to H) Various Pearce element ratio diagrams (PER) showing the similar geochemical compositions of mafic rocks and the lack of hydrothermal fluid circulation across the shear zone. Black lines are simple estimations of interpreted trends.

chemistry: they appear to be high-Mg basalts with higher K₂O and Rb values (yet still low; e.g. 9-10 ppm Rb) and the lowest Al₂O₃ values (~11-13 wt % Al₂O₃; **Table A1**). Primitive mantle-normalized rare earth element diagrams show a fairly consistent distribution with a flat pattern. This flat REE pattern is bracketed by the composition of mafic volcanic units throughout the NCGB, which include North and South rim volcanics, Opapimiskan and Forester lakes volcanics (**Fig. 1.5A**; Duff 2014). LREE composition throughout the NCGB varies from 1-2 order of magnitude, however samples from the DSZ fall in the range of composition indicating little mobility of REE. Furthermore, petrographic observation does not show signs of secondary alteration minerals (e.g. biotite, sericite, chlorite) or veining. In the center of the Dinnick Lake shear zone, the sheared granitoid is a clearly different unit from the surrounding basalts. These L-tectonites form a cluster within the additional granite samples on the TiO₂ vs. Zr plot, indicating that they are probably co-magmatic (i.e. the L-tectonite is derived from surrounding granites; **Fig. 1.5C**). The PER diagram shows no outlying values that would suggest metasomatism in Ca, Na and K (**Fig. 1.5D**). There is also a quite narrow range of Rb/Sr values indicating little fluid movement, as well as no consistent enrichment or depletion in sheared compared to more massive granites (**Fig. 1.5E**). Additionally, samples plot on a tight fractionation line with no sign of silicification (**Fig. 1.5F**), consistent with the lack of visible hydrothermal alteration at the outcrop (e.g. secondary minerals, quartz veins, etc.). On the primitive mantle-normalized REE diagram, surrounding undeformed granitoids and the L-tectonite follow the same trend, which is enriched in LREE, indicating no mobility in REE (**Fig. 1.5B**).

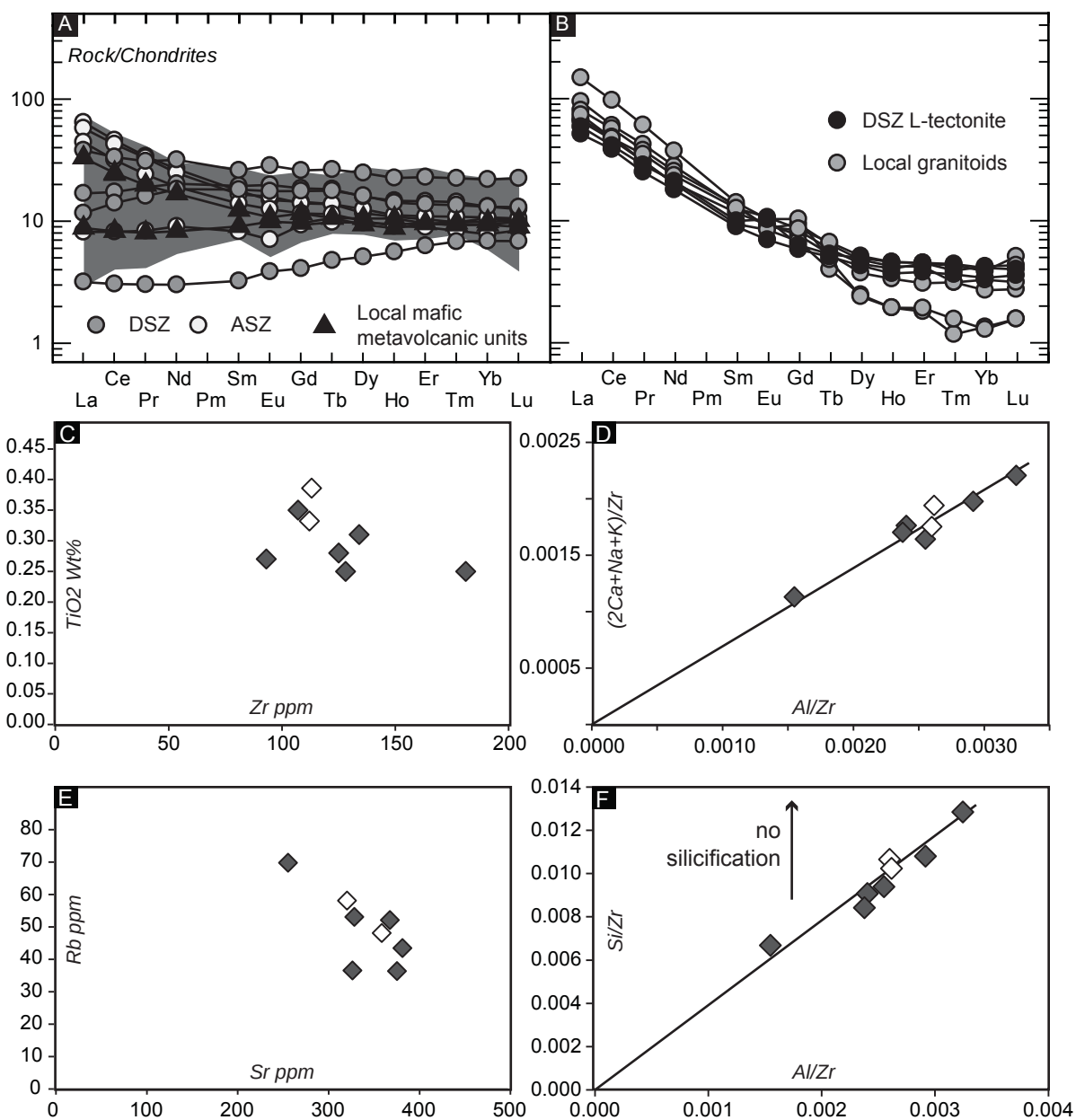


Figure 1.5: A)-B) Primitive-mantle-normalized spider diagrams of mafic volcanic units and granitoids in the Dinnick and Akow Lakes areas (Sun and McDonough 1989). A) Dark grey circles represent mafic volcanic units in the Dinnick Lake shear zone (DSZ), light grey circles represent mafic volcanic units in the Akow Lake shear zone (ASZ) and black triangles represent surrounding less deformed mafic volcanic rocks. Solid grey area represent composition of mafic volcanics throughout the NCGB including South and North rim volcanics, Opapimiskan and Forester lakes volcanics, unpublished data from Duff 2014. B) Black circles represent the sheared-granite unit (L-tectonite) in the center of the DSZ and grey circles represent surrounding less deformed granitoids. C)-F) Whole rock geochemistry of granitic units in the DSZ area. Grey diamonds represent mafic volcanic rocks whereas white diamonds represent sheared granite units. C) TiO₂ (Wt%) and Zr (ppm) diagram showing that the sheared granite (L-tectonite) is derived from surrounding granitic bodies, as it plots within the cluster defined by undeformed granites. D)-E)-F) Various ratios and elemental plots showing tight trends in composition, highlighting the lack of hydrothermal alteration. Black lines are simple estimations of interpreted trends.

5.3. EBSD methods

EBSD is a scanning electron microscope (SEM)-based method focused on the evaluation of electron diffraction patterns from target phases in order to determine their full crystallographic orientation. EBSD is often used for microstructural and textural investigations and permits orientation mapping at a high spatial resolution of ~ 100 nm, varying for the different phases and grain sizes present (Ullemeyer et al. 2000, Peterzell et al. 2010). EBSD provides several advantages for texture measurements such as in situ, site specific orientation analysis at high spatial resolution, but it requires relatively long analytical time, limiting data collection in the context of this study. We selected samples that were homogeneous, and identified 2-3 smaller representative areas (up to $2\text{-}3\text{ mm}^2$) to perform crystallographic orientation mapping, instead of analyzing the entire section. Data was acquired at the University of Vienna, Austria, on a FEI Quanta 3D field-emission gun electron microscope equipped with an Ametek EDAX Pegasus Apex 4 system consisting of a Digiview IV EBSD camera and an Apollo XV Silicon drift detector for energy dispersive x-ray spectrometry. A step size ranging between $0.4\text{-}3\text{ }\mu\text{m}$ was used depending on grain size where fine-grained materials require smaller step sizes. The EDAX OIM Data Collection and Analysis software v.6.2.0 was used for contemporaneous EBSD and EDX data collection and processing. See **Appendix B** for detailed analytical parameters. Software automated indexing was applied to diffraction patterns of each data point. Misindexed points were removed by several statistical cleaning procedures such as confidence index standardization, neighbor orientation correlation or grain dilation. To assess the quality of the data, several maps were generated from each dataset such as image quality, misorientation, phase and grain maps. As a complement to the OIM data analysis, our results report data that was

analyzed via MTEX, a command-based MATLAB toolbox that can be used to visualize microstructural data.

5.3.1. Pole figures

Microstructural data displayed as pole figures show the density distribution of poles normal to a particular crystal face that highlight crystallographic orientations and fabric development in a material, plotted as upper hemisphere stereographic projections. They are single-phase plots used to visualize the texture of a sample, which can give information about deformation mechanisms, temperature conditions and strain kinematics (Schmid et al. 1986). Density distributions of lattice orientations were calculated using MTEX with 10° half-widths. In the pole figures, the y-axis (corresponding to the width of the thin section) is plotted horizontally and the x-axis (corresponding to the length of the thin section) is plotted vertically (**Appendix C**). The main fabric is broadly oriented along the x-axis on pole figures, which represents a N-S trend (foliation strike and lineation trend are marked with a black tick, **Fig. 1.6**). Thin sections that were cut slightly oblique to the planar fabric required additional rotation based on Euler angles. This step ensured that the foliation traces are represented along the x-axes in the pole figures and that the Y strain axis is centered (note that Y strain axis differs from y-axis corresponding to thin section reference system), removing any unnecessary asymmetry in the patterns. Euler angles α , β and γ were determined by the procedures defined in Abalos et al. (2011, **Appendix C**).

5.3.2. Grain boundary misorientation study

Another use of EBSD data is to examine grain boundary misorientations of deformed samples. The misorientation between two grains of the same phase is a minimum angle at which their respective c-axis can rotate to come in alignment. This is a single-phase analysis and

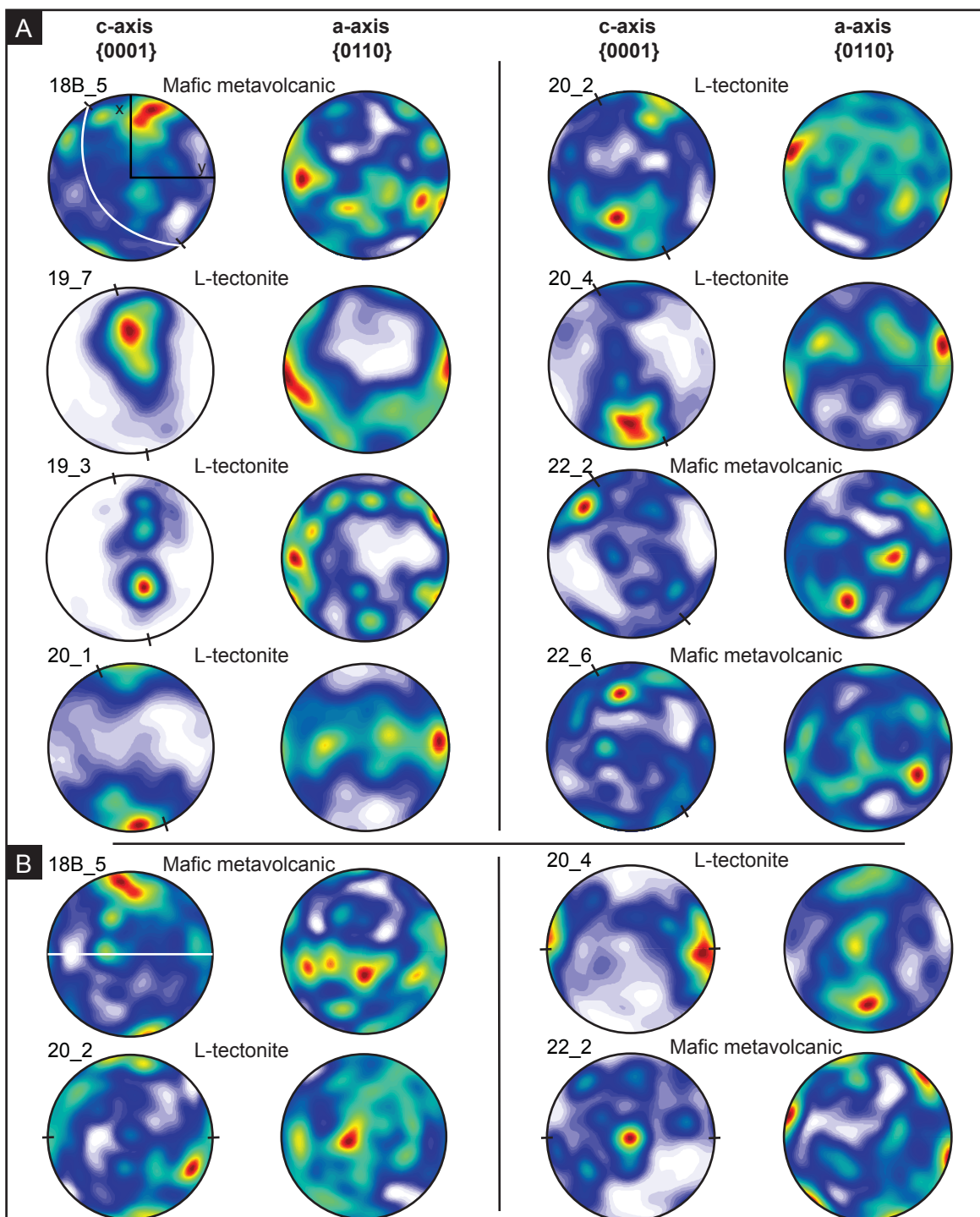


Figure 1.6: Upper hemisphere projections of density distribution of quartz poles to crystallographic faces (EBSD data) from the Dinnick Lake shear zone. Sample numbers are labeled beside respective pole figure. Strike of fabrics (without dip/plunge), comprising foliation and lineation, are illustrated with black ticks to show the relationship with patterns (note that N-S is approximately at the top and bottom poles). A) Quartz a- and c-axis orientation distributions. X- and y-axis representing thin section directions are plotted on the first figure (see appendix B for schematic). B) Pole figures of rotated EBSD data showing orientation distributions in the X-Y plane of the major strain axes, with the foliation trace forming an E-W line. To better visualize the effect of the rotation, foliation planes are plotted on pole figures of NCB12-18B_5 (see appendix B for detailed procedure).

requires two types of pairs to be observed. First we determine misorientation angles between two neighboring grains (correlated), which displays the texture of the sample. Then we determine misorientation angles between two random grains (uncorrelated), which shows the crystal symmetry of the specific phase. The results are represented in the form of a histogram, showing the misorientation angles on the x-axis and the frequency on the y-axis. Grain boundaries with misorientation angles below 5° were discarded due to high probability of indexing error. In order to quantifiably determine how the sample is deformed, a statistical test can be used to compare the two distributions, although it is intuitive just by examining the histogram distributions. Using the Kolmogorov-Smirnov statistical test (KS test; **Appendix D**), we calculated if the correlated and uncorrelated histograms were statistically different. If they are statistically different, grains interacted with each other or inherited their texture from parent grains. If the distributions are statistically similar, grains are random and no deformation occurred (i.e. the histogram will show an unchanged crystallographic structure).

5.4. EBSD results

5.4.1. Pole figures

Quartz is often the most useful phase in texture analyses and has been widely studied in terms of microstructures and implications during deformation stages. Our study is mainly focused on quartz data in order to infer deformation mechanisms and consequently temperature estimates. Sample NCB12-19 is an L-tectonite located in the core of the Dinnick shear zone. The c-axis pole figures show a strong maximum near the center (**Fig. 1.6A**). In addition, a-axis pole figures exhibit a girdle around the perimeter of the figure. These patterns are typical for modest metamorphic conditions and deformation by prism a-slip (Unzog et al. 2000, Passchier et al.

2005, Abalos et al. 2011). NCB12-20 is also a strongly lineated tectonite from the center of the shear zone. The c-axis pole figures are transitional between a single maximum near the center of the figure to small circle girdles near the N-S poles of the pole figures. The a-axes, which correspond to single maximum c-axes, form a girdle around the perimeter of the pole figure, whereas those corresponding to N-S small circles define a girdle that bisects the center of the figure (**Fig. 1.6A**). The latter patterns suggest slightly higher temperature or higher strain conditions, where both prism a-slip and c-slip systems were active (Abalos et al. 2011). The former patterns reflect medium temperature conditions similar to the first sample.

Adjacent to the felsic L-tectonite are mafic metavolcanic rocks that appear to have witnessed lower strain, as the intensity of CPOs decrease and it is more difficult to discern clear patterns. In sample NCB12-18B, the c-axis pole figure indicates a maximum near the top with a possible girdle on the perimeter of the figure. The a-axis figure shows a girdle bisecting the center in an E-W fashion (**Fig. 1.6A**). For sample NCB12-22, c-axes pole figures seem to show type 1 crossed girdle patterns (Passchier et al. 2005), whereas a-axes figures show a NE-SW trending girdle through the center of the figure (**Fig. 1.6A**). These combinations of patterns indicate slightly lower temperature conditions and dominant basal a-slip (Passchier et al. 2005). Due to the asymmetry in pole figure patterns induced by slightly oblique thin sections, the EBSD data for samples NCB12-18B, -20 and -22 have been rotated according to specific Euler angles (**Fig. 1.6B, Appendix C**). This step ensured that the foliation traces and Y strain axis are centered in the pole figures (i.e. foliation strikes are now at N-S poles of pole figures). Sample NCB12-18B possesses scattered patterns, with two possible c-axis maxima normal to foliation and an a-axis girdle or maxima around the great circle, supporting a decrease in CPO. This indicates medium-low T conditions. Sample NCB12-20 is slightly improved by the rotation,

better emphasizing the small circle girdles at N-S poles of c-axes pole figures with corresponding a-axes girdles that cross the center of the figure, suggesting higher temperature or strain. Sample NCB12-22 was also improved by the rotations, which produced a single c-axis maximum in the center, associated with six a-axis maxima around the periphery of the pole figure. These are representative of medium temperature and strain (**Fig. 1.6B**, Abalos et al. 2011).

Pole figures for feldspar CPOs did not yield discernable patterns within and between samples that show resolvable trends in deformation or temperature conditions (**Fig. 1.7A** shows some representative pole figures). For example, sample NCB12-20 shows one 001 pole figure with a maximum in the center, whereas another one shows two girdles at NW-SE poles. Amphiboles on the other hand, which are only present in mafic metavolcanic rocks on either sides of the felsic L-tectonite clearly show preferred crystallographic orientation. Two analyses from a sample on the eastern side of the shear zone (NCB12-22) show two c-axes (001) maxima at the E and W sections of the pole figure. The (110) and (010) pole figures, which are thought to be important for amphiboles microstructures (Passchier et al. 2005), show maxima that form a N-S trending girdle, sub-parallel to outcrop foliation. The (001) pole figure for sample NCB12-18B shows a maximum near the left section of the pole figure forming an E-W girdle through the center. For this sample, (010) pole figure forms a girdle that is normal to the foliation, whereas (110) shows two small circle girdles at N-S poles of the figure, subparallel to foliation (**Fig. 1.7B**).

5.4.2. Grain boundary misorientation

For quartz, all grain boundary misorientation histograms (**Fig. 1.8**) illustrate two notable features and KS tests conclude that there is an 80% to 99.99% probability that the two distributions are indeed different. A peak of misorientation angles at 55-60° is associated with

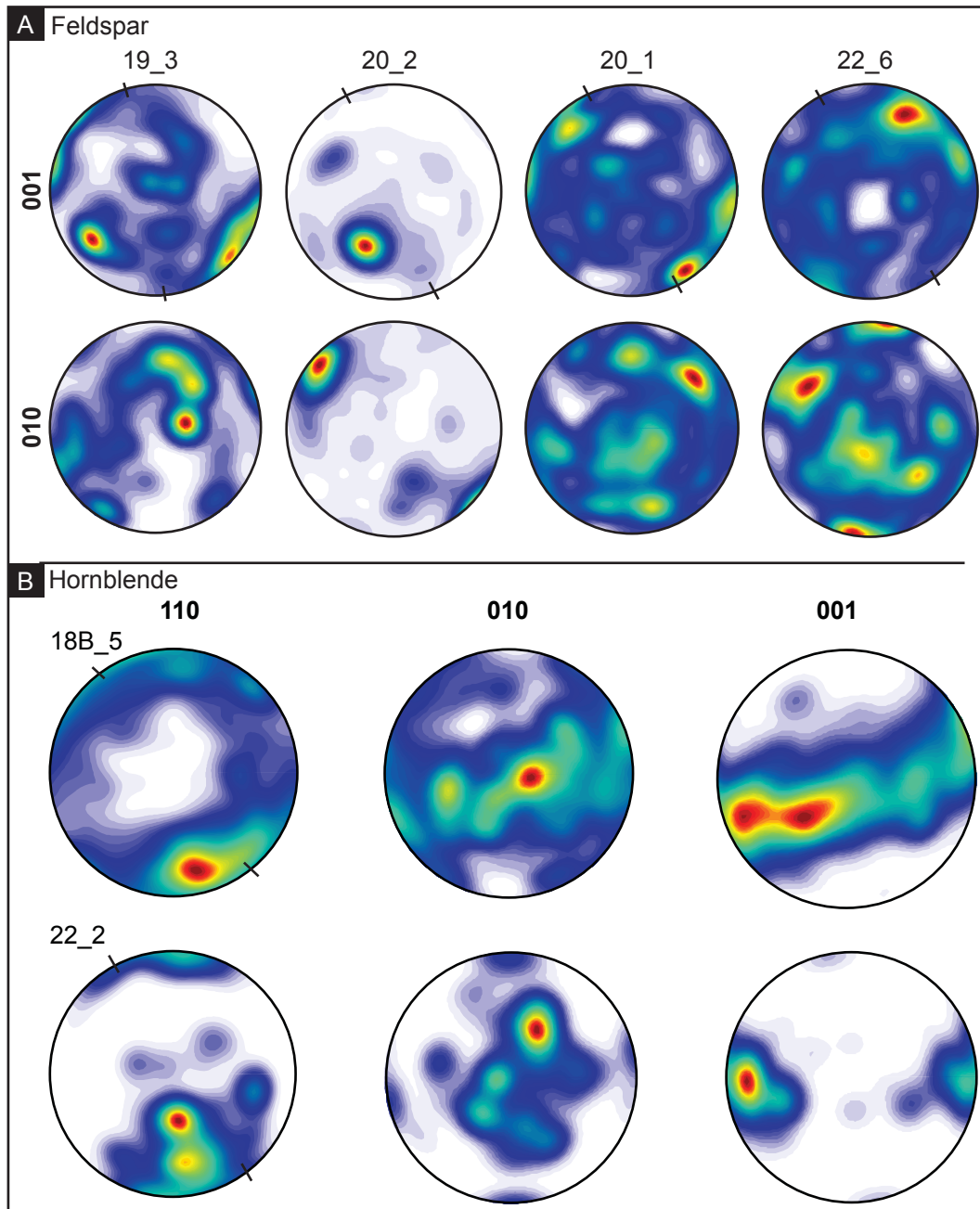


Figure 1.7: Representative pole figures of feldspar (include Pl and Kfsp) and hornblende (upper hemisphere projections). Strike of fabrics (without dip/plunge) are plotted to show the relationship with patterns (note that N-S is approximately at the top and bottom poles). A) Pole figure of feldspar showing no consistent trends in their patterns/CPO. B) Pole figures of hornblende showing a moderate CPO. See appendices D and E for complete dataset of pole figures.

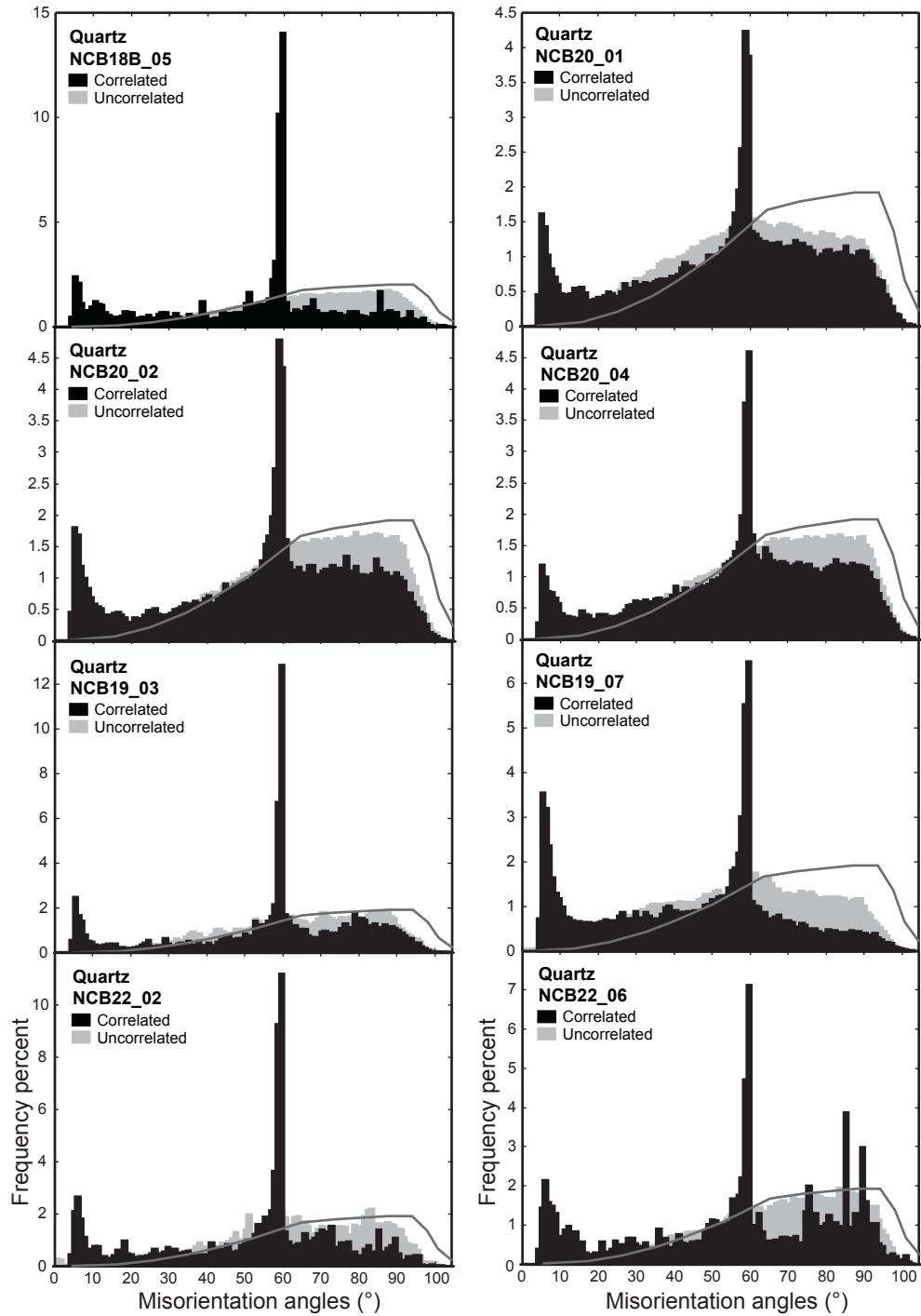


Figure 1.8: Grain boundary misorientation histogram of quartz across the Dinnick Lake shear zone. Histograms show the recrystallized texture of the Qz with an abundance of misorientation at low angles (5-15°), which represent subgrain formation. See appendix F and G for Fsp and Hbl grain boundary misorientation histograms.

Dauphiné twins likely formed as a product of deformation. Another peak at low angles, 5-15°, is associated with subgrains, which is direct evidence of subgrain rotation recrystallization. The correlated and uncorrelated misorientation distributions are different, requiring that neighboring grains have interacted together through bulging and subgrain rotation, which is expected during deformation (Wheeler et al. 2003).

Feldspars show a peak at 180°, indicative of albite twinning, otherwise the misorientation histograms show the presence of very few subgrains (small peak at angles below 15°). The KS tests did not yield good results as most attempts generated a p -value smaller than the significance level, meaning that the test cannot be accepted; some tests that were acceptable indicate an 80-90% probability the two distributions are different. Similar to feldspar, hornblende misorientation histograms do not show any features other than a peak at 180° representing twinning. The KS tests for this phase also did not yield acceptable p -values (all smaller than significance level). These results suggest brittle deformation rather than crystal plastic deformation (**Appendix C**). Brittle deformation in feldspar and hornblende is consistent with petrological observations such as the presence of very few subgrains or the fractured nature of some hornblende grains, reflecting the stronger nature of these minerals under these metamorphic conditions.

6. Discussion

Many ductile to brittle deformation zones are found on the northern margins of the NCGB, the details of which highlight the complex and protracted nature of Archean accretion. Based on extensive field observations across the belt, several metamorphic trends can be identified: 1) an increase in peak metamorphic grade toward the north, 2) an increase in peak

metamorphic grade toward the east, 3) contact metamorphism aureoles in proximity to small intrusions, defined by cordierite, and 4) occurrences of high grade assemblages, localized along loci of higher strain. Upper greenschist to amphibolite facies index minerals include garnet, staurolite, andalusite and sillimanite in metasedimentary units, whereas mafic volcanic units are characterized by hornblende porphyroblasts, exhibiting syn- to post-tectonic growth. Lower grade assemblages are characterized by chlorite, biotite and muscovite (Breaks et al. 2001, Kelly et al. 2013). Steeply-dipping foliations and shallow-plunging lineations record dominant oblique, horizontal tectonism in shear zones across the NCGB. A detailed microstructural analysis of the DSZ, which deforms mafic volcanic units of the North Rim volcanics and a sheared granite showing L-tectonite fabric, provided insights on the nature of this transpressive system. Quartz microstructures indicate deformation activating predominant basal a-slip to prism c-slip systems, which are characteristic of amphibolite facies conditions ($>500^{\circ}\text{C}$; discussed below) at common natural strain rates. Recrystallization mechanisms include subgrain rotation and initiation of grain boundary migration in highest strain zones. Other phases such as feldspar and hornblende show brittle deformation rather than crystal plasticity as they are stronger during deformation at medium metamorphic conditions.

6.1. Synchronous metamorphism and deformation in the NCGB

Metamorphism across the belt is heterogeneous along strike and varies from sub-greenschist to middle amphibolite facies assemblages. A number of factors influenced the current metamorphic patterns such as minor intrusions and fluid flow, and regional and localized deformation. Most middle amphibolite facies index minerals such as andalusite, staurolite and sillimanite are concentrated in zones that were mapped as deformation zones. Additionally, the

syn-deformation growth microstructures represented by their shape preferred alignment within the main foliation, the geometry of inclusion trail traces, fabric-forming minerals wrapping around them, and so on (**Fig. 1.2**), indicate contemporaneous metamorphism and deformation episodes recorded in the NCGB. Therefore, we cannot only identify spatial relationships between zones of high strain and high temperatures, but recent data also point to a temporal relationship between these events. It is, however, difficult to prove the contemporaneity of metamorphism and deformation in all parts of the belt, as patterns are very complex and irregular. Several thermal and deformation events likely occurred in different areas at different times, outlined by previous studies in the belt (e.g. Kalbfleisch 2012, Biczok et al. 2012). Thus we preferably focused on localized high strain areas such as the Dinnick Lake shear zone.

The relationship observed in the NCGB between major structures, metamorphic grade and mineralization is comparable to other greenstone belts in the western Superior, such as Hemlo and Red Lake greenstone belts. In the Red Lake greenstone belt, evidence of spatiotemporal relationships between isograd patterns and shear zones suggest an overlap of metamorphic and deformation events, with the heterogeneous deformation outlasting metamorphic reactions and focused in narrow zones (Thompson 2003). Many greenstone belt gold deposits typically occur near the biotite isograd (e.g. Western Australia and Timmins camps, Thompson 2003), which is where much of the volatiles are released during metamorphic reactions. Such is not the case at Musselwhite, where the deposit is well within the amphibolite facies, and other deposits formed near the transition from upper greenschist to amphibolite conditions, such as Red Lake and Timmins areas, as well as in the Yellowknife and Western Australia greenstone belts (Thompson 2003 and references therein). It is therefore important to consider biotite zones as well as amphibolite facies when exploring for lode gold deposits.

6.2. Dinnick Lake shear zone

The felsic L-tectonite at the core of the Dinnick Lake shear zone consists of recrystallized quartz and a mix of plagioclase and potassic feldspars. Intense deformation under amphibolite facies conditions occurred in this part of the shear zone as indicated by quartz microstructures. A strong 0001 CPO represents preferential alignment of quartz c-axes into shallow dipping rods, the dominant structure of this rock. The majority of c-axes CPO patterns show a maximum near the center of pole figures with a moderate tendency to elongate toward lineations and a-axes maxima around the periphery of the pole figure, which indicate moderate metamorphic conditions and dominating deformation in the prism a-slip system (**Fig. 1.6**, Unzog et al. 2000 and Passchier et al. 2005). However one sample that is noted as representing the highest recorded strain or temperature shows two small circle girdles at N-S poles of pole figures with associated a-axes girdles crossing the center, suggesting dominant c-slip at slightly higher temperature conditions (**Fig. 1.6**, Abalos et al. 2011). These types of slip systems are generally active at a wide range of temperatures, between 400-700°C depending on strain rates and fluid conditions (Vernon 2004). Our grain boundary misorientation study as well as petrographic observations show a significant number of quartz subgrains, identified by low angle boundaries. This is indicative of subgrain rotation recrystallization as the dominant dynamic recrystallization mechanism (**Fig. 1.8**) and corresponds to temperatures of 400-500°C in quartz-rich material. The CPO patterns also suggest a minor component of grain boundary migration which occurs above 500°C (Stipp et al. 2002b, Mancktelow and Pennacchioni 2004). Exceeding these conditions at moderate strain rates would have resulted in a transition to quartz recovery, thus annealing subgrains. With increasing distance from the fault core, strain decreases resulting in a weaker CPO in quartz 0001 pole figures. Quartz a-axes patterns show girdles that tend to be more on the

periphery of the pole figure, whereas c-axes cluster in the center, both suggesting slightly lower temperature conditions and a stronger a-slip component (Passchier et al. 2005). An abundance of quartz subgrains indicate subgrain rotation dynamic recrystallization is the main recrystallization mechanism across the shear zone. Therefore a slight strain or temperature gradient is evident through CPO patterns across the Dinnick Lake shear zone with a range of temperature likely around 500-600°C, which is in the medium metamorphic conditions field (**Fig. 1.9**).

Furthermore, the presence of polycrystalline quartz ribbons, which are ribbons composed of multiple quartz crystals, in shear zones of the NCGB support deformation at medium or amphibolite facies conditions; field observations show their presence in several other deformation zones besides the DSZ, such as MSZ, ASZ and NCT. Deformation was presumably partitioned in quartz rich domains as this phase behaves plastically under these conditions. Polycrystalline ribbons generally appear at temperatures above 350-400°C and their internal structures can be used to infer their tectonothermal development (Boullier and Bouchez 1978). Quartz ribbons in the NCGB generally consist of elongated grains with polygonal to interlobate grain boundaries, undulose extinction and reflect a strong crystallographic preferred orientation. Grain sizes are variable within ribbons, grains are often elongated in the main fabric direction and many subgrains border the limit of the ribbons. However in higher strain zones, such as shear zone cores, many ribbons contain shape preferred orientation represented by elongated grains at $>45^\circ$ angle with regard to the fabric, fewer subgrains and more equant grain sizes. These characteristics are consistent with plastic deformation with syn-tectonic recrystallization of parent grains (Boullier and Bouchez 1978). The decrease in numbers of subgrains in shear zone cores may suggest boundary migrations of smaller grains into larger, elongated grains that preserved their parent's internal orientation (Boullier and Bouchez 1978). This is consistent with

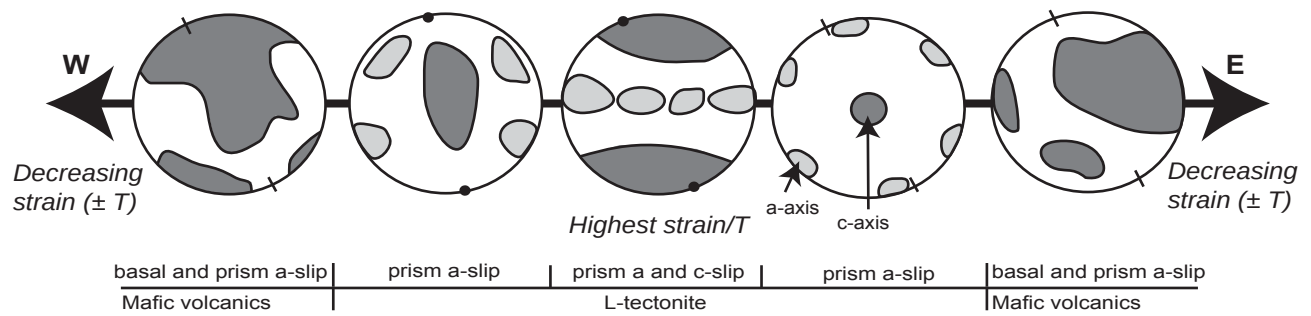


Figure 1.9: Schematic of quartz c and a-axes pole figures showing a slight strain/temperature gradient through a ~1 km traverse across the Dinnick Lake shear zone. Temperature estimates range between 500-600°C. Dark gray represent c-axes patterns whereas light gray represent a-axes patterns. Foliation strikes and lineation trends are plotted to illustrate the general relationship with the girdles.

microstructural data showing the onset of grain boundary migration as a recrystallization mechanism in highest strain zones.

Feldspar, on the other hand, recrystallizes and ductily deforms under different conditions; feldspar is a stronger phase than quartz during deformation under greenschist to middle amphibolite metamorphic conditions (Vernon 2004, Baratoux et al. 2005). Pole figures of various crystal faces of feldspar show no consistent trends in CPO patterns, therefore suggesting a relatively random alignment of this phase in the L-tectonite and volcanics. In a polymineralic rock, strain is preferentially accommodated by weaker phases (e.g. quartz and micas). Thus in the Dinnick shear zone, feldspar likely behaved in a brittle fashion under these conditions, which would not have induced preferential alignment of crystals. Moreover, the grain boundary misorientation data indicate very few subgrains are present. This may suggest that feldspar grains were in the initial stages of dynamic recrystallization by subgrain rotation, which has been suggested to occur at the transition between greenschist to amphibolite facies conditions (~500°C, Mancktelow and Pennacchioni 2004).

Similarly, amphibole is also thought to be one of the strongest silicate minerals during deformation, with brittle behavior over a wider range of temperatures than quartz (Imon et al. 2004, Baratoux et al. 2005, Aspiroz et al. 2007). In the Dinnick shear zone, hornblende can be classified into two categories: elongated grains that define the foliation and pre-tectonic corroded porphyroclasts (**Fig. 1.3E-F**). Most of the porphyroclasts and elongated grains show undulose extinction and fractures, as well as a lower birefringence, suggesting higher strain. Very few amphibole subgrains are evident from the misorientation data, consistent with petrographic observations of this stronger phase. With these observations, we hypothesize that hornblende (older) porphyroclasts deformed by rigid body rotation, inducing dislocation creep that caused

undulose extinction. This deformation episode also developed a moderate CPO, which was likely fostered by synchronous metamorphic growth of the elongated crystals (Gapais et al. 1981, Passchier et al. 2005). The growth of metamorphic hornblende and rigid body rotation of hornblende crystals within a plagioclase matrix is frequently observed in medium metamorphic/deformation environments (above 500°C depending on fluid conditions and strain rates; Winter 2001, Aspiroz et al. 2007). Temperatures between 500-600°C, estimated from quartz and feldspar microstructural data, were likely too low to accommodate crystal plastic deformation in amphiboles.

In addition to strain rate and temperature, the presence of fluids can also influence the nature and degree of deformation (e.g. Mancktelow and Pennacchioni 2004). Different combinations of syn-tectonic conditions lead to different recrystallization mechanisms and deformation patterns. Whole rock geochemistry from the DSZ shows no evidence of open system hydrothermal alteration (e.g. potassic alteration or silicification), thus a low likelihood of fluid circulation through the shear zone during deformation. As fluids generally facilitate crystal plastic deformation, we could suspect that this relatively dry deformation occurred at higher temperatures (>500°C) rather than lower temperatures. These estimates are consistent with paleothermometry data from Musselwhite mine (545-645°C; Otto 2002), as well as paleothermometry from the country rocks and batholiths (540-600°C; Otto 2002, Kalbfleisch 2012, Van Lankvelt 2013). However, these temperatures are thought to represent peak metamorphic conditions that occurred syn-mineralization at the mine, which implicates deformation in a fluid-rich environment, contrasting with our current observations in the DSZ just north of the mine. This further emphasizes the heterogeneous nature of deformation conditions throughout the belt. Therefore fluid circulation in other shear zones and their timing

of formation need to be better defined in order to understand the complete evolution of the NCGB and the implication of crustal-scale shear zones in channeling fluids during deformation.

6.3. Transpression in shear zones of the NCGB, implications for horizontal tectonism

Our field observations (e.g. shallow plunging lineations) and microtextural study in the NCGB show a strong horizontal component in the deformation. This is partly in agreement with some of the currently proposed models for the NW Superior that implicates synchronous vertical and horizontal movements as a mode of tectonism in the Archean. Although at first look, the NCGB might present evidence for dome and keel structures with the presence of external, domal batholiths impinging the narrow greenstone belt, shear zones that have been studied at granite-greenstone contacts in the central portion of the belt indicate no evidence for this vertical movement. They rather show a strong shallow plunging stretching and a shearing component, consistent with transpressive deformation. Structures indicating vertical movement such as steeply plunging stretching lineations have been recorded in shear zones at granite-greenstone contacts in other parts of the NW Superior Province (Hemlo, Cross Lake greenstone belts, Parmenter et al. 2005, Lin et al. 2013), but so far our field and empirical observations are lacking this vertical component. Furthermore, pervasive fabrics displaying strike-slip shear sense that show dominant dextral kinematics support horizontal to oblique deformation. Our observations seem to correlate more with a transpression model with horizontal compression and shearing components, similar to a suggested model in Western Australia (Chen et al. 2001). This mode of tectonism implicate a horizontal compression caused by amalgamation of terranes to the NCS, which wedged greenstone belts in between remnants of continental crust and granitoid intrusions. Deformation was focused in rheologically weaker zones at granite-greenstone

contacts, forming major shear zones. These crustal-scale deformation zones were formed under amphibolite facies conditions, recording this horizontal movement. We cannot however exclude the possibility of vertical motion occurring at shallow structural levels, early in the collisional history, as it would now be eroded away or overprinted as suggested for Hemlo greenstone belt (Lin et al. 2013).

Investigating the mode of tectonism in the Western Superior is likely not as easy as choosing one model over another. As Zibra et al. (2014) suggested for a greenstone belt in the Yilgarn craton, tectonothermal evolution of a craton can be very complex. Their microstructural and geochronological investigations show an inclined transpressive system implicating progressive emplacement of plutons during the formation of the craton, where shear zones record both horizontal and vertical components. More structural and microtextural work needs to be conducted across other shear zones in the NCGB as well as into the batholiths to further constrain the relationship of deformation between granitoids and the greenstone belt.

Additionally, in many orogenic gold systems (e.g. Hemlo greenstone belt), shear zones at granite-greenstone contacts are thought to be of importance in the transport of mineralizing fluids. Although the DSZ does not seem to support this model, as it appears to have formed under dry conditions, the Musselwhite mine located some 20 km south evidently has witnessed fluid circulation during peak metamorphic conditions (Breaks et al. 2001, Biczok et al. 2012). In terms of implications for mineralization and shear zones associated with the Musselwhite gold deposit, heterogeneity of crustal conditions and timing of deformation at a km-scale need to be further investigated in order to better understand the implication of other shear zones in the orogenic system evolution, but our microstructural data point towards a dominant horizontal tectonic system.

7. Summary

New field observations, microstructural and geochemical data from the North Caribou greenstone belt show spatial and temporal relationships between deformation focusing and peak-metamorphic conditions, occurring during Archean transpressive tectonism in the Western Superior. Relationships are best identified with amphibolite facies index minerals including garnet, staurolite, andalusite and sillimanite showing syn- to post-tectonic growth, which are abundant in zones of higher strain located mainly on the northern margins of the belt. Crustal conditions in shear zones during transpressive deformation were determined as being well within the amphibolite facies (above 500°C) based on a variety of microstructures. 1) Quartz in the L-tectonite deformed by prism a- and c-slip and recrystallized by subgrain rotation and minor grain boundary migration (focused in polycrystalline quartz ribbons). Away from the L-tectonite, quartz deformation by dominant prism a-slip and minor basal a-slip also occurred. This suggests deformation temperatures between 400 and 700°C, with the highest strain conditions in the center of the shear zone. 2) The decrease in quartz CPO intensity, pole figure patterns and petrological observations suggest a slight strain/temperature gradient across the shear zone. 3) Hornblende CPO is a consequence of preferred growth of elongated grains parallel to main foliation during synchronous metamorphism and deformation, suggesting temperatures above 500°C. Continuing deformation under lower temperature conditions furthermore caused minor undulose extinction. Additionally, larger porphyroclasts deformed by rigid body rotation and dislocation creep display strong undulose extinction and no subgrains, indicating a pre-tectonic origin. 4) Feldspar shows no consistent trends in CPO patterns and formed very few subgrains, indicating a transition into crystal plastic deformation, around 500°C. Additionally, whole rock geochemistry data for elements such as Ca, Na, Mg and K, which are often good indicators of

hydrothermal fluid interaction, show little variation between highly strained and more massive units, suggesting deformation under low fluid mobility conditions. Therefore, a compilation of microstructural and geochemical data suggests that the Dinnick Lake shear zone formed under dry, mid-crustal conditions, likely between 500-600°C. Additionally, microstructures and textures as well as field observations and petrography support a transpressive system in the NCGB (horizontal shortening and shearing components). Although vertical movement could be suspected with dome and keel structures, shallow linear fabrics and dominant dextral kinematics in shear zones at granite-greenstone contacts indicate otherwise.

Part II

Geochronology and geochemistry of transpressive deformation zones in the North Caribou greenstone belt (NW Superior): Implications for the tectonothermal evolution during the Archean

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Abstract

Transpressive deformation zones in the Archean North Caribou greenstone belt present a potential for hydrothermal alteration of the shallow crust that could be linked to the mineralizing event at the Musselwhite mine. Shear zone hosted Au deposits are common in the Superior Province; however the Musselwhite mine is markedly different from other deposits as it preserves middle amphibolite metamorphic facies conditions of the host rock, which can veil hydrothermal alteration signatures. The relationship and timing of metamorphism with deformation is still equivocal, yet high metamorphic grade assemblages seem to be focused along deformation zones on the northern margins of the belt. Metasedimentary units bear index minerals such as garnet, staurolite, andalusite and sillimanite in high grade metamorphic zones, whereas lowest assemblages are characterized by chlorite and biotite. Moreover, geochemical and microstructural analyses from shear zones in the central part of the belt indicate deformation occurring above 500°C under dry conditions (e.g. Dinnick Lake shear zone), whereas monazite recrystallization may record fluid-facilitated deformation in the southern arm (e.g. Markop Lake deformation zone). In situ U-total-Pb geochronology of small (<100 µm) monazites found in high strain zones and K-Ar ages of fabric-forming micas were obtained in an attempt to resolve the timing of deformation recorded in shear zones. The ages are consistent with protracted metamorphism and deformation corresponding to the amalgamation of the Superior craton from ca. 2.75 to 2.4 Ga. A strong 2.5-2.4 Ga signature is recorded in many deformation zones and may reflect the emplacement of large igneous provinces throughout the Superior during this period. The heterogeneous nature of deformation during the 400 m.y. tectonothermal evolution of the belt and the high metamorphic grade of the host rock in the NCGB may obscure tectonic signatures, however some structural and geochemical characteristics are consistent with other

greenstone belts (e.g. Hemlo, Yilgarn) where vertical and horizontal tectonism focused in crustal-scale shear zones may be responsible for channeling fluids.

1. Introduction

The Archean North Caribou greenstone belt (NCGB) in northwestern Ontario is part of the nucleus of Canada's western Superior Province (North Caribou Superterrane, NCS), a suite of east-west trending terranes and superterranes that represent remnants of microcontinents and oceanic basins (**Fig. 2.1A**; Percival et al. 2006). The belt comprises 3.0-2.7 Ga metavolcanic-metasedimentary assemblages and is host to the Musselwhite lode gold deposit, currently under mining and exploration by Goldcorp, Inc. (**Fig. 2.1B**). The ore occurs in a moderately metamorphosed banded iron formation (BIF) and resides in synclinal keels and their sheared limbs, often found at intersections with shear zones. A number of shear zones define the borders of the NCGB, thought to be formed or reactivated during the many accretion events that occurred throughout NCS amalgamation, both from the north and south during the Neoarchean Uchian Orogeny (Percival et al. 1994, Breaks et al. 2001, Kalbfleisch 2012; Gagnon et al. submitted). Some workers have suggested that the BIF-hosted Au mineralization formed contemporaneously with the formation of major structures associated with the emplacement of plutons at 2.87 Ga and later channels for hydrothermal fluids at 2.7 Ga, consistent with models for orogenic gold deposits in the Superior, yet microstructural studies in some parts of the belt may indicate otherwise (Fyon et al. 1992, Percival et al. 2006, Biczok et al. 2012, Gagnon et al. 2015 submitted).

One characteristic of the NCGB that makes it stand out from many others in the western Superior Province is the amphibolite facies metamorphic grade of the host rock, compared to the

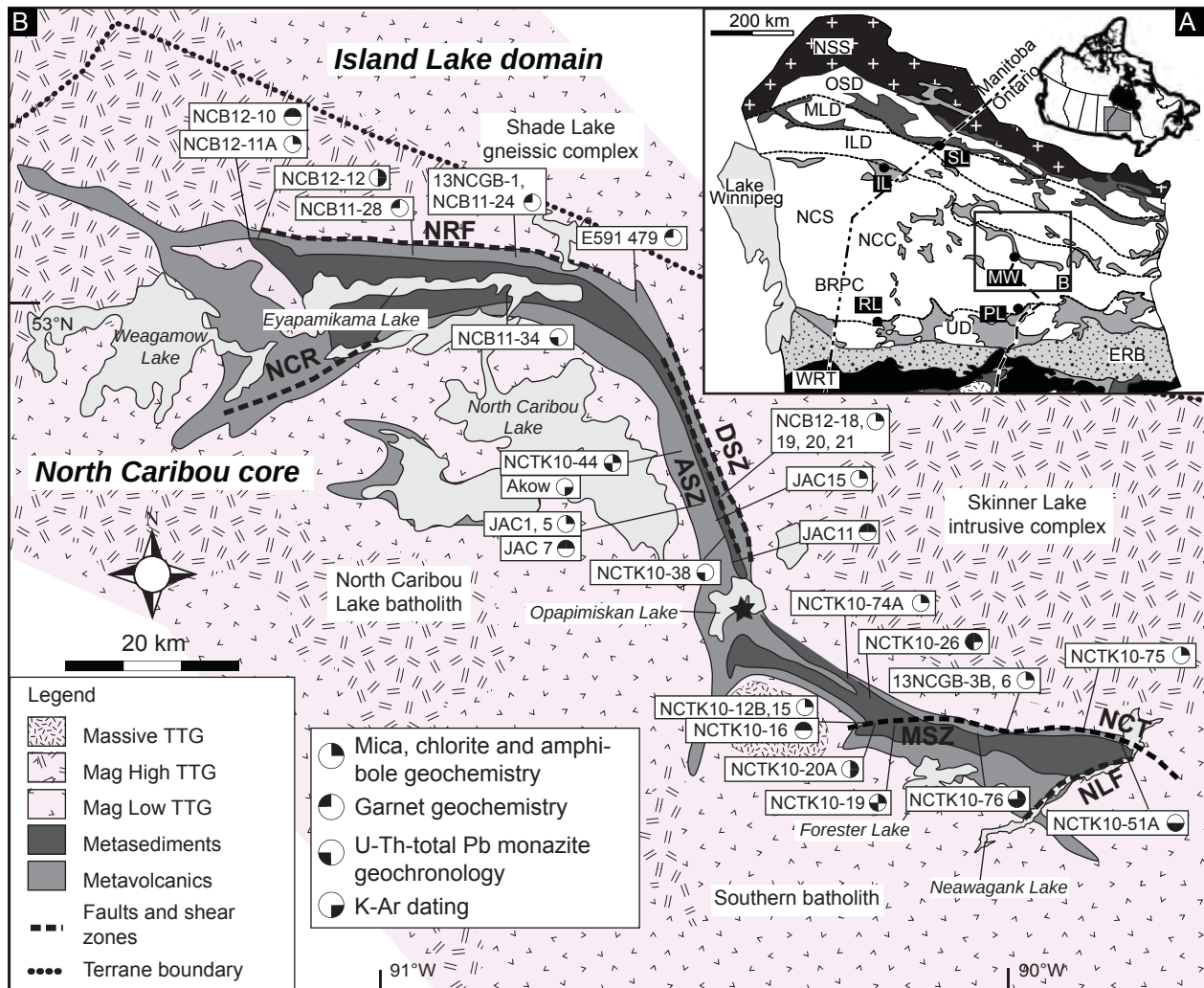


Figure 2.1: Location and regional geological map of the North Caribou greenstone belt in Northwestern Ontario, modified from Gagnon et al. 2015 (submitted). A) Modified from Percival et al. 2006. Location of the NCGB in the Western Superior Province. NSS, Northern Superior superterrane; NCS, North Caribou superterrane; OSD, Oxford-Stull domain; MLD, Munroe Lake domain; ILD, Island Lake domain; NCC, North Caribou core; BRPC, Berens River plutonic complex; UD, Uchi domain; SL, Stull Lake; IL, Island Lake; MW, Musselwhite; RL, Red Lake; PL, Pickle Lake; WRT: Winnipeg River terrane; ERB: English River basin. B) Modified from Breaks et al. 2001. Regional geological map of the NCGB surrounded by TTG granitoids classified by their aeromagnetic signatures. Sample locations and analytical techniques are shown in white boxes. Musselwhite mine is represented by the star. ASZ, Akow Lake shear zone; DSZ, Dinnick Lake shear zone; MSZ, Markop Lake shear zone; NCT, North Caribou-Totogan deformation zone; NCR, North Caribou River fault; NLF, Negawank Lake fault; NRF, North Rim fault zone.

more typical greenschist facies conditions often observed in many other western Superior greenstone belts. The high metamorphic grade background obscures hydrothermal and other low-temperature signatures, making it more difficult to resolve the tectonothermal evolution of the belt and identify zone of ore deposit-related alteration. Applying geochronology to this matter has been met with mixed success. Voluminous magmatism occurred between 2.9 and 2.7 Ga, and regional metamorphism and fluid circulation is thought to have occurred ca. 2.73 Ga or slightly younger based on U-Pb zircon rim ages (Kelly and Schneider 2015) and Sm/Nd whole rock-garnet ages of 2.72-2.66 Ga (Biczok et al. 2012). The youngest dates in the belt are as young as 2.4 Ga ($^{40}\text{Ar}/^{39}\text{Ar}$ ages, Biczok et al. 2012), interpreted as being either a late resetting by fluids from regional dyke swarms (e.g. Matachewan), or protracted metamorphism where the earlier metamorphic events kept the crust warm until 2.4 Ga. Therefore, better understanding of the timing and crustal conditions during the protracted metamorphism and deformation in the NCGB will provide insights into regional tectonism during assembly of the Western Superior Province, as well as on the implications of crustal-scale transpressive zones in the formation of orogenic mineral deposits that are thought to originate from collisional systems during the Archean (Biczok et al. 2012).

We have conducted extensive field work in order to resolve metamorphic zones and patterns across the belt. This was coupled to geochemical and geochronological work to determine timing and crustal conditions in zones of high strain, which mostly correlate with high metamorphic grade domains. Major shear zones are thought to have formed as a product of tectonic assemblage of the western Superior Province, possibly syn-mineralization. However microstructural studies of a major shear zone north and along strike of the deposit indicate deformation at elevated temperatures in a relatively dry environment, reflecting the heterogeneity

in crustal conditions on a km-scale during collision (Gagnon et al. submitted). The objectives of characterizing the timing and crustal conditions of deformation in shear zones is important for understanding the significance of major structures in the tectonic evolution of Archean greenstone belt as well as their implication in mineralization events.

2. Geological setting

2.1. Archean tectonics of the western Superior Province

The Superior Province is one of the best-preserved and largest Archean terranes, and possesses valuable ore deposits. The main phase of tectonic accretion in the western Superior ceased by ca. 2.6 Ga resulting in E-W to NW-SE trending subprovinces separated by large-scale boundary faults (Percival et al. 2006 and references herein). This crustal amalgamation occurred during the Neoarchean Uchian orogeny, creating a pattern of scattered and narrow greenstone belts representing relicts of oceanic basins between older continental crust terranes (Percival et al. 2006). The five accretionary events that define the Uchian orogeny were closely linked to coeval widespread magmatism, regional metamorphism and deformation events and can be identified in the rock record (Percival et al. 2006 and references herein). Geochronology, isotopic work and aeromagnetic surveys across the Province have permitted the classification of these subprovinces into a series of terranes and superterranes.

In the NW part of the Province, from south to north are the North Caribou superterrane (NCS), the Island Lake Domain (ILD), the Oxford-Stull domain (OSD) and the Northern Superior superterrane (NSS, Lin et al. 2006, Percival et al. 2006). The nucleus of the Superior Province is thought to be the NCS with an age of ca. 3.0 Ga, to which younger microcontinents and island arcs accreted both from the north and south (Williams 1990, Thurston et al. 1991,

Percival et al. 2006). The northern margin of the NCS represent the suture zone of an ancient southward dipping subduction zone that led to the docking of the ca. 3.7 Ga Northern Superior Superterrane (oldest Eoarchean microcontinent, Böhm et al. 2000, 2003, Skulski et al. 2000, Percival et al. 2006). This is evinced by the presence of south-over-north shear zone movement (Lin et al. 2006) and the occurrence of arc magmatism, which occurred between 2.775 and 2.733 Ga across the Island Lake, Munroe Lake, and Oxford-Stull domains (**Fig. 2.1A**, Corkery et al. 2000, Skulski et al. 2000, Parks et al. 2006). In contrast, the southern margin of the NCS records ca. 2.75-2.71 Ga arc magmatism across the Berens River plutonic complex and Uchi domain (Corfu et al. 1995), which is interpreted as northward subduction that led to the docking of the ca. 3.40 Ga Winnipeg River terrane (**Fig. 2.1A**, Percival et al. 2006).

This study is focused on the North Caribou greenstone belt located within the NCS (**Fig. 2.1B**). The NCS is a Mesoarchean microcontinent characterized by ca. 3.0 Ga juvenile crust overlain by ca. 2.9 Ga metasedimentary and mafic to ultramafic units. The latter assemblage is thought to represent platformal or rift-type sequences (Thurston and Chivers 1990, Thurston et al. 1991). Available geochronological data indicate a complex tectonic evolution during the assembly of the Superior craton. Regional metamorphism coeval with magmatism occurred at 2.86 Ga during the docking of the ILD to the north. Whole rock Sm-Nd garnet ages appear to show a hydrothermal alteration event at 2.72-2.66 Ga recorded at the Musselwhite mine (Biczok et al. 2012). Other evidence of this hydrothermal metamorphism can be seen in zircon rims from metasedimentary rocks in the NCGB dated at ca. 2.73-2.71 Ga (Kelly and Schneider, 2015), as well as altered zircon from the Southern batholith and Schade Lake gneissic complex at 2.73-2.71 Ga and 2.76-2.70 Ga, respectively (Van Lankvelt 2013). A slightly younger event was identified with $^{40}\text{Ar}/^{39}\text{Ar}$ dating on fabric-forming biotite at 2.59 Ga overlying a mineralized unit

at the deposit, possibly representing retrograde metamorphism implicating fluid channeling and brittle fracturing of hydrothermal garnet (Biczok et al. 2012, Kalbfleisch 2012). The youngest tectonic signature in the NCGB is represented by our data at ca. 2.44 Ga, which broadly correlate with a 2.50-2.42 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages from an unmineralized unit at the mine (Biczok et al. 2012).

Prevailing thought on the mode of tectonism suggests that this arcuate greenstone belt trapped between granitoid domes could have originated as a product of vertical tectonism, permitting sagduction of heavier greenstone units during domal emplacement of granitoids (e.g. Gorman et al. 1978, Goodwin and Smith 1980, Chardon et al. 1996, 1998, Lin 2005, Parmenter et al. 2006, François et al. 2012). Deformation zones bounding the northern margins of the NCGB are of particular interest as they are a direct product of deformation occurring during the accretion of terranes and generally record information on the nature of tectonism. A recent structural study however suggest a dominant horizontal, transpressive system that produced steeply-dipping planar and shallow-plunging linear fabrics, which trend broadly with the doubly arcuate shape of the belt (Gagnon et al. 2015, submitted). Additionally, fluid circulation seems to be absent in the central portion of the belt, directly north of the Musselwhite deposit. However orogenic gold deposits in Archean cratons have been defined by workers as structurally controlled lode Au deposits formed during orogenies (Biczok et al. 2012 and references therein). Characteristics such as spatial relationships with crustal-scale shear zones and variable metamorphic grade of the host rock seem to be common in many orogenic systems. Source of fluids is equivocal but are thought to have originated from local magmatic bodies and from the surrounding rocks during metamorphism, and subsequently channeled in crustal-scale shear zones (Biczok et al. 2012 and references therein). In the NCGB, timing and source of fluids are

still under questioning, yet available geochronological and geochemical data reflect a complex and protracted evolution, with ages from ca. 2.86 to 2.4 Ga and a strong metamorphic fluid input (Biczok et al. 2012, Duff 2012, Kalbfleisch 2012). Better characterization of timing between shear zones, fluids and regional metamorphism could prove to be useful in exploring for ore deposits in similar Archean terrains.

2.2. Geology of the North Caribou greenstone belt

The NCGB is a 3.0-2.7 Ga metavolcanic-metasedimentary belt located in the North Caribou Superterrane. This greenstone belt is surrounded by slightly younger granitoid and gneiss domes that mark the end of accretion at 2.87-2.7 Ga (Thurston et al. 1991, Biczok et al. 2012). It is characterized by a doubly arcuate geometry with two E-W trending arms and a central NNW-SSE portion. Lithologies across this ~150 km long belt include metasediments and volcanic sequences that have been categorized into up to nine packages according to different workers in the region. The oldest dated supracrustal unit is the Agutua Arm metavolcanic assemblage at c. 2981 Ma (U-Pb zircon, deKemp 1987, Biczok et al. 2012). It is unconformably overlain by the c. 2980 Ma package of Keeyask Lake metasedimentary and komatiite-rich metavolcanic rocks (KLS/V). Mafic sequences of the North Rim and South Rim volcanics (NRV and SRV, respectively) overlie, both in depositional and tectonic contact, the Keeyask assemblage and are dominated by foliated amphibolites locally intruded by small felsic or pegmatitic intrusions. Other volcanic sequences include the Opapimiskan-Markop and Forester-Neawagank volcanics. These volcanic sequences were previously correlated with the McGruer volcanic assemblage, but in light of geochronology and geochemical work, were treated as distinct units (Thurston et al. 1991, Breaks et al. 2001, Biczok et al. 2012). On top of these

volcanic assemblages are the Eyapamikama Lake sediments (ELS) and Zeemel-Heaton sediments (ZHS) that compose the majority (~50%) of the NCGB. These sediments are interpreted as being submarine turbidite fan deposits and include cobble to pebble quartz conglomerates grading upward to quartz-rich wackes and are ideal for determining peak metamorphic conditions as they often contain index minerals (Breaks et al. 2001 and references therein, Biczok et al. 2012). These supracrustal assemblages of the NCGB are surrounded by slightly younger granitoid bodies: The Shade Lake gneissic complex (SLGC) to the east and north, the North Caribou Lake batholith (NCLB) to the south and west, and the Southern batholith to the north (**Fig. 2.1B**, Breaks et al. 2001, Biczok et al. 2012, Van Lankvelt, 2013).

Protracted deformation has left an indelible mark on the greenstone belt. The NCGB is bordered to the north by many crustal-scale deformation zones, which are a feature often observed in greenstone belts of the NW Superior (e.g. Chen et al. 2001, Parmenter et al. 2006, Lin and Beakhouse 2013). Several ductile deformation events can be discerned with the presence of folding, pervasive steep planar fabrics and shallow linear fabrics forming tectonite or mylonitic textures. Late brittle-ductile events were also recorded in a few fault zones suggesting a reactivation of pre-existing ductile structures at shallower depths, evidenced by fragmented mylonite or tectonite (representing the earlier ductile conditions) at their fault core (Breaks et al. 2001). Some deformation events are more difficult to recognize as they are localized or overprinted by later deformation (Biczok et al. 2012). The distribution of strain intensity in the belt is irregular and varies spatially from weak to very strong. The southern arm of the belt usually exhibits a more pervasive structure than the northern arm, where primary sedimentary features are still preserved. Deformation zones also seem to be more abundant in the southern arm. Microstructural and geochemical data available for the central portion of the belt north of

the deposit appear to record transpressive deformation under amphibolite facies conditions with no fluid circulating through the shear zone (Gagnon et al. 2015).

The >5.8 M oz Musselwhite orogenic gold deposit is hosted in a moderately metamorphosed BIF that is tightly folded and averages 6-7 g/t (Biczok et al. 2012). Gold mostly resides in synclinal keels and sheared fold limbs, often at the intersection with high strain zones (Biczok et al. 2012). Although the deposit lies near the boundary between the NCS and the ILD, there is no evidence for the location of the deposit being controlled by a major crustal-scale shear zone (Biczok et al. 2012). Gold was deposited under amphibolite facies conditions of 540-600°C and the sources for mineralizing fluids are equivocal, but are thought to be a mix of magmatic- and metamorphic-derived fluids that circulated through crustal-scale shear zones located on the northern margins of the belt (Otto 2002, Biczok et al. 2012, Kalbfleisch 2012, Duff 2014). The majority of mineralization is located in the garnet-grünerite silicate facies of the BIF and is characterized by pyrrhotite veinlets in the host rock as well as fracture-filling in garnet. Ore zones can be identified by green amphibole replacing grünerite, quartz veining, chlorite patches and the growth of large hydrothermal garnet. Additionally, chlorite replacing garnet, green amphibole and grünerite indicate a retrograde metamorphic path at 210-250°C in high strain zones (Otto 2002, Biczok et al. 2012). An age of mineralization was reported at ca. 2720-2660 Ma based on Sm-Nd whole rock garnet ages at the mine (Biczok et al. 2012), however this age is still debated. The significance of the many crustal-scale deformation zones in the genesis of the deposit as well as development of the greenstone belt is still under question, thus a geochemical and geochronological investigation of shear zones was performed in an attempt to better resolve their significance.

3. Metamorphism of the NCGB

During our study we were able to better define the regional metamorphic patterns of the NCGB. Extensive field work and sampling conducted over a 4-year period was necessary to cover the extent of the belt, and coupled with detailed petrography and mineral chemistry data (below) was compiled to produce a detailed map, which includes the understudied southern arm of the greenstone belt (**Fig. 2.2**; sample descriptions and locations are available in **appendix G**). Some features previously observed such as occurrences of kyanite and cordierite near the Markop Lake and Miskeesik Lake areas, and a narrow contact aureole along the southern edge of the Northern arm (Breaks and Bartlett 1991, Breaks et al. 2001) were not observed in any of our mapping. Metamorphic grade of the host rock ranges from lower greenschist facies up to middle amphibolite facies conditions, which poses a difficulty in resolving hydrothermal signatures from the metamorphic background. Metamorphic patterns in the NCGB were previously studied by Breaks et al. (2001) and limited to a simple isograd map of the N-S trending portion and northwestern arm of the belt. Two main metamorphic trends can be identified based on mineral assemblages. The first being an increase of metamorphic grade from the northwest, dominated by chlorite + biotite, to the deposit exhibiting an assemblage of garnet + staurolite + grunerite ± sillimanite. This trend was interpreted as being evidence for hotter conditions or deeper structural position near the gold deposit. The second trend is a zonal increase in grade to the north in the Eyapamikama Lake area, northwestern arm of the belt. This increase is noted by the presence of biotite + chlorite near the southern boundary of the belt that grades into garnet + staurolite + andalusite along the northern boundary. Additionally, the presence of cordierite was included as part of the assemblage showing evidence of this increase in grade by Breaks et al. (2001); this mineral is generally a product of low P/high T settings. Furthermore, cordierite was only

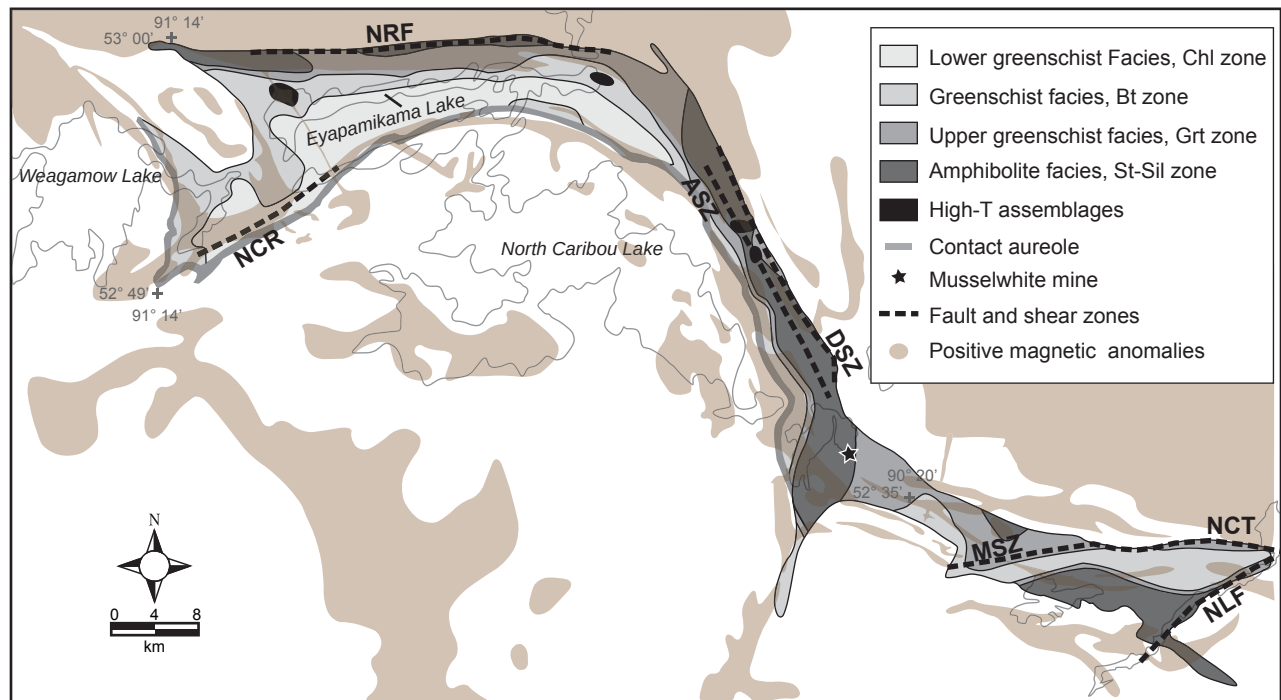


Figure 2.2: Map of the North Caribou greenstone belt showing metamorphic facies in relation to positive magnetic anomalies. Modified from Kelly et al. 2013. Distribution and extent of magnetic anomalies were taken from propriety sources. The northwestern part of the belt was modified from Breaks et al. (2001). Contact aureole is from Breaks et al. (2001) original map, however was not observed. Abbreviations: ASZ, Akow Lake shear zone; DSZ, Dinnick Lake shear zone; MSZ, Markop Lake deformation zone; NCT, North Caribou-Totogan deformation zone; NCR, North Caribou River fault; NLF, Negawank Lake fault; NRF, North Rim fault zone.

observed in small areas directly adjacent to small intrusive bodies, illustrating probably late localized contact metamorphism (**Fig. 2.2, 2.3A-B**). To better visualize the relationship between cordierite and small intrusive bodies, our metamorphic map includes regional magnetic anomalies, and the most evident case is found in the northwest region of Eyapamikama Lake (**Fig. 2.2**).

The curved geometry of metamorphic patterns, mostly in the northern portion, was interpreted as a consequence of possible domal emplacement of the North Caribou Lake batholith (2870 Ma) adjacent to the belt (Breaks et al. 2001), intruding in an already metamorphosed greenstone belt. Evidence of this was found in thin contact aureoles adjacent to the batholith, overprinting the regional metamorphic grade. We were not able to traverse in these locations due to scarcity of outcrops; however the model would indicate that this particular batholith was not the source of heat that produced the regional pattern (Breaks et al. 2001). In the southern arm of the belt, patterns are much more complex and irregular. No clear trend can be discerned and the majority of high grade metamorphic assemblages are not present in this portion of the belt. Contrarily to the northern portion of the belt, garnet and staurolite in the southern arm are only present in few locations in proximity to major shear zones (e.g. Markop Lake shear zone). It is likely that the abundance of deformation zones disturbed the regional metamorphic patterns, therefore producing an irregular pattern (**Fig. 2.2**).

Metamorphic zones that were identified, in order of increasing grade, include lower greenschist facies (chlorite zone), greenschist facies (biotite zone), upper greenschist facies (garnet zone), amphibolite facies (sillimanite and staurolite zone) and a high T/low P assemblage (**Fig. 2.2**). Each metamorphic zone can be identified based on the occurrence of specific stable mineral assemblages. Typical lower greenschist facies assemblage in metasedimentary units of

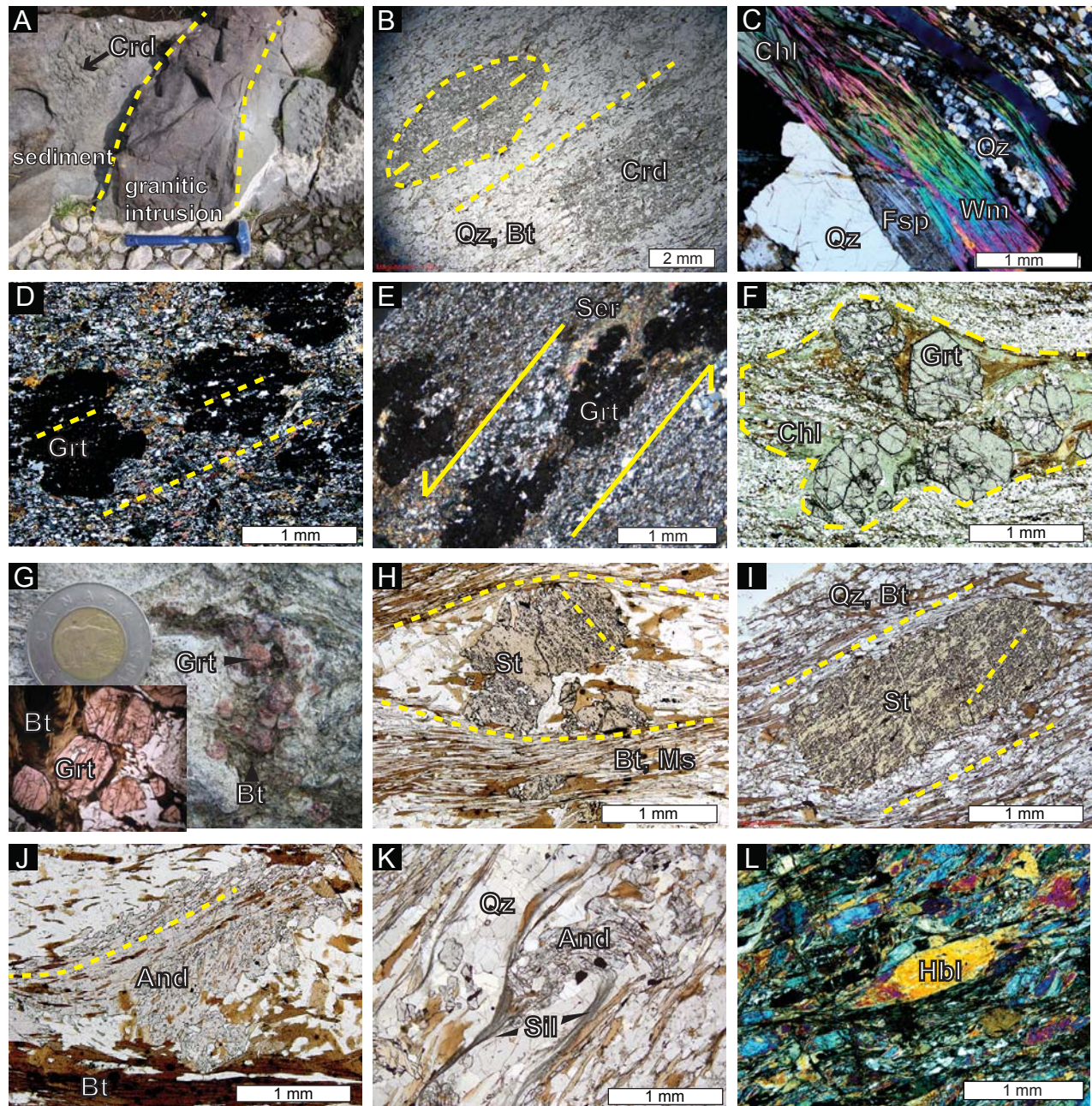


Figure 2.3

Figure 2.3: Photomicrographs of peak metamorphic mineral assemblages and deformation textures in metasedimentary and mafic metavolcanic rocks from the North Caribou greenstone belt. A) Field photo of cordierite (Crd) nodules growing adjacent to a small granitic intrusion on eastern Eyapamikama Lake. B) Plane polarized light photo of post-tectonic cordierite porphyroblasts from a metasedimentary rock on eastern Eyapamikama Lake. C) Cross-polarized photo of a bundle of intergrown white mica (Wm) and chlorite (Chl) surrounded by dynamically recrystallized quartz from the NCT area (NCTK10-51A). Representing greenschist facies conditions and main regional fabric. D)-E) Cross-polarized photos of pre- to syn-tectonic garnet (Grt; e.g. McGruer Lake, 13NCGB-1) showing irregular crystal faces, flattening and fracturing. Inclusion trails are generally parallel to fabric and some garnet are good shear sense indicators. F)-G) Plane polarized light and field photos of hydrothermal garnet clusters (e.g. ASZ, MSZ). Clusters of almost euhedral garnets are generally surrounded by biotite (Bt) and chlorite. H)-I)-J)-K) Plane-polarized light photos of peak metamorphic mineral assemblages in metasedimentary rocks from the Akow Lake area showing pre- to syn-tectonic staurolite (St), andalusite (And), and sillimanite (Sil). Commonly, the staurolite and andalusite is poikiloblastic and corroded; Sillimanite is generally found growing on andalusite. Note the inclusion trails within the refractory index minerals, which are oblique to the main rock structure. L) Cross-polarized light photos of hornblende (Hbl) porphyroblasts in foliated mafic volcanic rocks from the Dinnick Lake and Akow Lake shear zones showing sinistral shearing. Finer Hbl define a finer foliation surrounding the larger porphyroblasts.

the NCGB comprises chlorite + white micas, which define the main steeply dipping regional foliation. Metavolcanic rocks in this facies generally are aphanitic (fine grained hornblende and plagioclase) and contain chlorite (Breaks and Bartlett 1991, Breaks et al. 1991). Lower greenschist facies conditions are only exposed along the northern arm of the belt, stretching from the southern half of Eyapamikama Lake to the southern edge of the greenstone belt (**Fig. 2.2**). The greenschist facies is identifiable in metasedimentary units with the presence of an assemblage containing biotite and white micas $\pm$ chlorite. Moderate to strong regional rock structure is generally defined by laths of biotite and white micas ($\pm$ chlorite) and is pervasive in almost all units (**Fig. 2.3C**). Another population of biotite grains are found at random orientation in some units, representing a possible second growth episode. In metaconglomerate, fabric-forming minerals wrap around recrystallized/deformed quartz-plagioclase cobbles and pebbles. The greenschist facies is more difficult to identify in mafic metavolcanic rocks as they often contain less than 1% biotite (Breaks and Bartlett 1991). This zone is present across the entire belt as a thin band following the regional strike. In the northern arm, the biotite zone completely surrounds the chlorite zone (**Fig. 2.2**). The upper greenschist facies or garnet zone parallels the biotite zone, stretching along the length of the belt, and is characterized by garnet and biotite in metasedimentary rocks, with the latter defining the regional foliation and often wrapping around garnet porphyroblasts (**Fig. 2.3D to G**). In metavolcanic rocks, garnet is less abundant (<5%) and generally found in clusters enveloped by chlorite and biotite or at proximity to quartz veining and zones of higher strain (Breaks et al. 1991). Metamorphic garnets are hypidioblastic and show some flattening or fracturing caused by strain (**Fig. 2.3D-E**). Another set of garnet can be considered based on context within rocks. Cluster of more euhedral garnet completely enveloped by chlorite and biotite were interpreted as being of hydrothermal origin, thought to have formed

in a fluid-rich environment in some areas of the belt, mainly around the Markop Lake deformation zone and the Musselwhite mine (**Fig. 2.3F-G**; additional discussion below and in Kalbfleisch 2012 and Duff 2014).

Amphibolite facies conditions are more isolated across the NCGB and are mainly found on the northern margins around zones of higher strain (**Fig. 2.2**). Amphibolite assemblage comprises garnet, staurolite, andalusite and sillimanite in metasedimentary units, whereas mafic metavolcanic rocks contain hornblende porphyroblasts and plagioclase. Garnets in this zone are highly corroded and poikiloblastic suggesting conditions surpassing their stability field of the upper greenschist facies. Staurolite and andalusite are in abundance in the Akow Lake areas as well as all along the northern arm of the belt. They are often poikiloblastic and a strong fabric defined by biotite and white micas wraps around them (**Fig. 2.3H to J**). In certain units, sillimanite fibers are found to have grown on andalusite (**Fig. 2.3K**). Hornblende in mafic metavolcanic units can be classified into two categories: elongated grains that define the foliation and older corroded porphyroclasts (**Fig. 2.3L**). Most of the porphyroclasts and elongated grains show undulose extinction and fractures, as well as a lower birefringence, suggesting higher strain. Lastly, several localities in the NCGB display high T/low P assemblage containing cordierite. This mineral is generally a product of contact metamorphism and only occurs in pods around small intrusions or near magnetic anomalies (**Fig. 2.2, 2.3A**). Cordierite is often flattened and almost completely replaced by sericite or chlorite (**Fig. 2.3B**). Alteration in these rocks is exhibited as fine and cloudy sericite in feldspar, chlorite replacing biotite and calcite precipitation in fractures.

4. Mineral chemistry of phyllosilicate, amphibole and garnet

As a complement to mineralogical characterization of metamorphic zones, we conducted in situ major element mineral chemical analysis of amphibole, garnet and fabric-forming phyllosilicate phases that are part of the mafic metavolcanic and metasedimentary units across the belt. The JEOL JXA-8230 SuperProbe (University of Ottawa) was used on individual biotite, white mica (Wm), chlorite, garnet and amphibole crystals, using an accelerated voltage of 20 kV and a beam diameter of 5 μm . End-member calculations were performed using Excel spreadsheets and their percentages calculated by selecting the most abundant end-members then weighing them against each other (Vidal et al. 2001, Para et al. 2002, Hawthorne and Oberti 2012). Additionally, four x-ray maps of Ca, Fe, Mn, Mg and Y were acquired on garnets for samples NCTK10-26B, JAC11 and 13NCGB-1 using the wavelength dispersive spectrometer (WDS) and the energy dispersive spectrometer (EDS) of the electron microprobe in order to investigate zoning, which can be indicative of their growth environment. Sample descriptions are available in **Appendix G**, detailed methodologies in **Appendix H** and EMPA results are summarized in **Appendix I (Tables I1-5)**.

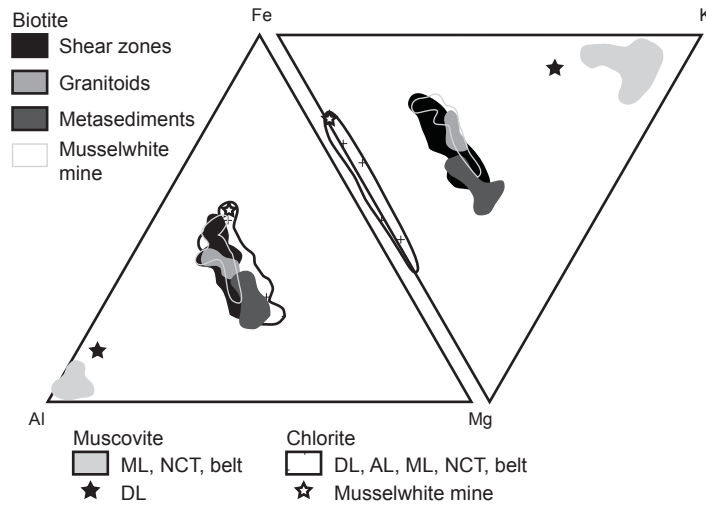
4.1 Fabric forming minerals

Fabric-forming minerals include chlorite, biotite and white micas, which are present in most metasedimentary units, whereas mafic volcanic units only contain chlorite and minor biotite in the lowest metamorphic assemblages. In most rocks, fabric-forming minerals define the main regional rock fabric that is broadly parallel to the trend of the greenstone belt. Some second generation biotite and chlorite can be observed at angle to the main foliation in few locations, indicating low strain, late growth. Chlorite, white mica and biotite are often found intergrown in

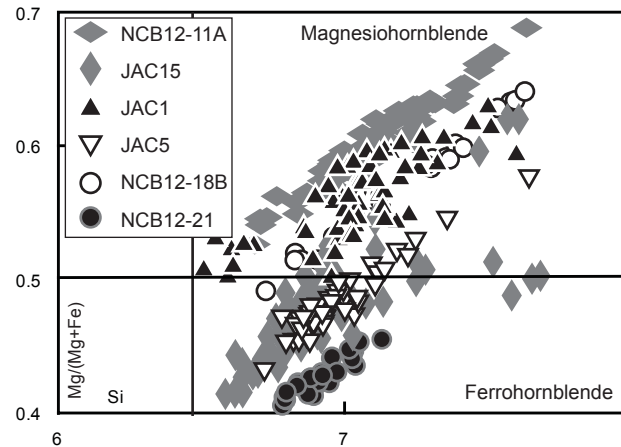
sinuous bundles, wrapping around porphyroblasts when present or segregated from feldspar and quartz domains. End-member components used in white mica calculations include muscovite, paragonite, Fe-Al celadonite and pyrophyllite (Parra et al. 2002). Biotite chemistry comprises annite, phlogopite and Fe-Al celadonite end-members. Lastly, chlorite compositions were calculated using a combination of four end-members from Vidal et al. (2001). Our data as well as a compilation of data from Otto (2002) and Isaac (2008) reflects uniform muscovite, biotite and chlorite compositions throughout the belt (**Fig. 2.4A; Tables I1-3**).

Biotite in the Akow Lake area (JAC7, 11 and 15) shows an average composition of 32-45% annite, 25-33% Fe-Al celadonite and 22-43% phlogopite. Biotite in two samples from the Miskeesik Lake area (NCB12-10, 11A) show a composition that is more magnesium-rich with a 61-62% phlogopite component, whereas annite only contributes to 15% of the composition and Fe-Al celadonite to 23-24%. Biotite composition in the MSZ area (NCTK10-12B, 20A and 76) is 28-49% phlogopite, 21-39% annite and 28-32% Fe-Al celadonite. Samples collected 5-10 km north of the MSZ (NCTK10-26A, 74A) show biotite compositions ranging from 43-65% phlogopite, 20-30% Fe-Al celadonite and 15-27% annite. The eastern end of the NCT (NCTK10-51A, 75) is represented by biotite composition of 32-48% annite, 19-37% phlogopite and 30-33% Fe-Al celadonite. Lastly, biotite from two samples in the Dinnick Lake shear zone (NCB12-19, 20), which is present as a minor phase in a sheared granite, have a composition averaging 48-54% annite, 36% Fe-Al celadonite and 9-17% phlogopite. Composition of biotite across the belt is fairly consistently dominated by annite, with a slight increase in magnesium content to the north. This trend is evident on the ternary diagrams (**Fig. 2.4A**) where we can also notice metasedimentary units have slightly higher magnesium content than other lithotypes.

A fabric forming minerals



B calcic amphiboles



C garnet

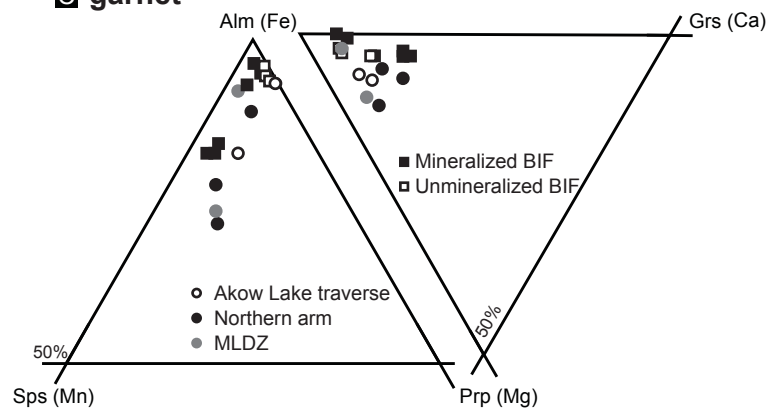


Figure 2.4: Major element geochemistry of common metamorphic minerals across the NCGB. A) Ternary diagrams showing the geochemistry of fabric forming minerals, including biotite, muscovite and chlorite. Data was compiled from Otto 2002, Isaac 2008, Kalbfleisch 2012 and this study. B) Diagram showing composition of calcic amphiboles, which varies between magnesio- and ferrohornblende. C) Top half of ternary diagrams showing garnet compositions. Data was compiled from Kalbfleisch 2012, Duff 2014 and this study.

White micas from the Akow Lake area (NCTK10-44A, B) have a composition of 79% muscovite, 17% paragonite, 2% Fe-Al celadonite and 2% pyrophyllite. One sample from the northwestern part of the belt contains white micas that have a composition of 85% muscovite, 11% paragonite, 3% Fe-Al celadonite and 2% pyrophyllite. White micas from the Dinnick Lake shear zone's sheared granite have a composition of 79% muscovite, 19% Fe-Al celadonite, 2% paragonite and 1% pyrophyllite. White micas from four samples in the MSZ area (NCTK10-12B, 15, 16 and 20B) have a composition of 82-89% muscovite, 3-11% paragonite, 3-8% Fe-Al celadonite and 2-6% pyrophyllite. One sample just north of the MSZ (NCTK10-74A) shows a white mica composition of 88% muscovite, 6% Fe-Al celadonite, and 3% paragonite and pyrophyllite. The central portion of the southern arm (13NCGB-3B, 6, NCTK10-76) is characterized by white mica composition that averages 84-87% muscovite, 6-7% paragonite, 5-9% Fe-Al celadonite and 1% pyrophyllite. Lastly, compositions of white mica from the easternmost edge of the belt (NCTK10-75, 51A) have an average composition of 84-85% muscovite, 7-9% paragonite, 4-8% Fe-Al celadonite and 1-2% pyrophyllite. Composition of white micas across the belt is consistent and dominantly muscovite.

Chlorite is part of lowest metamorphic grade assemblages and is found in both metasedimentary and metavolcanic units. Composition of chlorite in the Akow Lake area (JAC1, 5, 7; NCTK10-44A, B) is on average 57-73% clinochlore, 5-25% daphnite, 13-18% Mg-amesite and 1-6% Mg-sudoite. One analyzed sample from this area (JAC11) show a slightly different geochemistry with 60% daphnite, 30% clinochlore, 9% Mg-amesite and 1% Mg-sudoite. Two samples from the northwestern part of the belt (NCB12-10, 11A) have a composition of 78-81% clinochlore, 14-18% Mg-amesite, 4% daphnite and 1% Mg-sudoite. Another sample from this area (NCB12-12) show slightly different composition with 55% daphnite, 31% clinochlore, 11%

Mg-amesite and 2% Mg-sudoite. The MSZ area is characterized by variable chlorite compositions averaging 51-67% clinocllore, 10-37% daphnite, 8-15% Mg-amesite and 1-8% Mg-sudoite. Sample NCTK10-16 (A and B) is different from the others with a composition of 98-99% daphnite and less than 1% for the other end-members. Two samples north of the MSZ have a composition of 67-81% clinocllore, 8-18% Mg-amesite, 6-13% daphnite and 3-5% Mg-sudoite. The central portion of the southern arm of the belt (13NCGB-6, 3B) is represented by chlorite compositions averaging 63-65% daphnite, 25-26% clinocllore, 8-9% Mg-amesite and 2% Mg-sudoite. The easternmost end of the NCT (NCTK10-51A, 75) shows chlorite compositions of 25-57% daphnite, 29-61% clinocllore, 11-13% Mg-amesite and 2-3% Mg-sudoite. Chlorite compositions are more variable than micas due to a higher possibility of this phase being a product of alteration or retrograde metamorphism. Generally, chlorite composition is dominantly clinocllore in composition. However a weak trend can be identified as daphnite composition in the southern arm that increasingly gives way to clinocllore in the northern arm, suggesting a northerly increase in magnesium, consistent with biotite geochemistry (**Fig. 2.4A**).

4.2 Amphiboles

Amphibole is an abundant amphibolite facies index mineral in mafic metavolcanics of the NCGB. Generally, two groups of amphiboles can be identified based on textures. The first one is characterized by coarse porphyroclasts that are corroded and highly deformed; they show moderate to strong undulose extinction and low interference colors that commonly indicated high strain. The other amphibole group consists of elongated to prismatic crystals that define the foliation. These are less deformed as they exhibit very little undulose extinction and normal interference colors. Most of the grains show fracturing as well as moderate oscillatory-zoning,

which is not resolvable with the 5 μm beam size of the probe. Radiating amphiboles can be observed in units from Miskeesik Lake area, overprinting the main fabric and suggesting a late or strain-free growth. Although amphiboles have variable textures, they all possess the same geochemical composition. In situ analyses of six samples across the belt show a composition that varies between magnesio- and ferro-hornblende (**Fig. 2.4B**). Five of these samples are from the DSZ and ASZ and no spatial trend can be discerned, however hornblende from one sample located in the Miskeesik Lake area have the highest magnesium content, which may suggest an increase in magnesium toward the north.

4.3 Garnets

Garnet is a very useful mineral in metamorphic and hydrothermal terrains. Petrography, major and trace element geochemistry can be used to help determine between metamorphic or hydrothermal genesis. In this section we present a synthesis of both metamorphic and hydrothermal garnets in the North Caribou greenstone belt, using major element geochemistry and petrography on diverse samples collected at various locations and settings. In this study, garnets in three samples from the Akow Lake region and the northwestern end of the belt (JAC7, JAC11 and NCB12-10) were analysed via in situ major element EMPA in order to determine their composition. Additionally, data acquired on five samples from Kalbfleisch (2012) are also included (NCTK10-26B, 16B, E591 479, NCB11-24, 28). These samples represent garnet-bearing metasedimentary rocks from upper greenschist to lower amphibolite metamorphic grades that display syn-tectonic deformation textures such as cobble flattening, spatial association with fold hinges/limbs and micro-shear zones (detailed sample descriptions are available in **Appendix G**). Results of in situ EMPA major elements are summarized in **Table I4** as wt% oxide, atom per

formula units and end-member% for each of the eight samples. Data from samples NCTK10-26B, 16B, E591 479, NCB11-24 and -28 are reported for core, mean and rim analyses for individual garnet (**Table I4b**), whereas JAC7, JAC11 and NCB12-10 are reported as minimum, mean and maximum of all analyzed garnets in the sample (**Table I4a**). Mean values for rims and cores were also included for JAC7 and JAC11. These were averaged from few single spots near rims and cores of several garnets. Relative end-member compositions as well as X-ray maps were compiled in **Fig. 2.4C-5** (along with data from Otto 2002 and Duff 2014).

Sample NCB12-10, a metaconglomerate collected in the northwestern end of the belt, contains a ~4 mm pod of garnet crystals of possible hydrothermal origin. These garnets are hypidioblastic, slightly fractured and contain quartz inclusions mainly within the rims. The cluster is nested in biotite and chlorite laths that wrap around them. Garnets in this pod have 62-64% almandine, 15% pyrope and 16-17% spessartine components, whereas grossular contributes to only 5% of the composition.

Garnets in JAC7, a biotite-garnet schist in the Akow Lake area, are hypidioblastic to xenoblastic, also found in clusters surrounded by chlorite and biotite, as well as dispersed in the matrix. Grains are heavily fractured, indicating brittle deformation, and contain a moderate amount of quartz-biotite-sulphide inclusions. Some are flattened and strongly corroded, perhaps indicating that they are pre-tectonic garnets (**Fig 2.3D-E**). The end-member compositions of garnets in this sample consist of 65-78% almandine, 7-13% pyrope, 5-10% grossular and 5-18% spessartine. Examining the mean rim and core values, we observe that there is a slight depletion of iron (~1 wt%) and an enrichment of manganese (~2 wt%) towards the core.

Sample JAC11, also a biotite-garnet schist from the Akow Lake area, contains larger hypidioblastic garnets (up to 0.5 cm) that are evenly distributed throughout the sample, in a

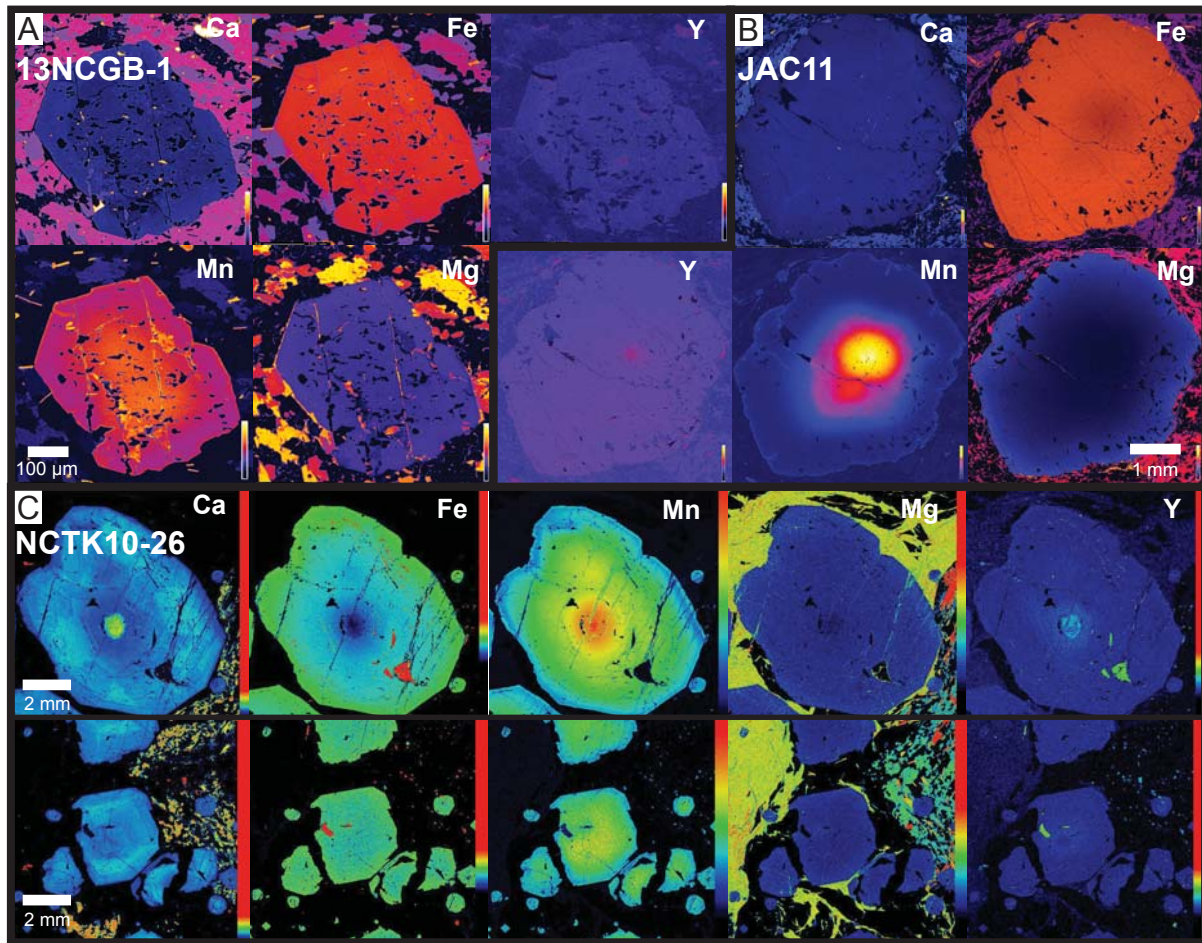


Figure 2.5: X-ray maps of garnet porphyroblasts in the NCGB showing variability in Ca, Fe, Mg, Mn and Y composition between metamorphic (A, B) and hydrothermal (C) growths. A) Metamorphic garnet in 13NCGB-1, probably altered by fluids. B) Metamorphic garnet in JAC11 showing zoning in Fe, Mn and Mg. C) Two hydrothermal garnets in NCTK10-26B showing patchy Ca, Fe and Mn zoning, particularly around the rim of the crystal.

matrix of quartz and feldspar with abundant biotite defining a strong foliation. Grains are moderately fractured and contain some quartz-sulphide inclusions. Garnet end-members in this sample are 78-87% almandine with 6-13% pyrope and 5-8% grossular. The spessartine end-member contributes very little to the geochemistry of these garnets with less than 5%. Chemical X-ray maps show little zoning in major elements (**Fig. 2.5B**). Only manganese shows a strong enrichment in the core of the garnet. Other elements such as iron and magnesium exhibit a weak depletion in the core, whereas yttrium is weakly enriched in the core. Mean wt% oxide values from rims and cores however only show a <1 wt% enrichment of manganese and depletion of Mg in the core.

Sample E591 479 is a garnet schist collected from the NRV near the northern bend of the NCGB (**Fig. 2.1B**). It contains up to 7%, 2 mm round to ellipsoid euhedral garnet porphyroblasts within a very fine-grained siliceous matrix bearing abundant phyllosilicate minerals. The long axis of ellipsoidal garnets is roughly parallel to foliation and garnets present in strain shadows are oriented more randomly with respect to principal strain direction. Foliation, defined by phyllosilicate minerals, wraps around some porphyroblasts and, though on occasion form sigmoidal shapes, dextral kinematics can be observed. Garnets are composed of 66% almandine, 21% pyrope, 7% grossular and 6% spessartine.

Sample NCTK10-26B north of the MSZ is a highly deformed garnet-biotite rich conglomerate. Garnets in this sample are most likely of hydrothermal origin as they are found in a pod of alteration (**Fig. 2.3G**). Some garnets are also found along foliation planes defined by biotite grains. The end-member composition comprises 66% almandine, 16% spessartine, 13% pyrope and only 4% grossular. Two X-ray maps for Fe, Mn, Mg, Ca and Y are shown in **Fig. 2.5C** for this sample. Garnets appear to be sector zoned in terms of Ca, strongly concentrically

zoned in terms of Mn and less so in terms of Fe, Mg and Y; this zoning is more evident in the larger garnet.

Sample NCTK10-16B is a chlorite schist situated within the MSZ, and garnet is associated with quartz sweats in the limbs and hinge zones of tight mesoscopic folds that plunge 35° to the ENE. This sample is peppered with fine-grained chlorite that defines a fairly heterogeneous foliation within a quartz-dominated matrix. Garnet grains are up to 5 mm in diameter and full of quartz inclusions. Their composition is averaging 81% almandine, whereas spessartine, pyrope and grossular only contribute to 6-7% of the composition.

Garnets in 13NCGB-1 are found in the metasedimentary layers of this rock and are evenly distributed in the matrix. They are hypidio- to xenoblastic and contain inclusion trails that are oriented parallel to or at an angle to the main foliation, which is defined by biotite and chlorite (**Fig. 2.3D**). Major element geochemistry was not conducted on this sample as data was acquired on garnets from NCB11-24 at the same location (see below). Chemical X-ray maps obtained show very little zoning of major elements (**Fig. 2.5A**). Manganese is enriched in the core of the garnet, whereas calcium shows a faint depletion.

Sample NCB11-24 is a biotite schist collected from the ELS near the NRF. Garnets are mostly localized in highly strained areas, often at lithological contacts or bedding planes, and are elongated, subhedral and fractured. Commonly accompanied by aggregates of smaller euhedral crystals and locally bearing some inclusion trails, garnets appear to have grown preferentially and been brittlely deformed or boudinaged with respect to the foliation. Grains (or fragments) range in size from 1 to 3 mm and very fine-grained biotite defines the foliation. Alteration is seen as sericite radiating from garnet, commonly in proximity to carbonate-altered domains within

shear bands. Composition is a contribution of 77% almandine, 10% grossular, 8% pyrope and 5% spessartine.

Sample NCB11-28 is a hornblende schist located approximately 10 km west of NCB11-24. A few fractured garnets are found in spatial association with small shear bands as well as at proximity to contacts between metavolcanics and metasedimentary units. One euhedral garnet is relatively inclusion-free and is situated among abundant coarse-grained biotite and green amphibole that are oriented randomly within a dilation crack (potentially hydrothermal). Garnets have end-member compositions of 66% almandine, 14% spessartine, 11% grossular and 10% pyrope.

4.3.1. Metamorphic garnet

Below we summarize characteristics of metamorphic and hydrothermal garnets in the North Caribou greenstone belt. Metamorphic garnets are usually hypidioblastic to idioblastic, and exhibit fracturing and flattening, due to brittle deformation brought by low-temperature strain in many parts of the belts. Some quartz and sulphide inclusions may be present, typically near the rims, which indicate that these garnets were probably corroded by fluids after or at the end of their growth episode. Most of the garnets are found evenly distributed in deformed metasedimentary rocks, in a matrix containing quartz and feldspar with foliation defined mainly by biotite and chlorite. Metamorphic garnet zoning tends to have enrichment of manganese and in some cases calcium in their core, whereas iron is slightly depleted (**Fig. 2.5**). Kalbfleisch (2012) and Duff (2014) reported that trace element signatures in metamorphic garnets from the NCGB are not zoned. However they have a high HREE/LREE ratio as well as a shallow LREE slope and low Eu anomalies (Kalbfleisch 2012, Duff 2014). These patterns are typically found in cores of most garnets, indicating an initial growth in a low water/rock ratio. End-member

composition for these garnets is mainly almandine (~80%) with slight zoning in pyrope and grossular components (**Fig. 2.4C**). Spessartine component is generally very weak. Based on these criteria, garnet from samples JAC11 and 13NCGB-1 are examples of a metamorphic origin.

4.3.2. Hydrothermal garnet

Although it is difficult to distinguish between hydrothermal and metamorphic sources, there are key geochemical signatures that strongly suggest the presence of fluids during the growth of garnets. Petrographically, these garnets are xenoblastic to hypidioblastic and contain abundant inclusions, classified as poikiloblastic. Inclusions are mainly quartz, micas and sulphides. At the Musselwhite deposit, gold can be found in these garnets as inclusions or in fractures, which indicate a direct interaction with mineralizing fluids. In outcrop, garnets are found in clusters or pods nested in chlorite and biotite, or in quartz veins. Geochemically, zoning is strongly heterogeneous within single garnets (**Fig. 2.5C**). Trace elements (Kalbfleisch 2012, Duff 2014) show heterogeneous LREE slopes and a high variability in HREE enrichment (in cases >2 order of magnitude). Europium anomalies are high compared to metamorphic garnets. These very heterogeneous geochemical variations are a strong indication of an open system. End-member compositions are mainly almandine, although it varies from ~50-80%. Pyrope, grossular and spessartine are also contributing in the composition, much more so than in metamorphic garnets (**Fig. 2.4C**). Among analysed garnets in this study, clusters of garnets found in samples NCTK10-26B, JAC7 and NCB12-10 are good examples of hydrothermal origin as their geochemistry and textures are consistent with that of compiled data.

5. Geochronology

Available geochronological data from the NCGB illustrates a large spread in ages, ranging from 2.9 to 2.4 Ga (deKemp 1987, Thurston et al. 1991, Corfu and Stone 1998, Davis and Stott 2001, Percival et al. 2006, Heaman et al. 2011, Biczok et al. 2012, Van Lankvelt 2013, Kelly and Schneider 2015). In this paper, K-Ar geochronology of fabric forming minerals, including biotite and white mica, is presented here, as well as *in situ* U-Th-total Pb geochronology of small monazites (<100 μm) from high strain zones. Results of K-Ar dating are summarized in **Table 2.1** and for the U-Th-total Pb dating in **Fig. 2.6-2.8** and **appendix J**. Ages from the mine were also included in the figures for reference, as those dates are thought to be reflective of the mineralization event (**Fig. 2.9**).

5.1 K-Ar ages of fabric forming minerals

Nine samples were selected for K-Ar dating using the Argon Laboratory Facility at the University of Manitoba (Winnipeg, Canada). Prior to the analyses, several biotite or muscovite grains per sample were hand-picked and weighed using a micro-balance and placed in small vials. Each of these vials contained an average of 10 to 20 mica grains for fine-grained samples, and 2 to 3 grains for coarse-grained minerals. For the Ar analyses, samples were loaded in a copper sample tray in a high vacuum extraction line and were fused using a 100 W CO₂ laser. Sample viewing during laser fusion was monitored by a video camera system and positioning was via a motorized sample stage. Reactive gases were removed by three NP-10 SAES getters (two at room temperature and one at 450 °C) prior to being admitted to an ARGUS VI mass spectrometer by expansion. Three argon isotopes were measured simultaneously over a period of 7 minutes (⁴⁰Ar, ³⁸Ar, ³⁶Ar). Measured isotope abundances were corrected for extraction-line

Table 1: K-Ar muscovite and biotite ages

Sample	Mineral	K2O		Weight		40Ar meas		36Ar meas		40K		40Ar*		Age		error
		Wt%	±	mg	±	fAmps	±	fAmps	±	mol/g	±	mol/g	±	Ma	±	
NCTK10-76	Biotite	9.40	0.50	0.065	0.001	4.974E+04	3.690E+00	1.054E-01	1.940E-01	2.277E-07	1.211E-08	4.831E-08	1.094E-09	1996	70	
NCTK10-76	Biotite	9.40	0.50	0.071	0.001	5.325E+04	6.385E+00	1.145E+00	6.179E-01	2.277E-07	1.211E-08	4.704E-08	1.037E-09	1965	69	
NCTK10-20A	Biotite	9.35	0.50	0.024	0.001	3.012E+04	1.000E+02	2.342E-02	1.000E-03	2.264E-07	1.211E-08	7.921E-08	3.562E-09	2647	97	
NCB12-12	Muscovite	9.90	0.54	0.190	0.001	2.393E+05	3.055E+01	5.631E+00	1.207E+00	2.398E-07	1.308E-08	7.949E-08	1.379E-09	2564	78	
NCB12-12	Muscovite	9.90	0.54	0.200	0.001	2.752E+05	1.003E+00	5.767E-01	7.579E-01	2.398E-07	1.308E-08	8.686E-08	1.506E-09	2695	80	
AKOW	Biotite	9.00	0.54	0.170	0.001	2.309E+05	2.754E+01	8.939E-01	1.521E+00	2.180E-07	1.308E-08	8.553E-08	1.517E-09	2811	89	
NCTK10-51A	Muscovite	9.99	0.50	0.105	0.001	1.289E+05	1.565E+01	2.593E+00	5.973E-01	2.419E-07	1.211E-08	8.035E-08	1.477E-09	2518	73	
NCTK10-51A	Biotite	8.72	0.50	0.057	0.001	6.371E+04	7.761E+00	1.955E+00	3.262E-01	2.112E-07	1.211E-08	6.992E-08	1.692E-09	2572	85	

blanks. A value of 295.5 was used for the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ (Steiger and Jäger 1977) for the purposes of routine measurement of mass spectrometer discrimination using air aliquots, and correction for atmospheric argon in the K/Ar age calculation. Due to high concentration of gas in these Archean micas, an average of ten heating steps was required in order to completely fuse the material without saturating the system. Laser power varied in increments from 0.24 to 4 W with a spot size of 2-3 mm. Three crystals of the widely used Fish Canyon sanidine standard of 28.31 ± 0.04 Ma (Renne et al. 2010) were used to determine a sensitivity of $1.136\text{E-}03 \pm 1.900\text{E-}5$ Amps/Torr. The K/Ar age was calculated using the EMPA-derived K_2O content, weight of the sample, and sensitivity. Source of errors include that of the mass spectrometer, the high sensitivity of the micro-balance below 0.1 mg and the possibility of grain loss during the transferring stages. Errors were calculated and encompass those derived from the weighing process (± 0.001 mg), K_2O measurements on the probe ($\pm 0.50\text{-}0.54$ wt%) and isotope measurements on the mass spectrometer (refer to **Table 2.1**).

5.1.2. Results

Samples were selected based on abundance and textural position of micas, plus ensuring a good geographic distribution across the belt. NCTK10-51A is a highly strained two-mica schist that was collected at the easternmost edge of the greenstone belt in the Neawagank Lake area. Muscovite is abundant in the sample and segregated in thick bands (up to 0.5 mm) from quartz and feldspar domains. Individual grains can be up to 1 mm long and define a strong fabric. Biotite is found intergrown with muscovite, though less abundant, suggesting coeval origin. This sample yielded one muscovite and one biotite age of 2518 ± 73 and 2572 ± 85 Ma, respectively (**Table 2.1**). NCTK10-76 is a two-mica schist in the middle of the southern arm near the MSZ. Micas are found intergrown in sinuous bands, similar to NCTK10-51A, segregated from quartz

and feldspar domains. Phyllosilicates in this sample appear more altered as their boundaries are more irregular and they display a lower interference colour under petrographic analysis. Two biotite analyses yielded ages of 1996 ± 70 and 1965 ± 69 Ma (**Table 2.1**). These ages were not included in the discussion since they would represent an event which reset the K-Ar system at that location ~400 m.y. after the tectonic activity of the NCGB. Sample NCTK10-20A from the Markop Lake deformation zone contains fine grained biotite defining a moderate foliation pervasive throughout the sample and yielded a biotite age of 2647 ± 97 Ma (**Table 2.1**). Sample Akow, an andalusite-staurolite schist, contains abundant white micas and biotite defining a strong fabric. Phyllosilicate grains are coarse and up to 1 mm in length, wrapping around porphyroblasts. This sample yielded one biotite age of 2811 ± 89 Ma (**Table 2.1**), the oldest K-Ar age obtained with this method. This age was also not discussed as it corresponds to the oldest regional metamorphic event in the NCGB, however may also simply represent analytical errors during the multiple steps of the analysis. Lastly, sample NCB12-12 from the westernmost edge of the belt in the Miskeesik Lake area is flooded with white micas, which are locally segregated into thin bands. Two muscovite ages of 2564 ± 78 and 2695 ± 80 Ma were obtained (**Table 2.1**).

5.2 *In situ* monazite U-Th-total Pb geochronology

A Cameca SX-100 electron microprobe was used at New Mexico Institute of Mining and Technology (Socorro, USA) to obtain *in situ* U-Th-total Pb ages for <100- μ m anhedral resorbed to euhedral monazite grains that exhibit clear microstructural relationships with fabric elements (Williams et al. 1999). A description of the two-part EMPA portion of the investigation is provided in **Appendix J** and the results of *in situ* U-Th-total Pb geochronology of monazite from seven high-strain Eyapamikama Lake Assemblage metasedimentary samples are presented in

Table J1. After single-spot total-Pb ages were calculated, dates were plotted on relative probability diagrams using Isoplot v3.0 (Ludwig 2003) to assess the major populations of mineral-age domains for a given sample (i.e. "peaks"). Once populations were identified, weighted-mean ages were calculated using the standard error from individual analyses of similar age domains and are reported at the 1σ level. Total-Pb dates were sorted by increasing age and plotted on weighted average diagrams in order to calculate domain age and error. Age populations are displayed in terms of Pb vs. Th* where Th* combines the uranium content converted into the equivalent thorium that would have produced the same amount of lead plus the measured thorium (Cocherie et al. 1998). This approach allows us to assess monazite populations and the robustness of their ages.

5.2.2. Results

Monazite textures are illustrated in **Fig. 2.6**. The monazite grains in a meta-granule conglomerate (NCB11-34) near the contact of the ELS with the SRV on the southern shore of Eyapamikama Lake (**Fig. 2.1B**) are 50-60 μm long and only 10 μm wide, often kinked but roughly parallel to the foliation, and they have convoluted edges and sieve textures. Matrix material is found in tightly spaced microlithons segregated by pervasive foliation planes that wrap around granules of albite $\pm$ quartz to form a heterogeneous fabric. Ribbon quartz is highly strained and partially dynamically recrystallized. Monazites show a decrease in U, Th, and Y at the rims, and a slight positive correlation of Th content with age. Two age populations are reported from twelve single spot analyses of four monazite grains from NCB11-34; the older is 2342 ± 20 Ma (MSWD: 1.2), a weighted-mean average of six spot analyses for which Pb/Th* yields an R^2 value of 0.9959, and the younger is 2196 ± 47 Ma (MSWD: 2.7), a weighted-mean of five single spot analyses for which Pb/Th* yields a low R^2 value of 0.3414 (**Fig. 2.7-2.8**).

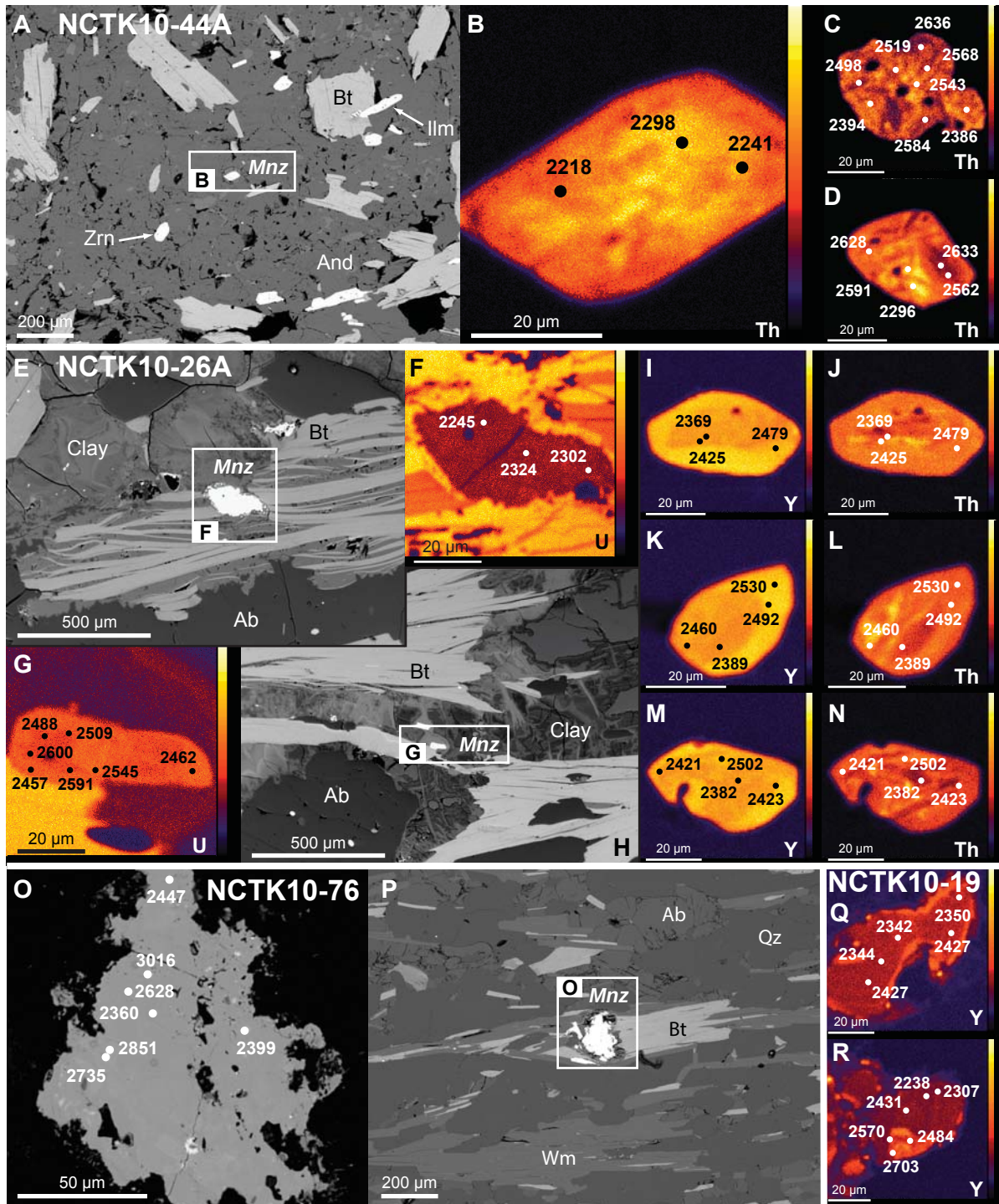


Figure 2.6: From Kalbfleisch 2012, unpublished. Collage of SEM backscatter electron images and X-ray maps of monazite grains from high strain metasedimentary rocks in the NCGB. Boxes in low magnification images (A), (E), (H), & (P) surround monazite grains for which X-ray maps are also shown. Measured element is noted in the corner of each figure. (A-D) is sample NCTK10-44. (E-N) is sample NCTK10-26A. (O-P) is sample NCTK10-76. (Q-R) is sample NCTK10-19. All maps, as well as the high magnification BSE image of O show spot locations and associated ages (Ma).

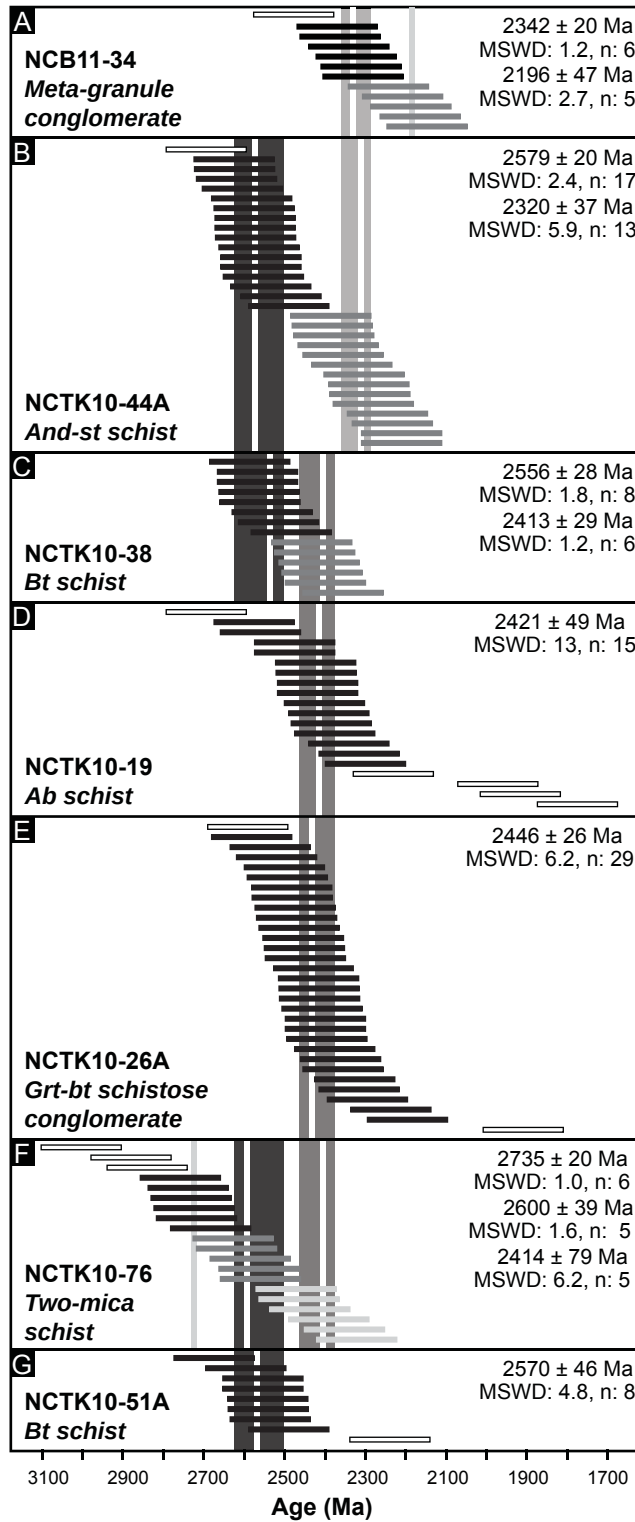


Figure 2.7: Data from Kalbfleisch 2012, unpublished. Weighted mean ages of U-Th-total Pb analyses of monazites from high-strain metasedimentary rocks in the NCB. Error bars shown at 2σ . Single spot analyses were sorted by age and populations are distinguished by colour. Each vertical white bar is a population mean that can be correlated to other population means within the bounds of the vertical grey bars. Means that are can't be correlated are pale grey and sit outside the bounds of grey bars.

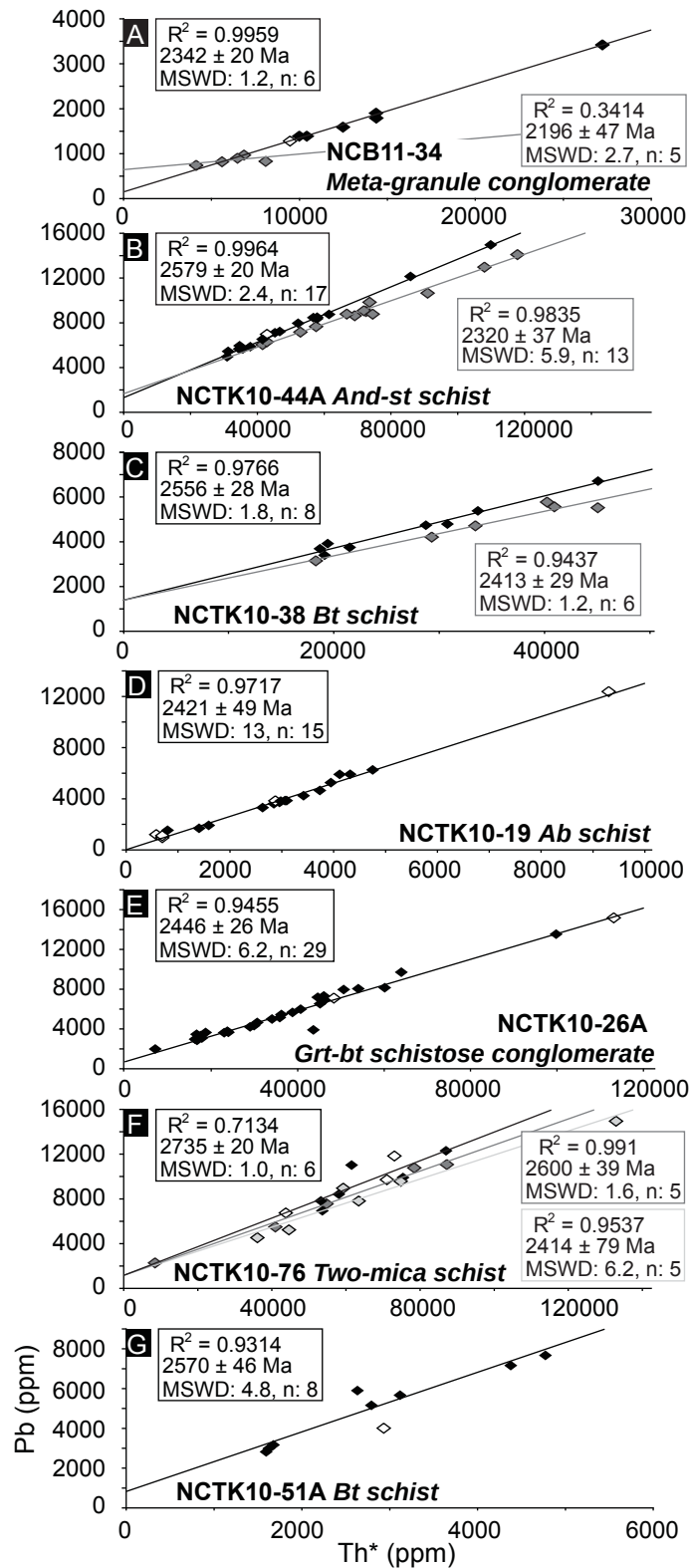


Figure 2.8: From Kalbfleisch 2012, unpublished. Scatter plots showing Pb content variation with Th* to demonstrate robustness of age populations. Thorium* values include the contribution from U converted into Th that would have produced the same amount of Pb. Age populations are distinguished by different shades of grey and R^2 values are shown for the lines defined by each. Empty diamonds represent analyses that were not included in the determination of the age populations.

The andalusite-staurolite schist (NCTK10-44A) from the ASZ that yielded a 2866 Ma U-Pb zircon age (Kalbfleisch 2012, Kelly and Schneider 2015) also contains monazite. Additionally, a sample from the same area (Akow) yielded a K-Ar biotite age of 2809 Ma. Six 30-40 μm monazite grains were analyzed and whereas one of these is an inclusion in poikiloblastic andalusite (**Fig. 2.6A-B**), the remaining are found in the matrix of plagioclase $\pm$ quartz, often in contact with (and more rarely embedded in) fabric forming micas (biotite $\pm$ muscovite or chlorite; e.g. **Fig. 2.6C-D**). Monazites display a patchy zoning in terms of U, Th, and Y but there is no correlation with age within the grains. Yttrium is relatively more abundant in the monazite grain included in andalusite and the grains generally contain high Y. The weighted mean age of the thirteen youngest single ages is 2320 ± 20 Ma (MSWD: 2.4) and the Pb/Th* values define a line with an R^2 of 0.9835 (**Fig. 2.7, 2.8B**). The seventeen oldest single ages yield a weighted mean age of 2579 ± 20 Ma (MSWD: 5.9) with an R^2 value for Pb/Th* of 0.9964 (**Fig. 2.7, 2.8B**). All six grains contain domains of both age populations except for the grain that is included in poikilolitic andalusite, which yields only ages of the younger population (**Table J1** in appendix B; **Fig. 2.6A**).

Three small foliation-elongate monazite grains found in a biotite schist (NCTK10-38) from the ASZ (**Fig. 2.1B**) are characterized by patchy thorium zoning and relatively low overall abundances of U, Th, and Y. They reside either at the boundary between quartz and albite or in contact with biotite $\pm$ ilmenite. The level of strain in the rock is indicated by dynamically recrystallized quartz isolated with albite in microlithons through segregation by penetrative SC-foliation planes defined by biotite and chlorite. The monazite yield two age populations; the older 2556 ± 28 Ma (MSWD: 1.8) age is the weighted-mean average of eight single spot analyses, has a Pb/Th* R^2 value of 0.9766, and is similar to the older population of NCTK10-

44A, whereas the younger 2413 ± 29 Ma (MSWD: 1.2) age is averaged over six single spot analyses, defines a Pb/Th* line with an R^2 of 0.9437, and is older than the youngest age of NCTK10-44A (**Fig. 2.7, 2.8C**).

An albite schist (NCTK10-19) situated within the MSZ (**Fig. 2.1B**) is characterized by a weak SC-fabric, and sigmoidal strain shadows cast by albite porphyroblasts. One of the 40-70 μm -long fabric-elongate monazite grains is broken and deformed and single spot analyses yielded anomalously low Th values (5120-7420 ppm, **Table J1**), so it was omitted from the probability plot. The remaining three grains form a group that parallels local foliation bundles of biotite and white mica and sparsely peppered blocky biotite throughout the matrix. They are found at the boundary between plagioclase matrix and a foliation sub-parallel quartz ribbon. The monazite grains have diffuse boundaries and are surrounded by a combination of allanite and clay minerals. The monazite is chemically zoned in terms of Th, U, and Y and the age domains appear to be somewhat controlled by this chemistry (e.g. Y, **Fig. 2.6R**). There is a slight positive correlation of Th content with age, and a general decrease in age in the same direction across each of the grains. A single population of 2421 ± 49 Ma (MSWD: 13) is reported as a weighted mean average of fifteen single ages and this age is represented through linear variation of Pb with Th* with an R^2 of 0.9717 (**Fig. 2.7, 2.8D**).

Eight monazite grains in a meta-granule to cobble conglomerate (NCTK10-26A) situated just north of the main strand of the MSZ were analyzed. These grains are predominantly fabric-elongate, ranging in size from 25 x 20 μm to 80 x 50 μm . They are found either at the boundary between albite grains in the matrix or surrounded by clay minerals, only sometimes in contact with or close to fabric-forming biotite $\pm$ chlorite. Grains in the matrix are fairly euhedral, free of inclusions and zoned in terms of Th and Y (e.g. **Fig. 2.6I-M**). EMPA analysis of monazite in this

sample yields a single robust total-Pb age with a weighted-mean average of 2446 ± 26 Ma (MSWD: 6.2) over 29 single spot analyses and Pb vs. Th* yields a linear relationship with an R^2 of 0.9648 (**Fig. 2.7, 2.8E**). The grain that yields the youngest ages differs from the other grains in that it has diffuse edges and is found in the foliation plane alongside biotite surrounded by clay-alteration phases (**Fig. 2.6E-F**). The grain that yields some of the oldest ages is found in a similar microfabric context but the clay appears to differ slightly in terms of U content (**Fig. 2.6G-H**).

The two-mica schist (NCTK10-76) of the NCT-MSZ transition that yielded a U-Pb zircon age of 2858 Ma (Kalbfleisch 2012, Kelly and Schneider 2015) and two K-Ar biotite ages of 1997-1965 Ma, was also investigated for U-Th-total Pb geochronology of monazite. Of the five monazite grains analyzed, two are small in size (~ 20 μm), have fairly smooth grain boundaries, display weak Th zoning, and yield four single ages that cluster within a 2600 ± 39 Ma (MSWD: 1.6) total-Pb age population (**Table J1; Fig. 2.8F**). In contrast, the remaining three grains range in size from $\sim 40 \times 30$ μm to >100 μm in diameter, have resorbed boundaries, have relatively low yet highly variable U, Th, and Y contents (e.g. Y, **Fig. 2.6**), and together yield sixteen single ages that span the three populations displayed in **Fig. 2.7**. The largest monazite grain is oriented perpendicular to the fabric, completely surrounded by biotite and muscovite (**Fig. 2.6P**), and the seven single spot analyses of this grain range in age from 2360 ± 50 to 3016 ± 50 Ma (**Fig. 2.6O**). There is no obvious trend among the three single spot analyses yielding ages >2800 Ma with respect to chemical zones and have been excluded from the main age populations. The oldest population is defined by a weighted-mean average of six single ages at 2735 ± 20 Ma (MSWD: 1.03) and Pb varies with Th* only weakly linearly with an R^2 of 0.7134 (**Fig. 2.7, 2.8F**). The youngest population consists of a weighted-mean average over six single ages at 2414 ± 79 Ma (MSWD: 6.2) and the plot of Pb/Th* weakly defines a line with an R^2

value of 0.9537 (**Fig. 2.7, 2.8F**). The most robust population of this sample has a weighted mean age of 2600 ± 39 Ma (MSWD: 1.6) over five spot analyses and Pb vs. Th* is linear with an R^2 of 0.991 (**Fig. 2.7, 2.8F**). The three lines on the Pb/Th* diagram are close together and there is some overlap between single spot ages of the different populations (**Fig. 2.8F**).

Sample NCTK10-51A is a highly strained biotite schist from the ELS at the eastern extremity of the belt in the NCT (**Fig. 2.1B**), which also yielded K-Ar biotite and muscovite ages of 2572 and 2576 Ma, respectively. Alignment of blocky biotite is a pervasive feature and long sinuous dextral bundles of biotite, chlorite, and muscovite weave between dynamically recrystallized microlithons of quartz and plagioclase feldspar among swarms of recovered quartz. Four small (~ 20 μm) monazite grains, situated at the junction between plagioclase grains, are somewhat elongate in the direction of foliation and in contact with biotite. The grains are characterized by patchy zoning of Th, U, and Y and the abundance of these elements is variable (e.g. Y, **Fig. 2.6**). As a result of the small grain size of the monazite in this sample, only nine analyses could be conducted over the four grains and the youngest of these was omitted from the weighted-mean age because of low Th content. The reported age population of 2570 ± 46 Ma (MSWD: 4.8) is a mean weighted average of eight single ages and similar to the older age populations of monazite in the ASZ (**Fig. 2.7, 2.8F**). Despite a few outliers, Pb/Th* has an R^2 of 0.9314 (**Fig. 2.8G**).

6. Discussion

6.1 Metamorphic patterns

Building from existing governmental reports and our extensive field work we were able to refine the metamorphic map previously limited to a simple isograd map of the northern and

central portion of the belt (Breaks et al. 2001). Greater details in the dominant metamorphic features permitted the identification of several trends: 1) an increase in metamorphic grade toward the north, 2) an increase in metamorphic grade toward the mine site (from west to east), 3) local contact metamorphism aureoles defined by cordierite porphyroblasts overprinting the existing fabric, found in proximity to small intrusions and 4) upper greenschist and amphibolite facies index minerals generally found in spatial relationship with deformation zones. These include garnet, staurolite, andalusite and sillimanite in metasedimentary units, whereas mafic metavolcanic units are mainly defined by hornblende porphyroblasts. Relationships with structural elements and inclusion trails of porphyroblasts show a syn- to post-tectonic origin. Steeply dipping planar fabrics that are pervasive throughout the belt are varying in spacing and intensity, but are generally stronger in narrow deformation zones, seen in abundance along the northern margins of the belt. Rock structure intensity and the concentration of deformation zones are more prevalent in the southern arm, where we also see more complex and irregular metamorphic map patterns. Geochemistry of metamorphic minerals including white micas, biotite, chlorite and amphibole throughout the belt is fairly consistent, exhibiting biotite with dominant annite to phlogopite compositions; white micas have a dominant muscovite composition; and chlorite has a dominant clinochlore to daphnite compositions. Amphiboles found in mafic metavolcanic have a composition varying from magnesio- to ferro-hornblende. We can identify a slight trend of increasing magnesium content to the north in the geochemistry of these major minerals.

Andalusite-sillimanite bearing assemblages are typical of low pressure, medium conditions regional metamorphism (Abukuma-type; Hiroi and Kishi 1989). Pressure estimates around 3 Kbars from amphibolite facies domains are consistent with high T/low P metamorphic

conditions, which implicate steep geothermal gradients (Breaks et al. 1991, Breaks et al. 2001). Occurrences of high P index minerals such as kyanite (e.g. Miskeesik Lake area, Breaks et al. 2001) that would indicate a Barrovian-type metamorphism were not observed during our study, yet we cannot exclude the possibility of them being part of some localized assemblages. Abukuma-type regional metamorphism has been recorded throughout the western Superior Province, suggesting high temperature conditions at shallow crustal depths caused by subduction-related heating during cratonization (Breaks and Moore 1992, Percival et al. 2006). Other pressure calculations indicate mid-crustal depths between 6-10 kbars in the surrounding granitoids and the mine area (Otto 2002, Van Lankvelt 2013) contrasting with the lower pressure Abukuma-type environment.

6.2 Timeline of the NCGB

K-Ar dating of micas and *in situ* U-Pb monazite dating was performed on samples across the NCGB to refine available ages in an attempt to resolve the tectonic evolution of the belt in a western Superior Province context. K-Ar ages of fabric forming muscovite and biotite show some variability, but the main trend seems to be a population between 2550 and 2700 Ma. Total-Pb monazite ages can be separated into three significant populations, including ca. 2735 Ma, ca. 2600-2550 Ma and ca. 2440 Ma. The oldest tectonic event recorded in the NCGB represents regional metamorphism associated with docking of the ILD and TTG magmatism at 2.86 Ga (Van Lankvelt 2013). Furthermore, with the compilation of other available geochronological data, several events could be considered (described in details below, **Fig. 2.9**): 1) 2.75-2.71 Ga Abukuma-type regional metamorphism and hydrothermal alteration pulse associated with the Uchian Orogeny, 2) 2.6-2.56 Ga retrograde metamorphism associated with mineralization and,

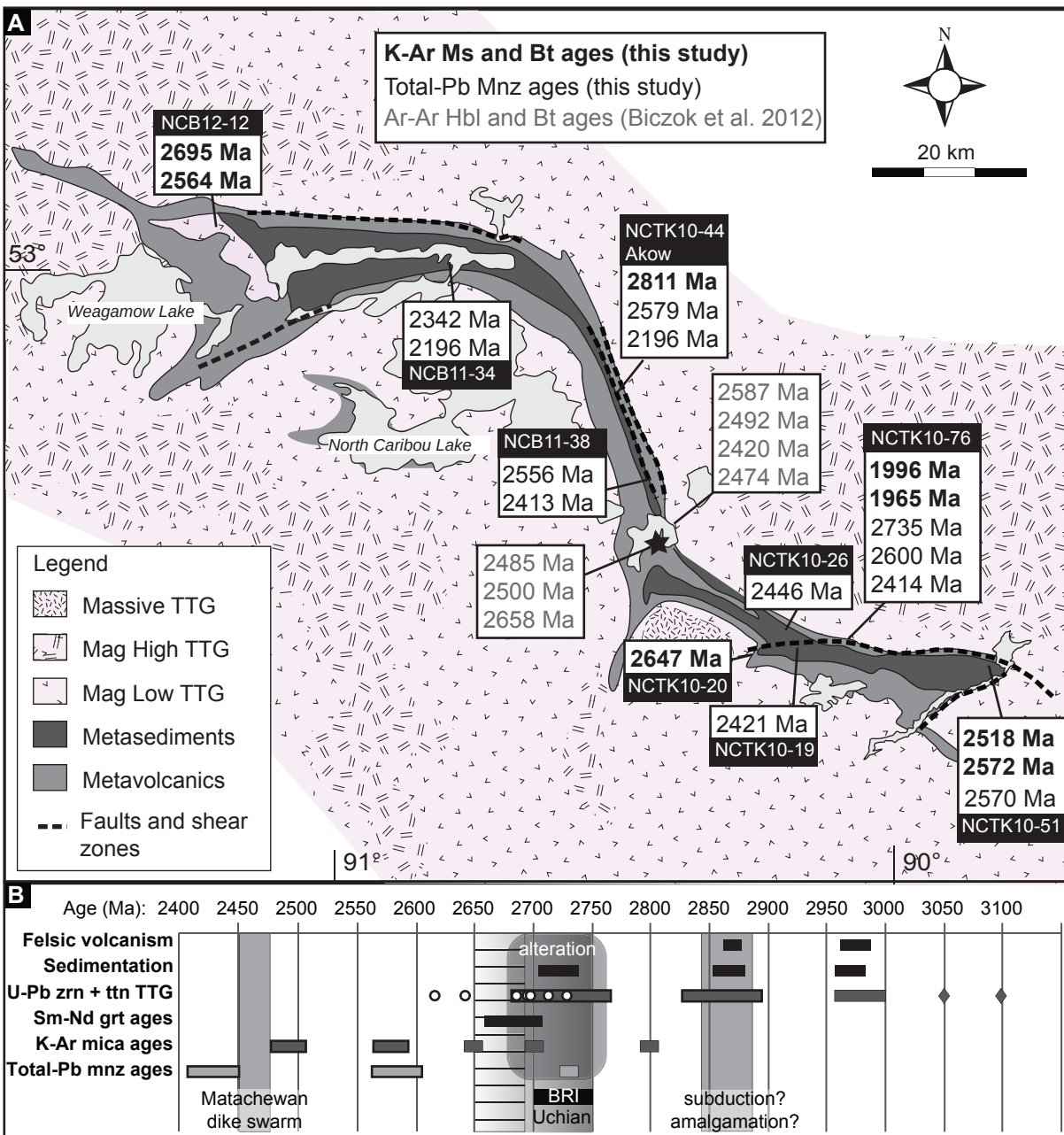


Figure 2.9: A) Age distribution in the NCGB. Sample locations used for K-Ar muscovite (Ms) and biotite (Bt) dating from this study are represented by bold black font. Ar-Ar hornblende (Hbl) and biotite ages from Musselwhite mine area (Biczok et al. 2012) are also shown with grey font, as well as Total-Pb monazite (Mnz) ages from Kalfleisch 2012 in black font. Musselwhite mine is represented by the star. B) Schematic timeline of geological events and mineral dates for the North Caribou greenstone belt. Shaded horizontal bars represent the range of activity or mineral dates; bars with a black outline represent significant populations of dates whereas bars without the black outline are single dates. White circles within the TTG group represent zircon ages from pegmatites and felsic bands of gneissic plutons. Diamond symbols at 3.05 and 3.10 Ga are inferred from detrital zircon ages and zircon core ages from the TTG suite. Alteration field at 2.76-2.68 Ga is resolved from zircon and titanite data of Van Lankvelt (2013). BRI: Berens River Intrusive event (2.75-2.71 Ga); Uchian: Uchian orogeny (2.75-2.69 Ga, Percival et al. 2006); thin horizontal lines ca. 2.70-2.65 Ga represent the moderate heating or enhanced hydrothermal event of Corfu and Stone (1998) and crustal underplating of Heaman et al. (2011). Other data from Gagnon, unpublished; Duff, 2014; Van Lankvelt, 2013; Kalfleisch, 2012; Biczok et al., 2012; Davis and Stott, 2001; Thurston et al., 1991; deKemp, 1987.

3) ca. 2.4 Ga hydrothermal flow and metamorphism. Although these ages can be separated into distinct events, our new data may suggest a more continuous evolution between 2.6 and 2.4 Ga rather than distinct events. Evidence of fluid in shear zones and the irregularity in Mnz/K-Ar ages in some locations of the southern arm strongly support the heterogeneity in fluid/temperature/strain conditions prevalent in this part of the belt, which would have created an irregular metamorphic pattern that could rather be metasomatic in origin. Deformation likely outlasted metamorphism in the evolution of the NCGB as monazite grains interpreted as being syn-deformation were dated at 2.6-2.56 Ga, post-dating the recorded metamorphic episodes (2.86 Ga and 2.75-2.71 Ga) by over 100 million years. This trend can also be observed in other shear zones as their syn-deformation textures are still visible, therefore not overprinted by thermal recovery. This observation is also consistent with microstructural data presented in Gagnon et al. (2015) that shows syn-tectonic quartz recrystallization by subgrain rotation, which was not overprinted by thermal recovery.

6.2.1 Abukuma-type regional metamorphism and hydrothermal alteration (2.75-2.71 Ga)

Monazite ages at 2.75-2.71 Ga are thought to represent fluid-facilitated deformation focused in shear zones, mainly in the southern arm of the belt. U-Th-Total-Pb dating of monazite from one metasedimentary sample in the North Caribou-Totogan shear zone yields a few age populations, the oldest of which is ca. 2.74 Ga. Monazite has two morphologies in this sample: big (~100 μm) with convoluted and cusped grain boundaries, which yield single spot analyses that span 600 m.y. (**Fig. 2.6O-P**), and small grains that possess a fabric-preferred orientation, all yielding similar single spot ages. Monazite is relatively stable across a range of metamorphic grades, and it can be quite challenging to implicate a meaning to the dates. The most commonly cited monazite-in reaction is the breakdown of allanite at 550°C (Overstreet 1967, Smith and

Barreiro 1990, Parrish 1990, Kingsbury et al. 1993, Wing et al. 2003). If allanite was present in the rocks it could have been a reactant to form monazite during ca. 2.75-2.71 Ga progressive metamorphism. Alternatively, monazite potentially formed during ca. 2.86 Ga metamorphism and acted as a precursor for the monazite that recrystallized during this subsequent event. The 2.72-2.66 Ga hydrothermal garnets in the mineralized high-strain limbs of the tightly folded BIF at Musselwhite mine (whole rock-garnet Sm-Nd age, Biczok et al. 2012) appear to also have potentially formed at this time. Evidence for magmatism within the NCGB during this period is manifested as discrete plutons present among voluminous metagranitoids that surround the North Caribou greenstone belt. Discrete magmatism is recorded south of Musselwhite mine at 2.72 Ga (Biczok et al. 2012). The Southern batholith is host to zircons that are ca. 2.72 Ga as well as ca. 2.73-2.71 Ga zircon rims on older cores (Van Lankvelt 2013). The Schade Lake gneissic complex also possesses low Th/U value rims on zircon cores (ca. 2.76-2.70 Ga) and Van Lankvelt (2013) interprets these dates to indicate widespread potassic alteration due to hydrothermal metamorphism. In addition, geochronological work utilizing SIMS depth-profiling approach on zircon from metasedimentary rocks of the NCGB also indicates thin hydrothermal zircon rims dated at ca. 2.73-2.71 Ga (Kelly et al. 2013, Kelly and Schneider 2015). These independent geochronology studies begin to converge on a significant fluid-derived thermal event occurring at ca. 2.75-2.71 Ga. Although fluid interaction seem to have implications in the formation of shear zones in the south, geochemistry and petrographic observations in the central portion (DSZ) show deformation in a relatively dry environment, indicating heterogeneity in fluid circulation on a km-scale (Gagnon et al. 2015). Furthermore, field and structural observations indicate that deformation was contemporaneous with peak metamorphic conditions

in the amphibolite facies (e.g. quartz microstructures, syn-tectonic porphyroblasts, etc.), suggesting the current metamorphic map pattern was produced at that time.

6.2.2 Retrograde metamorphism and hydrothermal alteration (2.60-2.56 Ga)

Several of our K-Ar muscovite and biotite ages seem to represent a population around 2.57 Ga, which is coeval with monazite population at ca. 2.60-2.56 Ga and $^{40}\text{Ar}/^{39}\text{Ar}$ age of ca. 2.59 Ga from the Musselwhite gold deposit (Biczok et al. 2012). Monazite grains from four high-strain metasedimentary rocks, two in the ASZ and two in the NCT, yield age populations in the range of 2.60 to 2.56 Ga (**Fig. 2.7, 2.8**). Most monazite grains are surrounded by quartz and plagioclase in the rock's matrix and many are in contact with, though rarely embedded in, fabric forming micas and chlorite (**Fig. 2.6**). Often roughly elongated within foliation and exhibiting resorbed and cusped grain boundaries, the grains commonly display patchy chemical zoning (**Fig. 2.6**). The crystallization of monazite from a melt typically results in concentric or sector zoning and, because the solid-state element diffusion of U, Th, and Pb is slow (e.g. Zhu and O'Nions 1999, Cherniak et al. 2000), older age domains with sharp boundaries are preserved through metamorphism even at high temperatures (Williams et al. 2007). The isotopic system is, however, sensitive to deformation-induced recrystallization, regulated by intracrystalline deformation mechanisms and the presence of fluids (Lanzirotti and Hanson 1996, Poitrasson et al. 1996, Krohe and Wawrzenitz 2000, Seydoux-Guillaume et al. 2002, Ayers et al. 2006, Harlov et al. 2011, Williams et al. 2011). Patchy zoning of Th, U, and Pb and the development of elemental domains are commonly the result of elemental redistribution within monazite in response to strain and in the presence of fluid during a process described by Warwenitz et al. (2012) as dissolution-precipitation creep. Fluid-assisted dissolution and (re?)precipitation of minerals operates at strain levels that are insufficient for initiation of dislocation creep and is an

efficient mechanism for isotope resetting of monazite even at very low-grade conditions (Frost and Ashby 1982, Carter and Tsenn 1987, Wawrzenitz et al. 2012). The monazite-bearing samples dated in this study were collected from crustal scale shear zones, in which the monazites possess fabric-preferred orientation and abundant microstructural features indicative of dissolution-precipitation creep. We interpret the chemical domains within monazite grains that yield single spot ages of 2.60-2.56 Ga as the result of fluid-induced dynamic recrystallization.

These ages bracket the ca. 2.59 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ age of foliation-bound biotite in metabasalts that stratigraphically overlie a mineralized unit at Opapimiskan Lake and the ca. 2.57 Ga K-Ar muscovite and biotite ages from shear zones. This event however post-dates the 2.72-2.66 Ga age of gold-bearing garnet at the mine by 60-100 m.y. (**Fig. 2.9**; Biczok et al. 2012). The only age determined for garnets hosting gold at the deposit represents a whole garnet fraction analysis and does not take into account a second phase of proposed "hydrothermal" growth of the garnet. These younger rims on presumably older garnets are localized in quartz-veined mineralized zones with distinct geochemistry and may have been generated during the ca. 2.75-2.71 Ga event described above, which further implicates a channeling of hydrothermal fluids bearing high field strength elements and silica at that time. It is therefore possible that the subsequent tectonism (strain, heat, fluids) responsible for monazite recrystallization at 2.60-2.56 Ga gave rise to brittle fracturing of the garnets (at temperatures as low as 210-250°C based on chlorite thermometry; Otto 2002) in the higher strain limbs of folded BIF units and provided a structural trap for gold deposition. Although these were not dated, garnets of hydrothermal origin are also seen in other parts of the belt, in clusters nested in biotite or chlorite bundles (e.g. ASZ, MSZ, **Fig. 2.3F-G**). Location of these hydrothermal garnet clusters, based on geochemical signatures and textures, could provide an additional tool in identifying evidence of fluid channeling in proximity to shear

zones. Additionally, it is worth noting that the most consistent ages from a single sample also coincide with this event. For example, sample NCTK10-51A yielded similar K-Ar and total-Pb monazite ages between 2570-2576 Ma (**Fig. 2.9A**).

6.2.3 Progressive metamorphism and hydrothermal alteration (2.50-2.44 Ga)

With the new geochronological data throughout the NCGB, we start to resolve a 2.4 Ga signature. A single and robust monazite age population of ca. 2.44 Ga is recorded in two metasedimentary rocks from the MSZ, and also observed elsewhere in samples proximal to it within the NCT and the ASZ. The morphology, internal zoning, and patchy chemical nature of the monazite grains are similar to those discussed in the previous section, and K-Ar ages are broadly similar at ca. 2.49 Ga. Additionally, ages particularly in the MSZ area (e.g. K-Ar and monazite ages for sample NCTK10-76; **Fig. 2.9A**) are very scattered with dates ranging from ca. 2.0 Ga to ca. 2.7 Ga suggesting protracted resetting during younger event(s) (**Fig. 2.9A**). Monazite from garnet-biotite schistose conglomerate (NCTK10-26, **Fig. 2.1B**) near the MSZ exhibits high concentrations of Y (mean: 11730 ppm, **Table I1**), typically an indication that its growth preceded garnet nucleation (Zhu and O’Nions 1999b), potentially at the expense of allanite or a previous generation of monazite. This garnet-bearing conglomerate is the only sample in which the single spot ages from the monazites display a positive correlation of Th with age (**Fig. 2.6I-M**), which may indicate inheritance of a magmatic (monazite) component as monazite in granitoids typically have significant quantities of Th (Franz et al. 1996, van Emden et al. 1997). Any monazite-altering event that occurs at temperatures <800°C (closure temperature for Pb diffusion in monazite) is thought to be strongly dependent on fluid (Williams et al. 2007). Euhedral garnets from a hydrothermal pod are found among the flattened cobbles in this garnet-biotite schistose conglomerate, which are also concentrically zoned in terms of Mn

(decreasing towards the rim) and sector zoned with respect to Ca (outward from a small high-Ca core, **Fig. 2.5C**). The major element zonation of these garnets is most similar to Duff et al.'s (2012) garnets in which the core is Mn-rich and the rim is more Mg-rich, and similar to Otto's (2002) results in which the rims are Fe-rich. Chondrite-normalized HREE patterns of individual garnets vary by up to 2 orders of magnitude (Kalbfleisch 2012, Duff et al. 2012, Duff 2014), evidence for crystallization during fluid evolution and remobilization (Spry et al. 2007 and references therein). There is also a slight positive correlation of Y with age across monazite grains in the conglomerate host to the pod (**Table I1**). The elevated Y content of the older population (ca. 2.60-2.56 Ga), in contrast with the younger (ca. 2.44 Ga) monazite population, suggests the crystallization of garnet involving preferential incorporation of Y from fluids localized in the MSZ, was synchronous with the (re?)crystallization of monazite in the later event. The 2.44 Ga monazite ages, are broadly coeval with the ca. 2.49 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ age of biotite in an unmineralized garnet-biotite schist unit at Musselwhite mine (Opapimiskan Lake; Biczok et al. 2012). This observation suggests recrystallization and diffusive Ar loss of biotite in response to the same tectonic strain accommodated dominantly by displacement in the Markop Lake deformation zone is responsible for recrystallizing monazite. Additionally, K-Ar mica ages range from ca. 2.0 to 2.7 Ga suggesting multiple resetting during that period. In fact, micas are easily recrystallized in response to strain even at low temperatures (Biczok et al. 2012) and as they are a pervasive component defining the fabric of the high-strain metasedimentary rocks in the southern arm of the NCGB, it is likely they were recrystallized by the latest reactivation of crustal scale shear focused in the southern arm.

6.2.4 Tectonic implications

The new geochronology and structural work is consistent with a supra-subduction zone environment coeval with magmatism that was the result of horizontal tectonism (the Uchian orogeny; Wyman et al. 2010, Biczok et al. 2012, Gagnon et al. 2015). A change from vertical to horizontal tectonism was in fact suggested for the Western Superior at late stages of Archean cratonization (Lin et al. 2013). The 2.75-2.69 Ga regional metamorphic event and 2.72-2.66 Ga mineralization is broadly synchronous with the Uchian Orogeny, more particularly the docking of the Winnipeg River terrane. This orogeny has been recorded throughout the IDL with shear zone formation and penetrative deformation at 2700-2669 Ma (Parks et al. 2003), as well as in the Hudson Bay terrane to the north in foliated granitoids resulting from compressional tectonism at 2705 Ma (Stott et al. 2010). In the NCGB, evidence for horizontal tectonism (e.g. shallow dipping lineations) is recorded in shear zones that boarder the greenstone belt, indicating that period of the Uchian orogeny was dominated by transpressive deformation. In terms of implications for gold mineralization, several deposits located along the suture between the ILD and the NCS yield similar mineralization ages (e.g. 2658 Ma High Rock Island gold deposit, Manitoba; Lin and Corfu 2002, Biczok et al. 2012), supporting a large-scale fluid-assisted metamorphic pulse during the orogeny. Therefore in exploring for ore deposits in the western Superior Province, major crustal-scale structures are important as they focus fluids and accommodate strain. Lastly, it was previously suggested that the 2.5-2.4 Ga event may represent cooling of the northwestern Superior Province through 300°C (biotite closure temperature), resulting in ca. 2.49 Ga $^{40}\text{Ar}/^{39}\text{Ar}$ age of biotite (Biczok et al. 2012). However new U-Pb monazite and K-Ar mica ages indicate that low temperature metamorphism and hydrothermal alteration more likely reset the ages at 2.5-2.4 Ga. This model implies a heat source with

associated fluids and deformation, possibly resulting from Large Igneous Provinces that were occurring at that time throughout the Superior. The 2.47-2.45 Ga Matachewan and 2.51 Ga Irsuaq dyke swarms are the only thermal events recorded in the Superior at that time, yet their large extent may have influenced rocks in the western Superior through fluid circulation and potentially uplift (Maurice et al. 2009, Stott and Josey 2009, Biczok et al. 2012; **Fig. 2.9B**).

7. Summary

- Four significant metamorphic trends can be identified throughout the NCGB: 1) a northerly increase in grade in the Eyapamikama Lake area, 2) an increase in grade from the western arm to the mine area, 3) nodal contact metamorphism marked by cordierite porphyroblasts at proximity to small intrusions and 4) upper greenschist and amphibolite facies index minerals focused in zones of high strain.
- Major element EMPA of fabric forming minerals and amphiboles throughout the belt show consistent geochemistry. A slight increase in magnesium content toward the north can be identified in biotite, chlorite and amphibole compositions.
- Field observations, microstructural and geochemical data from the central portion of the belt indicate dry deformation under amphibolite facies conditions. Whereas monazite recrystallization and scatter in geochronological data suggest fluid-facilitated deformation in the southern arm of the belt.
- Fluid-facilitated deformation that occurred mainly between the mine area and the MSZ at ca. 2.66 and 2.4 Ga postdates the regional metamorphic event that produced the current metamorphic map patterns at 2.75-2.71 Ga.
- This youngest event may not be as distinct, but rather a more continuous period of fluid flow as a product of large igneous provinces that occurred in the Superior at that time.

- Scatter in geochronological data and irregularity in metamorphic trends throughout the NCGB are evidence of the complex tectonic evolution during the assembly of the Superior. Resolving timing of tectonic events in high grade metamorphic terrains is not easy as the background metamorphic signature may be too high and obscure certain features.

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Émilie Gagnon

Summary

I'm a recent graduate from the University of Ottawa specializing in geology and I'm looking for employment in geosciences now that I have completed my MSc degree. The academic environment provided me with the opportunity to familiarize myself with analytical techniques such as diverse **microscopy** techniques, **geochemical** analyses and **data processing**, as well as how to present scientific data in an efficient and concise manner. I have completed several specialized geoscience courses and 3 summers of industry work, which provided me with experience in **mapping, exploration, sampling** and **core logging**. My academic formation has been specialized in geology, yet my interests in geosciences expand into environmental, hydrogeology, laboratory and geophysical sciences. I am very organized, enthusiastic, independent and motivated to learn by trying **new experiences**.

Education

MSc in Earth Sciences, *University of Ottawa*

2012-2015

- Thesis: Investigating regional metamorphism and deformation patterns of the Archean North Caribou Belt, Superior Province: Implications for hydrothermal lode Au deposits

BSc Honours with specialization in geology, *University of Ottawa*

2009-2012

- Honours thesis: Investigating titanite ages in skarns and gneisses: Implications for dating metamorphism and fluid flow in the Grenville Province, Otter Lake, Quebec
- Relevant course work: Hydrogeology, Statistical Analyses in Earth Sciences, Advance Mineral Deposits, Carbonate and Siliciclastic Sedimentology, Metamorphic and Igneous Petrology, Geochemistry

Research grants and scholarships

Admission Scholarship, University of Ottawa

2013-2014

Canada Foundation research grant, Society of Economic Geologists

2013, 2014

Queen Elizabeth II scholarship in Science & Technology

2013

Geoscience work experiences

Teaching assistant, *University of Ottawa*

Fall 2011-Spring 2015

- Responsibilities: Instructing and tutoring students, grading laboratory reports, conducting field trips
- Courses: Field Geology I, Mineralogy, Geochemistry, Metamorphic petrology, Introduction to earth's systems

Geological assistant, *Muskelwhite mine, Goldcorp Inc.*

Summer 2013

- Responsibilities: Surficial and underground mapping, core logging
- Supervisor: John Biczok and Katie Lucas, P. Geos.

Geological mapping assistant, *Transition Metals Corp.*

Summer 2012

- Responsibilities: Mapping, trenching, rock sampling
- Supervisor: Thomas Hart and Creg Collins, P. Geos.

Assistant-geologist, *SOQUEM inc., Société Québécoise d'exploration minière*

Summer 2011

- Responsibilities: Prospection, rock sampling, core cutting
- Supervisor: Serge Perreault, senior geologist

Research assistant (part-time), *Geological Survey of Canada*

2010-2011

- Responsibilities: Capturing archived field data using Microsoft Access and ArcGIS; Research on North American paleoclimate, 23 Ma to present
- Supervisor: David Sharpe, PhD, Don Cummings, PhD, and Hazen Russell

Geoscience skills

Field

- Bedrock mapping and structural analyses
- GPS orientation
- Construction and interpretation of stratigraphic columns
- Geologic traversing and prospecting
- Lithogeochemical and outcrop sampling

Experience:

- Iceland 2014: Advance Igneous Petrology
- NW Superior province and Musselwhite mine, Canada 2012-2013: Mine site and exploration work
- Basin & Range, USA 2012: Advance Geological Mapping
- Abitibi province, Canada 2010, 2011, 2013: Economic Geology and Mapping II, prospecting
- Central Appalachians, USA 2010: Geological Mapping I

Laboratory

- Rock and mineral identification with hand samples and in rock core
- Reflected light and transmitted light microscopy
- Sample preparation for geochemical and isotopic analyses (crushing, cutting, separating)
- Scanning electron microscopy (SEM) and electron microprobe analysis (EMP)
- Electron backscatter diffraction analysis (EBSD)
- Laser ablation ICP-MS U-Pb geochronology
- K-Ar geochronology

Computer

- MS Office (major text editing, spreadsheet, and presentation software)
- Adobe Creative Suite (graphics)
- ArcGIS (course completed) and Mapinfo (mapping)
- speciality software: IgPet, Isoplot, MATLAB, MTEX

Certifications, training, and volunteer experience

- French and English: Writing, reading and conversational
- Driver's License
- ATV training
- DELTA safety training
- Treasurer, Ottawa-Carleton SEG student-chapter

Publications

Gagnon, É., Kalbfleisch, T., Schneider, D.A., Biczok, J., Habler, G., 2015. Characterization of transpressive deformation in shear zones of the Archean North Caribou greenstone belt (NW Superior Province) and the relationship with regional metamorphism. Submitted to Tectonophysics, special issue: Tectonics of oblique plate boundary systems.

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Kelly, C.J., **Gagnon, E.**, Schneider, D.A., 2013. Redefining the pattern and timing of metamorphism in the North Caribou greenstone belt. Ontario Geological Survey, Open File Report 6290, p.59.1-59.8.

Gagnon, É., Schneider, D.A., Mcfarlane, C., 2013. Investigating the timing of hydrothermal alteration using in situ titanite U-Pb ages in skarns and gneisses, Otter Lake area (Québec), Grenville Province. PDAC 2013 mineral colloquium.

Appendix A

Whole rock geochemistry of basalts and granites in the Dinnick Lake area

Table A1. Whole rock geochemistry of basalts from the Dinnick Lake shear zone area

Sample	254936	254937	254938	438519	619688	619689	JAC1
Unit	North Rim	North Rim	North Rim	North Rim	North Rim	North Rim	South Rim
Wt% SiO ₂	51.17	48.04	49.16	50.00	50.83	49.86	49.32
Al ₂ O ₃	13.86	14.19	14.55	14.85	15.24	13.52	15.89
Fe ₂ O ₃	11.94	17.10	14.20	13.49	10.36	10.80	12.68
CaO	10.00	8.59	9.07	8.68	11.70	10.74	9.9
MnO	0.2	0.23	0.2	0.21	0.166	0.176	0.201
MgO	7.56	6.50	7.44	6.88	6.39	10.48	8.3
Na ₂ O	2.77	2.47	2.71	3.35	2.51	1.19	2.65
K ₂ O	0.13	0.09	0.15	0.38	0.24	0.39	0.05
TiO ₂	1.18	1.80	1.20	0.75	0.70	0.61	0.742
P ₂ O ₅	0.09	0.13	0.10	0.06	0.04	0.07	0.05
LOI	0.93	0.78	1.08	1.23	2.54	1.77	1.09
Total	99.91	99.97	99.92	99.91	100.70	99.61	100.9
ppm Ba	60	90	80	70	50	103	25
Nb	3	5	3	2	3	4	2.3
Rb	2	2	3	10	2	10	1
Sr	122	117	76	61	110	140	105
Y	23	27	25	15	14	15	13.2
Zr	65	96	65	36	40	57	44
Ag	-	0.05	0.1	-	1.2	1.1	< 0.5
As	-	1.6	124	-	2.5	6	< 5
Be	-	1	0.6	-	0.5	0.5	< 1
Bi	-	0.02	1	-	0.2	1.6	< 0.1
Ce	-	14.95	-	-	5.1	15.3	5.05
Co	72.44	50.8	22	-	38	55	44
Cr	-	262	575	-	190	550	320
Cs	-	1.91	-	-	0.25	0.25	0.1
Cu	-	95.9	18	-	110	70	100
Ge	-	0.17	-	-	2	2	1.7
Mo	-	0.4	1	-	1	1	2
Ni	-	114.5	114	-	70	200	160
Pb	-	3.9	13	-	2.5	2.5	< 5
Sb	-	0.21	6	-	0.8	0.6	0.5
Sc	36.82	-	29	-	43	32	37
Sn	-	0.7	-	-	2	2	< 1
Ta	-	0.26	-	-	0.2	0.3	0.17
Th	-	2.8	0.05	-	0.3	2.1	0.26
U	-	0.8	5	-	0.05	0.5	0.06
V	245.10	213	229	-	274	205	263
W	-	0.7	5	-	18	17	< 0.5
Zn	-	73	72	-	80	70	60
Dy	-	-	-	-	2.4	2.7	2.49
Er	-	-	-	-	1.6	1.6	1.6
Eu	-	-	-	-	0.58	0.63	0.414
Ga	-	15.3	10	-	16	14	15
Gd	-	-	-	-	2	2.4	1.93
Hf	-	-	-	-	1	1.4	1.1
Ho	-	-	-	-	0.5	0.6	0.54
La	-	-	-	-	2.1	7.9	1.95
Lu	-	-	-	-	0.26	0.23	0.252
Nd	-	-	-	-	3.9	7.9	4.27
Pr	-	-	-	-	0.77	1.89	0.8
Sm	-	-	-	-	1.4	1.9	1.27
Tb	-	-	-	-	0.4	0.4	0.37
Tm	-	-	-	-	0.25	0.24	0.238
Yb	-	-	-	-	1.7	1.6	1.62

Table A1. Whole rock geochemistry of basalts from the Dinnick Lake shear zone area

Sample Unit	JAC15 Central axis	JAC16 Central axis	JAC17 Central axis	NCB12-17B North Rim	NCB12-18B North Rim	NCB12-21 North Rim	NCB13-22 North Rim
Wt% SiO ₂	53.6	56.02	55.59	51.35	52.51	49.46	54.86
Al ₂ O ₃	14.26	16.86	11.44	10.56	13.62	14.2	13.68
Fe ₂ O ₃	10.75	9.81	11.3	12.2	11.02	12	14.53
CaO	9.17	8.56	11.11	11.74	10.7	11.16	7.8
MnO	0.182	0.171	0.237	0.237	0.183	0.197	0.158
MgO	6.15	4.36	7.65	10.42	7.32	7.96	4.33
Na ₂ O	1.27	1.55	1.12	1.6	2.39	2.57	3.26
K ₂ O	0.64	0.89	0.26	0.32	0.12	0.14	0.2
TiO ₂	0.715	0.78	0.5	0.247	1.15	1.137	1.374
P ₂ O ₅	0.11	0.08	0.05	0.02	0.11	0.09	0.25
LOI	1.83	1.69	1.55	2.08	0.58	0.77	0.47
Total	98.67	100.8	100.8	100.8	99.7	99.68	100.9
ppm Ba	78	306	63	123	38	40	80
Nb	4.8	4.5	3.1	0.7	2.5	2.4	6.2
Rb	16	29	6	9	< 1	1	2
Sr	119	186	122	50	131	110	95
Y	15.3	15.6	13	8.4	21.2	20	36.4
Zr	84	96	65	14	68	67	115
Ag	0.6	0.7	0.6	< 0.5	0.6	< 0.5	0.7
As	95	45	12	< 5	< 5	< 5	< 5
Be	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Bi	< 0.1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	0.2
Ce	28.4	26.4	19.6	1.89	10.7	8.7	20.7
Co	57	44	21	56	43	40	48
Cr	220	330	230	540	290	290	80
Cs	0.6	0.7	0.2	0.4	< 0.1	0.1	< 0.1
Cu	< 10	90	< 10	20	110	40	360
Ge	4.5	1.8	1.8	2.5	2.3	2.2	1.5
Mo	4	4	4	< 2	< 2	3	6
Ni	40	60	60	100	120	110	20
Pb	< 5	7	< 5	< 5	< 5	< 5	< 5
Sb	1.1	0.7	0.6	0.3	0.2	< 0.2	< 0.2
Sc	30	37	25	48	39	39	34
Sn	< 1	< 1	2	< 1	1	< 1	1
Ta	0.41	0.37	0.28	0.09	0.2	0.19	0.44
Th	4.03	3.84	2.62	0.13	0.25	0.22	0.92
U	1.12	1.07	0.74	0.04	0.07	0.07	0.22
V	199	229	164	217	356	358	299
W	3.7	< 0.5	0.6	< 0.5	< 0.5	2.6	< 0.5
Zn	70	60	60	60	80	80	70
Dy	2.98	3.21	2.57	1.31	4.07	4.14	6.36
Er	1.73	1.83	1.49	1.05	2.43	2.3	3.83
Eu	0.87	0.931	0.734	0.226	1.16	1.03	1.67
Ga	17	19	14	9	16	18	17
Gd	2.99	2.9	2.4	0.85	3.85	3.66	5.4
Hf	2.2	2.4	1.4	0.4	1.7	1.7	2.8
Ho	0.62	0.64	0.52	0.32	0.84	0.81	1.29
La	15.4	13.8	10.6	0.76	4.04	2.78	9.1
Lu	0.258	0.27	0.216	0.176	0.321	0.334	0.575
Nd	12.6	11.7	8.99	1.42	9.55	8.61	15
Pr	3.26	3.16	2.31	0.29	1.82	1.54	2.97
Sm	2.73	2.56	2.15	0.5	3	2.8	4.03
Tb	0.52	0.52	0.43	0.18	0.69	0.67	1
Tm	0.252	0.28	0.215	0.175	0.369	0.348	0.578
Yb	1.82	1.84	1.34	1.18	2.26	2.25	3.77

Table A2. Whole rock geochemistry of granite surrounding the Dinnick Lake shear zone area

Sample	E438515	E438517	E468976	E468977	E468979	NCB12_19	NCB12_20	E438520
Unit	Granite	Granite	Granite	Granite	Granite	L-tectonite	L-tectonite	Mylonite
Wt %								
SiO ₂	70.44	71.73	69.70	67.70	72.60	71.66	69.47	69.36
Al ₂ O ₃	16.26	15.39	15.70	16.25	14.30	14.85	15.08	15.91
Fe ₂ O ₃	2.52	2.15	2.94	3.12	2.83	2.61	3.13	2.92
CaO	2.54	2.66	3.39	3.15	2.89	2.43	3.29	2.97
MgO	0.59	0.68	0.94	0.77	0.69	0.72	0.94	0.91
Na ₂ O	4.93	4.38	4.82	5.03	4.67	4.34	4.43	4.57
K ₂ O	1.64	1.85	1.25	1.61	1.21	1.85	1.42	1.48
TiO ₂	0.28	0.27	0.25	0.31	0.25	0.332	0.386	0.35
MnO	0.03	0.03	0.04	0.04	0.03	0.031	0.044	0.04
P ₂ O ₅	0.08	0.07	0.07	0.10	0.08	0.09	0.09	0.08
LOI	0.45	0.43	0.68	1.67	0.30	0.71	0.87	1.12
Total	99.83	99.71	99.90	99.80	99.90	99.62	99.15	99.80
ppm								
As	2.5	6	6	8	6	< 5	< 5	5
Cr	34	32	16	10	11	80	110	10
Mo	2	2	2	2	2	5	7	2
Nb	5.8	7.2	4.2	4.8	3.5	4.3	4.4	4.3
Rb	53	69.7	43.4	52	36.3	58	48	36.5
Sr	331	258	384	370	378	323	361	329
Ta	0.9	0.8	0.3	0.2	0.1	0.48	0.42	0.4
Th	5.3	8.02	5.98	5.21	7.71	4.95	3.4	4.68
U	1.39	1.35	0.39	0.3	0.28	0.87	0.95	1.12
Y	5	7	6	3	2.7	5.4	6.1	7.2
Zr	125	93	128	134	181	112	113	107
Zn	50	30	40	50	50	< 30	30	30
V	19	28	24	27	18	38	46	40
Ba	263	281	315	346	356	-	-	411
Ce	28.4	37.1	34.9	29.7	59.5	23.6	25.3	29.1
Co	4.2	5.1	5.5	4.8	4	5	7	6.6
Cs	2.04	1.8	1.19	0.51	0.47	2.4	2	0.87
Dy	0.95	1.13	1.22	0.63	0.61	1.09	1.26	1.31
Er	0.51	0.74	0.7	0.3	0.32	0.63	0.75	0.75
Eu	0.54	0.52	0.51	0.49	0.6	0.406	0.596	0.62
Ga	21.6	18.1	18.6	20.4	17.6	18	19	18.7
Gd	1.57	1.71	1.93	1.4	2.13	1.2	1.3	1.77
Hf	3.3	3.2	3.3	3.3	4.7	2.4	2.6	3
Ho	0.19	0.23	0.24	0.11	0.11	0.21	0.26	0.26
La	15.5	22.5	19.1	16.1	35.3	12.2	14	17.5
Lu	0.07	0.13	0.08	0.04	0.04	0.091	0.102	0.11
Nd	9.5	13.1	11.9	9.4	17.5	8.41	9.86	11
Pr	2.94	4.03	3.6	2.94	5.8	2.39	2.73	3.34
Sm	1.78	1.99	2.05	1.44	2.16	1.37	1.53	1.94
Tb	0.2	0.22	0.24	0.15	0.18	0.19	0.2	0.25
Tm	0.08	0.11	0.08	0.03	0.04	0.093	0.113	0.1
Yb	0.46	0.66	0.56	0.23	0.22	0.58	0.7	0.72

Appendix B

EBSD parameters

Table B1. Analytical parameters for electron backscatter diffraction analyses

Samples	OIM DC- Version	WD	step size	EB Acc. Voltage	EB Probe Current	Camera Binning	Camera Exposure time	Camera indexing rate	Pattern Filter Normalize Intensity Histogram	Pattern Filter Background Subtraction	Pattern Filter Dynamic Background Subtraction	Hough Binned Pattern Size	Hough Theta Step Size	Hough Rho Fraction	Hough Min Peak Count	Hough Max Peak Count	Hough convolution mask	Hough Min Peak Distance
Unit		mm	μm	keV	nA		ms	points/s					[°]	%				[°]
NCB12-19_03	6.2.0	14	0.8	15	4.0	4x4	66	14	+	+	+	140	1	85	6	12	9x9	10
NCB12-19_07	6.2.0	13	2	15	4.0	4x4	34	14	+	+	+	140	1	85	6	12	9x9	10
NCB12-20_01	6.2.0	13	2.8	15	4.0	4x4	32	13	+	+	+	140	1	85	6	12	9x9	10
NCB12-20_02	6.2.0	13	3	15	4.0	4x4	32	13	+	+	+	140	1	85	6	12	9x9	10
NCB12-20_04	6.2.0	13	0.85	15	4.0	4x4	29	14	+	+	+	140	1	85	6	12	9x9	10
NCB12-18B_02	6.2.0	13	0.4	15	4.0	4x4	34	10	+	+	+	140	1	88	6	13	9x9	10
NCB12-18B_03	6.2.0	13	1	15	4.0	4x4	34	14	+	+	+	140	1	88	6	13	9x9	10
NCB12-18B_04	6.2.0	13	1	15	4.0	4x4	34	12	+	+	+	140	1	90	6	13	9x9	10
NCB12-18B_05	6.2.0	13	1.25	15	4.0	4x4	34	15	+	+	+	140	1	90	6	13	9x9	10
NCB12-22_01	6.2.0	13	1	15	4.0	4x4	29	14	+	+	+	140	1	86	6	13	9x9	10
NCB12-22_02	6.2.0	13	1.8	15	4.0	4x4	29	14	+	+	+	140	1	86	6	13	9x9	10
NCB12-22_06	6.2.0	13	1.9	15	4.0	4x4	31	10	+	+	+	140	1	85	6	14	9x9	10

Additional parameters

Stage tilt 70°

High vacuum < 1. 10 e-4 mbar

Appendix C

Pole figure reference system and
EBSD data rotation

Rotation of pole figures using Euler angles

Asymmetry in patterns is likely due to cutting of the thin sections slightly oblique to main fabric, therefore some of the Qz pole figures required additional rotation based on Euler angles. This step ensured that the foliations be represented as E-W lines in the pole figures and that the Y strain axis be centered, removing any unnecessary asymmetry in the patterns. Euler angles α , β and γ were determined by following the procedures defined in **Abalos et al. (2011)**. First, I plotted the foliation strike and the dominant c and a-axes girdles with the help of a stereonet. The Y axis is normal to the intersection between the c and a-axes girdles, within the c-axis girdle. The foliation can be traced with known strike and contains the Y-axis. The Z-axis corresponds to the pole to foliation and is within the a-axis girdle. The X-axis is the intersection between foliation and the a-axis girdle. These three strain axes should be orthogonal to each other. After determining the strain axes direction, Euler angles can be found. Alpha is the distance between X, and the intersection of the a-axis girdle and the great circle. Beta is the angle between the center of the pole figure and Y. Gamma is the angle between the a-axis girdle and the great circle, and the E-W mark on the great circle. Schematic pole figures showing rotation angles are shown on the following figure in appendix B. Then Mtex was used to produce rotated pole figures based on these specific Euler angles.

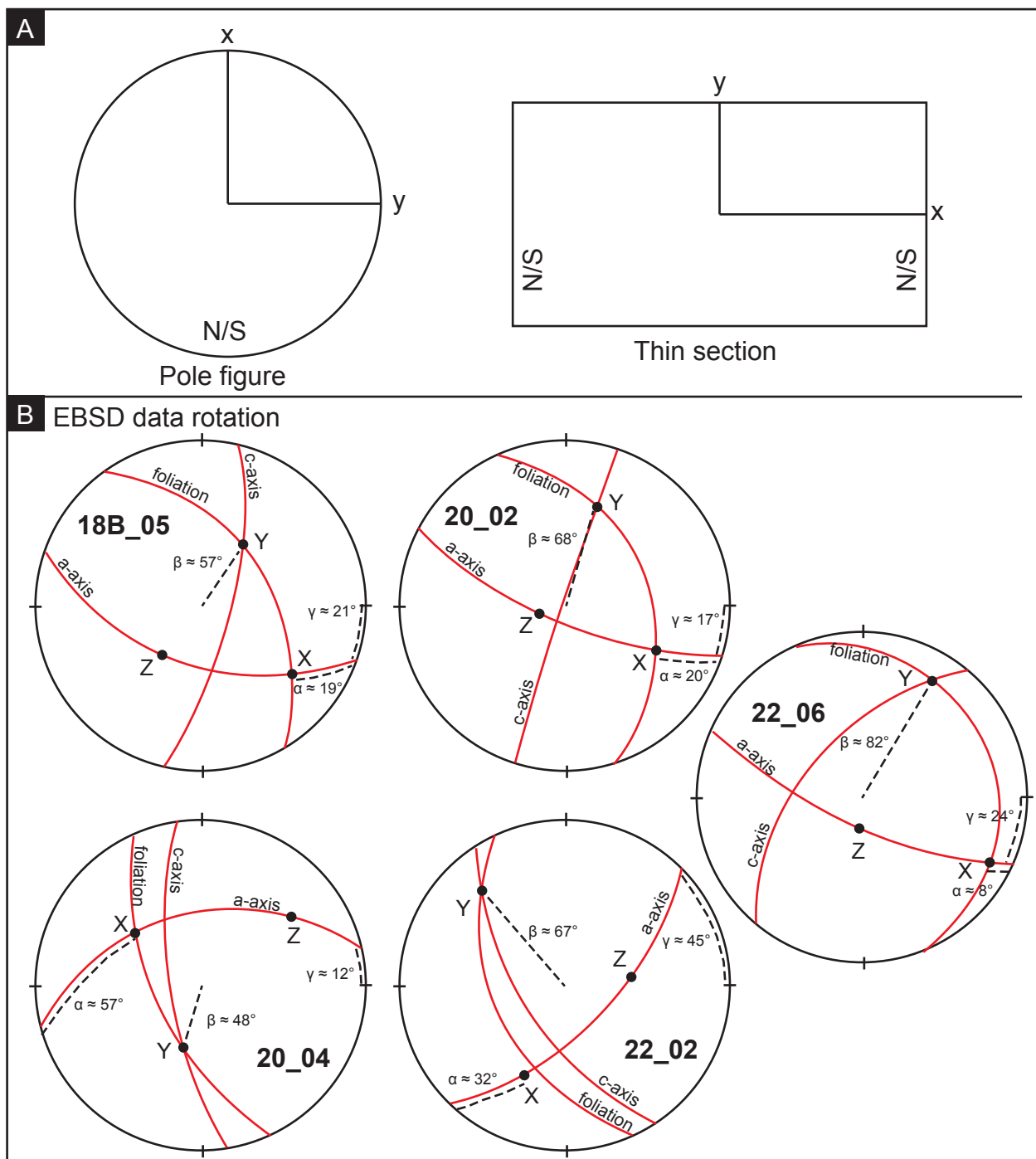


Figure C1: A) Schematic showing the orientation of pole figures in thin section reference frame. B) Euler angle determinations for EBSD data rotation. Selected samples were rotated to ensure foliations form a E-W line in pole figures, eliminating unnecessary asymmetry in CPO patterns.

Appendix D

Kolmogorov-Smirnov statistical test

Appendix D: Kolmogorov-Smirnov statistical test

The KS test is a statistical analysis that is used to test the null hypothesis ($h = 0$) that one distribution (correlated) is not the same as a hypothesized or ideal one (uncorrelated). Mtex offers simple and rapid set of commands to perform the KS test. First by using a fixed population (here each test was conducted with a population of $n = 50$) mtext calculated two cumulative frequency distributions (CDF) for correlated and uncorrelated pairs. From these, x_1 and x_2 , the KS test is performed at a significance level of 1% ($\alpha = 0.01$) and yields a result of 1 or 0 which corresponds to the rejection or acceptance of the null hypothesis, respectively. This also calculates the p -value, which is the probability of success of the test. The test is not significant if the p -value is smaller than the significance level ($p < 0.01$), therefore cannot be accepted. A summary of the results can be found **below**. The final step is to calculate the probability that two distributions are different. This is done by using a simple equation that only requires the maximum spacing (D) between the two distributions.

$$d = D \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}}$$

The value of d obtained with this equation is then compared to a standard table to determine the probability of the two distributions being different (**Table D1**).

Table D1: Table showing corresponding probability and d values. From Wheeler et al. 2001, Hoel 1962 p.411, Lindley and Scott 1995 p.70.

$d >$	1.07	1.224	1.358	1.628	1.949
%(different)	80	90	95	99	99.9

Results

N1=50*

N2=50

*number pairs tested with the K-S is the same for each sample, 50, and the numbers N1-2 correspond to X1-2 distributions.

NCB22 02

Quartz

X1= 0	0	3.3210	4.5756	1.5498	1.5941	0.6642	1.0480	1.4170	1.1070	0.6642
0.8266	1.1661	1.1070	1.6089	1.2103	1.3284	1.0037	0.7823	1.6827	1.4465	1.4908
1.3875	1.9631	2.4502	3.6753	4.2657	13.8450	12.9446	1.6827	2.2583	2.3911	2.8487
2.9373	2.8782	1.7417	1.9631	1.0923	1.4170	1.2251	2.1845	1.6679	1.5941	0.5904
0.9594	0.3247	0.0590	0.0590	0	0					

X2= 0.3608	0.1670	0.1711	0.2113	0.1691	0.2629	0.3773	0.3804	0.5412	0.5505	0.6247
0.7794	0.8969	0.7979	1.0216	1.3144	1.3577	1.3835	1.7196	1.7010	1.8402	2.1175
2.4278	2.6618	2.8154	2.8165	3.2835	3.4598	3.7402	3.7268	3.7897	3.6742	3.8453
3.7144	3.6484	3.7793	3.8360	3.8804	4.0608	4.1278	4.0061	3.8670	3.5360	2.8103
2.0124	1.1453	0.4402	0.1371	0.0113	0					

$h=0$, there is not relationship between x_1 - x_2

$p=0.0951 > \alpha=0.01$, therefore we accept $h=0$

$k(D \max)=0.24$

$d=1.2$, thus there is only ~15% chance x_1 - x_2 are the same (~85% chance they are different)

Albite

$x_1 = 0$	1.0455	1.1223	0.6379	0.3603	0.5493	0.3603	0.8919	1.4826	0.5375	0.3662
0.8624	0.3957	0.3249	0.4607	0.5316	0.7974	0.3012	0.4253	0.5493	0.5611	0.5611
0.4135	0.8447	0.6556	0.7442	0.4489	0.5729	0.8978	0.5493	0.9746	1.1045	0.9864
1.0219	0.8978	0.8624	0.9333	1.0573	0.9569	1.1577	1.5771	1.5594	1.5475	2.2268
1.9197	1.6893	1.3822	1.8901	58.0035	0					

$x_2 =$	1.3624	0.0945	0.1048	0.0637	0.1048	0.2795	0.2127	0.2250	0.4151	0.3339
0.6761	0.4757	0.7521	0.7727	0.9011	1.1939	1.3686	1.4313	1.6707	1.2515	1.2525
1.6522	1.6974	1.9851	1.9491	2.5122	1.9717	1.8248	2.2009	2.0961	2.6273	2.2594
2.3324	2.6643	2.9098	3.5500	3.4102	3.8161	3.2869	3.4277	4.1582	3.8983	3.4842
3.9620	4.0493	4.1767	4.1613	3.9681	5.0254	0				

$h=1$, there is a relationship btw x_1 - x_2

$p=3.6 \times 10^{-6} < \alpha=0.01$, therefore we don't accept the test

k=0.5

$d = 2.5$, thus there is <0.01% chance $x_1 - x_2$ are the same

Actinolite

$x_1 = 0$	1.4485	1.1105	0.9863	0.9381	0.4759	0.5242	0.8484	0.4345	1.1864	0.4759
0.2345	0.7242	0.3242	0.2276	0.3242	0.2483	0.4828	0.6346	0.2552	0.1173	1.3312
0.6622	0.2483	0.0897	0.4207	0.3242	0.0966	0.1035	0.1104	0.1655	0.1793	0.3242
0.2621	0.2966	0.3311	1.4209	0.7380	0.4070	0.7311	0.5104	0.5173	0.7242	0.5035
1.5726	1.1726	17.1127	1.6485	55.9939	0					

$x_2 =$	3.0081	0.2910	0.7651	0.4299	1.0130	1.4357	1.6609	1.7596	1.8707	1.7195
1.8532	2.0013	2.0352	1.8192	1.1230	1.6650	0.9081	1.4058	2.9567	1.9241	1.2166
0.8855	0.9996	0.5718	0.4669	0.4576	0.5687	1.2392	0.5790	0.4741	1.0366	0.6633
1.2588	1.5405	1.4429	1.9437	3.0112	2.4723	2.6625	2.4641	4.4057	3.7465	4.3820
3.9316	4.1805	6.3226	5.2438	4.6206	5.5668	0				

$h=1$, there is a relationship btw $x_1 - x_2$

$p = 4.02 \times 10^{-7} < \alpha = 0.01$, therefore we don't accept the test

k=0.54

$d = 2.7$, thus there is <0.01% chance $x_1 - x_2$ are the same

NCB22 06

Quartz

$x_1 = 0$	0	3.0611	5.0917	2.8489	2.5004	2.5458	1.5154	0.8789	0.8789	1.0153
1.3790	1.4093	1.5912	1.2881	1.1820	1.0456	1.6821	1.0759	1.5912	1.3790	1.3184
1.3032	2.6368	2.3488	2.7277	4.1067	7.9254	8.0012	2.3640	1.0911	1.2123	1.7124
1.3638	1.2729	3.0156	2.8489	2.4852	1.7578	2.0458	3.1217	2.4852	4.2431	2.2731
1.0759	0.4849	0.4243	0.3940	0	0					

$x_2 =$	0.1463	0.0691	0.0894	0.1179	0.1758	0.2398	0.2835	0.3425	0.4045	0.5112
0.5976	0.6595	0.7917	0.8648	1.0102	1.1890	1.3252	1.5325	1.6565	1.7723	1.8404
2.0264	2.3028	2.5183	2.8963	3.0650	3.2002	3.2886	3.3658	3.5945	3.5162	3.8536
3.7113	3.6392	3.9786	4.0162	4.0823	4.1046	4.0955	4.0000	3.9156	4.0955	3.6615
3.1585	2.1250	1.3780	0.5823	0.1850	0.0234	0				

$h=0$, there is not relationship btw $x_1 - x_2$

$p = 0.056 > \alpha = 0.01$, therefore we accept $h=0$

k=0.26

$d = 1.3$, thus there is <10% chance $x_1 - x_2$ are the same

Albite

x1 = 0	2.1766	1.7039	1.2312	1.2679	1.0956	0.8062	0.5643	0.8098	0.4764	0.5533
0.3994	0.4067	1.2019	0.7255	0.4287	0.6889	0.6706	0.3738	0.6486	0.4984	0.6376
0.3848	0.4141	0.3738	0.5863	0.6706	0.8135	0.8135	1.2129	1.1579	1.0114	1.1543
1.3631	0.9747	0.9088	0.8868	0.7145	1.1506	1.3155	1.5867	1.7919	2.1253	2.1986
2.2572	2.4771	2.2682	1.9714	50.0513	0					

x2 = 0.5221	0.0611	0.1028	0.1272	0.1822	0.2748	0.2290	0.3196	0.4274	0.4681	0.5709
0.8121	0.6869	0.9851	0.9342	1.1500	1.2477	1.2884	1.2701	1.3433	1.5530	1.4156
1.6141	1.6680	1.9071	1.7280	1.7362	2.1127	2.0384	2.2023	2.2888	2.7712	2.8902
2.9961	2.7763	2.9879	3.0765	3.3339	3.4510	3.9863	4.1359	4.1216	4.0952	4.0280
4.0972	4.2030	4.5592	4.5521	4.6712	0					

$h=1$, there is a relationship btw x_1 - x_2

$p=9.6 \times 10^{-4} < \alpha=0.01$, therefore we don't accept the test

$k=0.38$

$d=1.9$, thus there is $\sim 0.01\%$ chance x_1 - x_2 are the same

Actinolite

x1 = 0	2.9444	3.1359	3.0857	1.8834	1.1552	0.8413	0.7910	0.6309	0.5274	0.4206
0.1758	0.2448	0.4332	0.2197	0.1726	0.0157	0.0722	0.0879	0.0408	0.1067	0.0094
0.0471	0.0377	0.0879	0.0596	0.0220	0.0628	0.0283	0.0283	0.0910	0.1381	0.0596
0.1350	0.0879	0.2291	0.1915	0.1978	0.2794	0.2857	0.2511	0.6498	0.7126	0.6937
0.7283	1.0955	1.2682	2.5018	73.0358	0					

x2 = 0.8759	0.5962	0.7071	0.8637	1.0509	1.3531	1.3429	1.2829	1.6461	1.6837	1.5352
1.3236	1.1567	1.3032	1.3683	1.0825	1.1059	1.0936	0.7376	0.7945	0.8312	0.6460
0.6582	0.6196	0.5290	0.5677	0.5311	0.5738	0.5972	0.5280	0.6114	0.7264	0.7376
0.8871	0.9665	1.3541	1.8862	1.6939	2.9096	2.9920	3.6268	4.6340	5.2342	5.5842
6.3126	7.0166	8.4684	7.9902	7.3829	0					

$h=1$, there is a relationship btw x_1 - x_2

$p=1.98 \times 10^{-10} < \alpha=0.01$, therefore we don't accept the test

$k=0.66$

$d=3.3$, thus there is $< 0.01\%$ chance x_1 - x_2 are the same

NCB20_01

Quartz

x1 =	0	0	2.5306	2.6097	1.5843	1.0755	1.1699	1.2721	0.9521	0.9753	1.0755
	1.0755	1.1699	1.3337	1.4320	1.4744	1.5014	1.5920	1.6575	1.7944	2.0893	2.0315
	2.0372	2.4054	2.4613	2.9007	3.8760	7.7018	5.7937	3.0221	2.7157	2.9084	2.7003
	2.7966	2.8236	2.7157	2.4690	2.5441	2.4998	2.5730	2.5518	2.4882	2.5827	2.0276
	1.5342	0.9194	0.4144	0.1176	0.0231	0					

x2 =	0.0286	0.0827	0.0929	0.1490	0.2235	0.2572	0.4021	0.4858	0.6164	0.7552	
	0.8206	1.0104	1.1053	1.2849	1.3513	1.5656	1.7228	1.8656	1.9442	2.1351	2.2780
	2.4311	2.6311	2.8260	2.9260	3.1516	3.4578	3.5843	3.6211	3.7027	3.5445	3.6884
	3.7068	3.6639	3.6415	3.5323	3.4925	3.2986	3.3067	3.4649	3.3904	3.4057	3.1108
	2.5464	1.9157	1.0880	0.5021	0.1684	0.0235	0				

$h=0$, there is no relationship btw x_1 - x_2

$p=0.0171 > \alpha=0.01$, therefore we accept $h=0$

$k=0.3$

$d=1.5$, thus there is $<5\%$ that x_1 - x_2 are the same

Albite

x1 =	0	0.5387	0.4997	0.3348	0.3718	0.3328	0.2879	0.3923	0.4216	0.3787	0.4743
	0.4519	0.4782	0.5690	0.5797	0.6207	0.7339	0.7027	0.8188	0.8042	0.8618	0.9779
	1.1068	1.2600	1.5791	1.4327	1.2629	1.4171	1.4113	1.4640	2.2018	1.8934	1.7743
	1.8934	1.8456	1.9188	2.0047	1.9432	2.3599	2.3150	2.2770	2.2204	2.1325	2.5629
	2.8030	2.3921	2.3697	3.1436	37.3830	0					

x2 =	0.1256	0.0255	0.0398	0.0541	0.1072	0.1695	0.1695	0.2246	0.3073	0.3798	0.4268
	0.5493	0.6014	0.7351	0.8730	0.9230	1.0721	1.2201	1.2252	1.3478	1.4417	1.6163
	1.6765	1.8603	1.9930	2.2217	2.2044	2.3637	2.5720	2.5260	2.7711	2.9273	3.0569
	3.0620	3.3387	3.3490	3.4531	3.6624	3.6073	3.6420	3.7492	3.7819	4.0494	4.0657
	3.9891	4.1821	4.0392	3.9554	4.2658	0					

$h=1$, there is a relationship btw x_1 - x_2

$p=0.0044 < \alpha=0.01$, therefore we don't accept the test

$k=0.34$

$d=1.7$, thus there is $<1\%$ chance x_1 - x_2 are the same

NCB20_02

Quartz

x1 =	0	0	2.8128	3.0388	1.9271	1.3452	1.0636	0.9672	1.0451	0.6893	0.9079
	1.0895	1.1303	1.0117	1.0858	1.2415	1.3749	1.4564	1.5342	1.5713	1.6565	2.0679
	2.0679	2.1494	2.6164	2.8276	4.1024	8.4087	6.5335	2.7238	2.7572	2.6942	2.6534

2.6868	2.5904	2.8461	2.8202	2.6386	2.5460	2.8387	2.6349	2.5052	2.5237	1.9641
1.3971	0.9784	0.3298	0.1112	0.0371	0					

x2 = 0.0092	0.0339	0.0472	0.0770	0.1284	0.1551	0.2526	0.3276	0.3974	0.4714	0.6398
0.7158	0.8308	0.9232	1.0495	1.2179	1.3473	1.4972	1.6143	1.8320	2.0148	2.2346
2.3126	2.5693	2.6227	2.8600	3.1074	3.2789	3.3827	3.6168	3.6959	3.7277	3.7010
3.9280	3.9988	3.7903	3.9567	4.0111	4.0697	4.1036	4.0635	4.1344	3.8078	3.0181
2.2685	1.4182	0.5545	0.1705	0.0144	0					

$h=0$, there is no relationship btw x_1 - x_2

$\rho=0.0171 > \alpha=0.01$, therefore we accept $h=0$

$k=0.3$

$d=1.5$, thus there is $<5\%$ that x_1 - x_2 are the same

Albite

$x_1 = 0$	0.5647	0.4368	0.3301	0.2971	0.3308	0.3002	0.3343	0.2985	0.3168	0.3414
0.3452	0.3640	0.3533	0.3953	0.4281	0.5514	0.5393	0.6440	0.6060	0.5355	0.6959
0.5904	0.6402	0.7728	0.7322	0.7394	0.8473	0.8089	0.8217	1.0573	0.9968	1.0775
1.0988	1.0362	1.0875	1.0557	1.0469	1.2483	1.3283	1.2889	1.5167	1.4144	1.4555
1.5689	1.5454	1.6206	2.2200	61.3745	0					

$x_2 = 0.5983$	0.4953	0.3098	0.3007	0.1753	0.1814	0.2456	0.2813	0.3863	0.4566	0.5677
0.6482	0.6818	0.8174	0.8847	0.8694	1.0528	1.1507	1.4065	1.4850	1.3871	1.4371
1.5594	1.6766	1.7367	2.0282	1.9548	2.1189	2.1454	2.2616	2.4675	2.7243	2.6397
2.7416	2.7640	2.9740	3.1789	3.2359	3.3297	3.3440	3.4092	3.7048	3.8006	3.8617
3.9310	4.0034	4.5639	5.1693	6.8561	0					

$h=1$, there is a relationship btw x_1 - x_2

$\rho=1.023 \times 10^{-5} < \alpha=0.01$, therefore we don't accept the test

$k=0.48$

$d=2.4$, thus there is $<0.01\%$ chance x_1 - x_2 are the same

NCB20_04

Quartz

$x_1 = 0$	0	1.7828	1.9628	1.5319	0.9126	0.8448	0.9877	0.8268	0.8660	0.9422
0.8893	1.0068	1.3170	1.4536	1.5054	1.5181	1.5340	1.6431	1.8548	1.9628	1.9818
2.0274	2.2158	2.3333	2.9929	3.4068	6.4314	6.8464	2.9982	3.4195	2.9876	2.9590
2.8309	2.9727	2.8817	2.6604	2.6096	2.9569	2.8923	2.8648	2.8425	2.8298	2.3450
1.6409	1.0439	0.4605	0.1599	0.0656	0					

x2 = 0.0583	0.1002	0.1596	0.2005	0.2977	0.3243	0.4235	0.5278	0.6096	0.8163	0.8889
1.0249	1.1415	1.3042	1.4689	1.5006	1.6305	1.8893	1.9609	2.1399	2.1859	2.4734
2.5511	2.7270	2.9275	3.2262	3.3254	3.4134	3.5044	3.6313	3.6885	3.5934	3.5320
3.5259	3.4574	3.4154	3.4676	3.4922	3.4369	3.4697	3.5075	3.4594	3.1362	2.6605
1.8852	1.1334	0.5176	0.1729	0.0153	0					

$h=0$, there is not relationship btw x_1 - x_2

$p=0.0317 > \alpha=0.01$, therefore we accept $h=0$

$k=0.28$

$d=1.4$, thus there is $<5\%$ chance x_1 - x_2 are the same

Albite

x1 = 0	0.2967	0.1467	0.1137	0.1125	0.1243	0.1516	0.2661	0.3220	0.2710	0.3509
0.3195	0.3424	0.4068	0.4508	0.5172	0.7296	0.7296	0.8302	0.7487	0.7585	0.8848
0.9244	1.1734	1.4355	1.5830	1.2260	1.3189	1.5174	1.4909	2.5567	1.9661	1.8202
1.8859	1.8965	1.8304	1.8174	1.7338	2.1830	2.0562	2.1422	2.0636	2.0289	2.2091
2.4993	2.2360	2.0713	2.3925	43.0677	0					

x2 = 0.1585	0.0164	0.0307	0.0655	0.0839	0.1514	0.1841	0.2782	0.3038	0.3815	0.5042
0.5329	0.6750	0.7078	0.7937	0.9113	1.0616	1.0954	1.3153	1.3480	1.5147	1.5577
1.8522	1.8318	2.0271	2.1857	2.2982	2.3830	2.5088	2.6715	2.7472	2.8351	3.1031
3.1829	3.1808	3.3526	3.7034	3.4815	3.5531	3.5960	3.8047	3.8763	3.8886	3.9571
3.9489	4.1535	4.0011	4.1146	4.0900	0					

$h=1$, there is a relationship btw x_1 - x_2

$p=9.7 \times 10^{-4} < \alpha=0.01$, therefore we don't accept the test

$k=0.38$

$d=1.9$, thus there would be $\sim 0.01\%$ chance x_1 - x_2 are the same

NCB19 03

Quartz

x1 = 0	0	3.5497	3.2013	1.1800	0.7067	0.8151	0.8151	0.4601	0.4799	0.7001
1.1109	0.6475	1.0386	0.6541	0.9203	1.1208	0.9170	0.7888	0.8414	1.2030	1.6763
1.4363	1.7551	2.2153	3.1191	3.2736	9.6302	15.2802	3.1652	2.5341	1.9819	1.6105
2.3172	1.7749	2.4947	2.5538	3.8455	3.4741	2.8365	2.7445	2.5900	2.4749	1.7847
1.3147	0.6771	0.1808	0.0624	0.0460	0					

x2 = 1.0552	1.2112	1.2193	0.9400	0.8299	0.8666	0.6321	0.4486	0.4771	0.4537	0.6484
1.0409	1.5446	2.7843	2.7965	2.3184	2.4071	2.0227	1.6904	1.5384	1.7525	1.9962
2.5121	3.2961	4.1739	4.2249	4.1515	4.7326	3.7926	3.0677	2.5569	2.4071	2.5590

2.2664	2.2195	2.6752	2.7904	2.8659	2.3693	2.2389	2.5712	3.4541	3.1768	2.3571
1.5843	0.9594	0.2692	0.0459	0.0082	0					

$h=0$, there is no relationship btw x_1 - x_2

$\rho=0.2408 > \alpha=0.01$, therefore we accept $h=0$

$k=0.2$

$d=1$, thus there is ~20% chance that x_1 - x_2 are the same

Albite

$x_1 = 0$	0.3072	0.2995	0.2842	0.2458	0.1997	0.8909	1.2673	0.5223	0.3379	0.3763
0.4992	0.5530	0.5607	0.5146	1.0445	1.6820	1.1905	0.8602	1.0522	0.8525	1.2289
1.1060	1.4132	4.1014	3.7481	1.9508	1.6820	1.5284	1.4747	2.0737	1.6897	2.5653
2.4578	2.1505	2.2965	2.3349	1.9892	2.6498	2.2427	3.0338	5.3994	2.2581	3.0338
3.3717	3.0415	3.0722	2.5806	19.9846	0					

$x_2 = 1.6270$	0.3514	0.3740	0.1566	0.1092	0.1772	0.5832	0.4513	0.3112	0.4256	0.2978
0.4286	0.5626	0.7924	1.0603	1.0737	0.8563	1.1139	1.1685	1.5806	2.0041	1.2952
1.6383	1.8887	2.0732	2.5296	3.0366	2.4565	2.5853	3.4096	2.5224	2.6811	3.1551
2.7223	3.0912	2.6275	2.6533	2.6255	3.0892	3.2726	3.0459	3.6085	3.7404	3.4148
3.7177	4.2607	4.1855	3.9465	5.2211	0					

$h=0$, there is no relationship btw x_1 - x_2

$\rho=0.1546 > \alpha=0.01$, therefore we accept $h=0$

$k=0.22$

$d=1.1$, thus there is <20% chance that x_1 - x_2 are the same

NCB19 07

Quartz

$x_1 = 0$	0	5.3074	5.7695	3.0502	2.0518	1.5935	1.5764	1.4909	1.4376	1.6506
1.5650	1.9682	1.7191	1.9377	1.9320	1.7666	1.9891	2.2648	2.0785	2.1907	2.1678
2.2382	2.6927	2.9380	3.1320	4.6418	9.5347	8.0933	2.2610	1.8617	1.8636	1.5993
1.5859	1.3463	1.2988	1.0953	0.9527	1.1258	0.9736	1.0041	1.0459	0.9489	0.8595
0.6656	0.4336	0.2111	0.0799	0.0095	0					

$x_2 = 0.0340$	0.1382	0.2206	0.2959	0.4939	0.6413	0.7702	1.0331	1.2362	1.4053	
1.5538	1.7373	1.8652	2.0600	2.2219	2.3549	2.4952	2.4663	2.7684	2.8282	2.8313
3.0365	3.0746	3.2375	3.2829	3.4252	3.5654	3.6757	3.6798	3.5468	3.3602	3.2014
2.9694	2.9519	2.9581	2.7457	2.5601	2.4518	2.3704	2.2467	2.2085	2.0714	1.9343
1.6476	1.1311	0.7310	0.3794	0.0918	0.0134	0				

$h=0$, there is no relationship btw x_1 - x_2

$p=0.0171 > \alpha=0.01$, therefore we accept $h=0$

$k=0.3$

$d=1.5$, thus there is $<5\%$ chance that x_1 - x_2 are the same

Albite

$x_1 = 0$	0.8670	0.8413	0.7393	0.7008	0.6603	0.7579	0.7033	0.7797	0.6982	0.9157
0.6828	0.7823	0.8779	0.7604	0.8881	1.8250	1.2757	1.0723	1.1243	0.9838	1.0742
1.1820	1.4856	1.8969	1.5324	1.3983	1.5574	1.6146	1.6935	1.8173	1.8218	2.4327
2.6561	2.0862	2.0721	2.0220	1.9425	2.3134	2.3538	2.9153	3.0854	2.8492	2.9416
3.2253	2.9294	2.8916	3.1335	23.1397	0					

$x_2 = 0.1340$	0.0227	0.0577	0.0804	0.1340	0.2267	0.2772	0.3534	0.4307	0.5059	
0.6224	0.7203	0.7965	0.9377	1.0119	1.0851	1.1077	1.2396	1.3231	1.4148	1.4849
1.5694	1.6085	1.7559	1.7621	1.8960	2.0640	2.1000	2.2330	2.3752	2.4957	2.5957
2.7472	2.9038	2.9965	3.0923	3.2655	3.4942	3.5354	3.6952	3.6869	4.1310	4.0465
4.2341	4.2526	4.3732	4.3464	4.4216	4.3557	0				

$h=0$, there is no relationship btw x_1 - x_2

$p=0.0951 > \alpha=0.01$, therefore we accept $h=0$

$k=0.24$

$d=1.2$, thus there is $\sim 10\%$ chance that x_1 - x_2 are the same

NCB18B 05

Quartz

$x_1 = 0$	0	3.5043	3.1584	2.0153	2.7523	1.6694	1.1731	1.4889	1.3837	1.0678
1.0678	0.9626	1.6393	0.9776	1.1731	1.0528	1.1129	1.9101	0.7520	1.3987	1.2934
1.5190	2.3462	2.8726	2.3913	2.8726	14.7541	15.5512	1.5792	1.7296	2.7673	1.6845
1.3987	1.6393	1.2934	1.5341	1.4288	1.1280	1.4288	2.6019	1.5491	1.2032	1.2934
0.8422	0.7370	0.1354	0.1504	0.0150	0					

$x_2 = 0.0749$	0.0800	0.0688	0.0862	0.1703	0.2001	0.2319	0.3140	0.4207	0.5828	
0.6023	0.7747	0.7963	1.0374	1.1216	1.3114	1.4520	1.5217	1.6623	1.7680	1.9968
2.3262	2.3847	2.5273	2.6607	2.9409	3.0917	3.4139	3.4016	3.6212	3.7125	3.8059
3.7310	3.7556	3.9106	3.8244	3.7669	3.7823	3.9116	3.8418	4.0234	3.9783	3.7094
3.1461	2.2647	1.3750	0.6085	0.1796	0.0298	0				

$h=0$, there is no relationship btw x_1 - x_2

$p=0.0171 > \alpha=0.01$, therefore we accept $h=0$

k=0.3

$d = 1.5$, thus there is <5% chance that $x_1 - x_2$ are the same

Albite

$x_1 =$	0	1.2151	1.2119	1.1022	1.1394	1.0708	1.0153	0.8345	0.8038	0.5295	0.5086
	0.5726	0.4447	0.3944	0.4636	0.4172	0.3859	0.4087	0.4303	0.3735	0.4323	0.3944
	0.3767	0.4296	0.5295	0.6549	0.6516	0.5877	0.5609	0.6027	0.7150	0.7071	0.7901
	0.8260	0.6993	0.8599	1.0297	0.9069	1.3333	1.3190	1.5331	1.8929	2.1234	2.5223
	2.9213	3.3620	4.3669	5.7185	47.8309	0					

$x_2 =$	0.0788	0.0891	0.1823	0.3492	0.4096	0.5274	0.6216	0.7240	0.7434	0.7281	
	0.7127	0.7946	0.7700	0.8653	0.8816	0.9584	0.9933	1.1622	1.1694	1.2994	1.3558
	1.4203	1.4735	1.4766	1.5759	1.5861	1.7152	1.8575	2.0080	2.0152	2.1493	2.2036
	2.3644	2.3828	2.6245	2.6470	2.8927	3.0095	3.1539	3.3709	3.6280	3.9690	4.3304
	4.7206	4.6438	5.1588	5.1998	5.4670	5.5397	0				

$h=1$, there is a relationship btw $x_1 - x_2$

$p = 4.2 \times 10^{-4} < \alpha = 0.01$, therefore we don't accept the test

k=0.4

$d = 2$, thus there would be <0.01% chance that $x_1 - x_2$ are the same

Actinolite

$x_1 =$	0	1.9185	2.2661	1.5338	1.3583	1.2555	1.1723	1.0949	0.8108	0.7611	0.7588
	0.7173	0.6930	0.6907	0.6225	0.6387	0.6272	0.6618	0.6064	0.6018	0.5325	0.5532
	0.5891	0.6168	0.6306	0.5925	0.6699	0.6503	0.6110	0.7508	0.7230	0.7842	1.2104
	0.9459	0.8247	0.9563	0.8928	0.9563	1.0199	1.1307	1.3028	1.2497	1.6286	1.6551
	2.0270	2.1148	2.7535	3.3969	49.4410	0					

$x_2 =$	0.1373	0.0912	0.1916	0.2961	0.4355	0.6292	0.7255	0.9694	0.9735	1.1589	
	1.1589	1.3557	1.2184	1.3013	1.3495	1.3680	1.4335	1.4171	1.4592	1.3905	1.4089
	1.3731	1.3854	1.3423	1.4325	1.3987	1.4448	1.5001	1.4602	1.7102	1.6221	1.6723
	1.7963	1.8537	2.1467	2.1795	2.4428	2.5607	2.8476	3.1468	3.5577	3.7934	4.3549
	4.8673	4.9923	5.3120	5.5446	5.7608	6.0323	0				

$h=1$, there is a relationship btw $x_1 - x_2$

$p = 3.6 \times 10^{-6} < \alpha = 0.01$, therefore we don't accept the test

k=0.5

$d = 2.5$, thus there would be <0.01% chance that $x_1 - x_2$ are the same

Appendix E

All pole figures for Hbl and Fsp

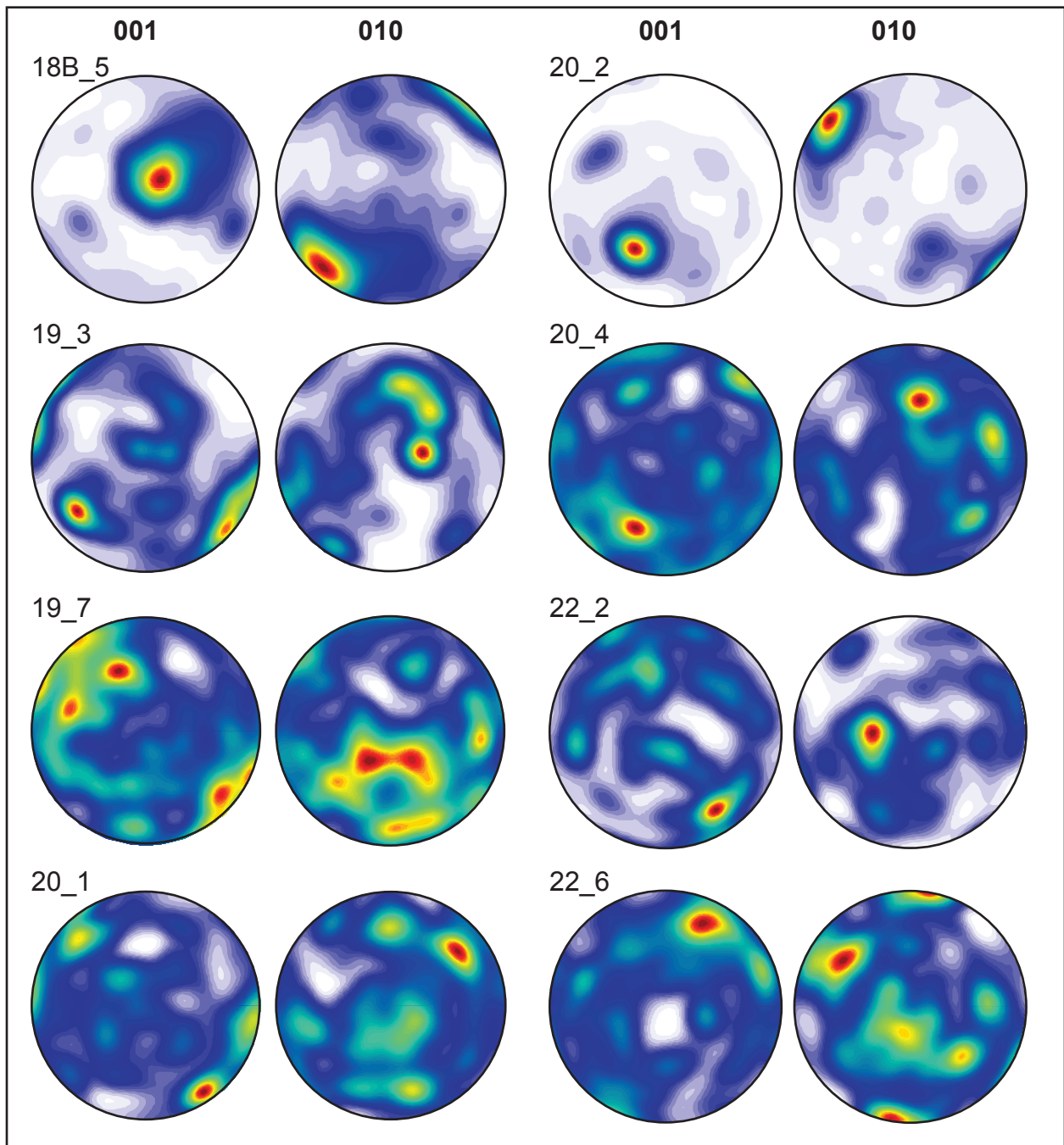


Figure E1: Complete dataset of feldspar pole figures. See Fig. 1.7 and section 5.3.1 for more details.

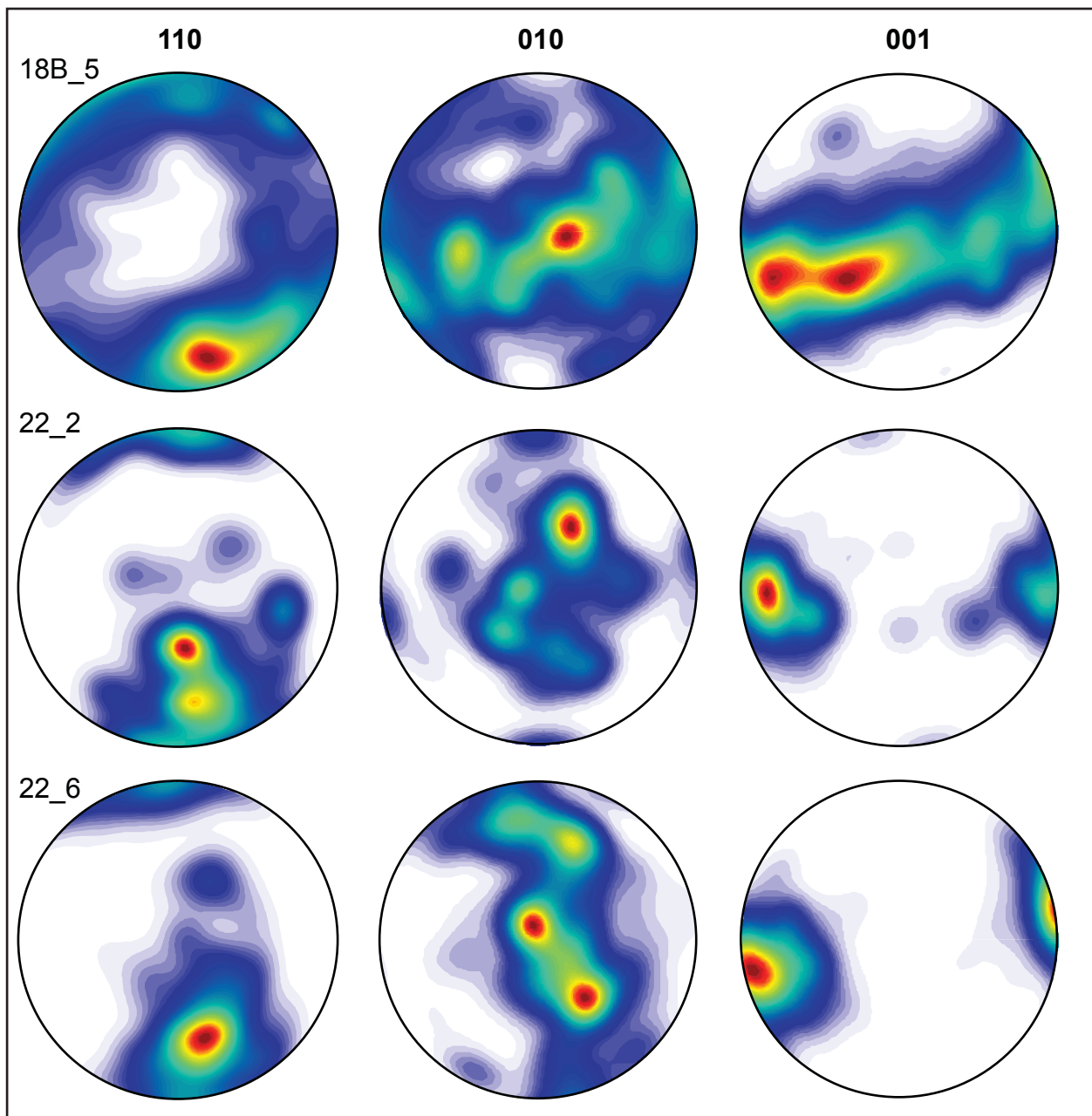


Figure E2: Complete dataset of hornblende pole figures. See Fig. 1.7 and section 5.3.1 for more details.

Appendix F

All grain boundary misorientation histograms for Hbl and Fsp

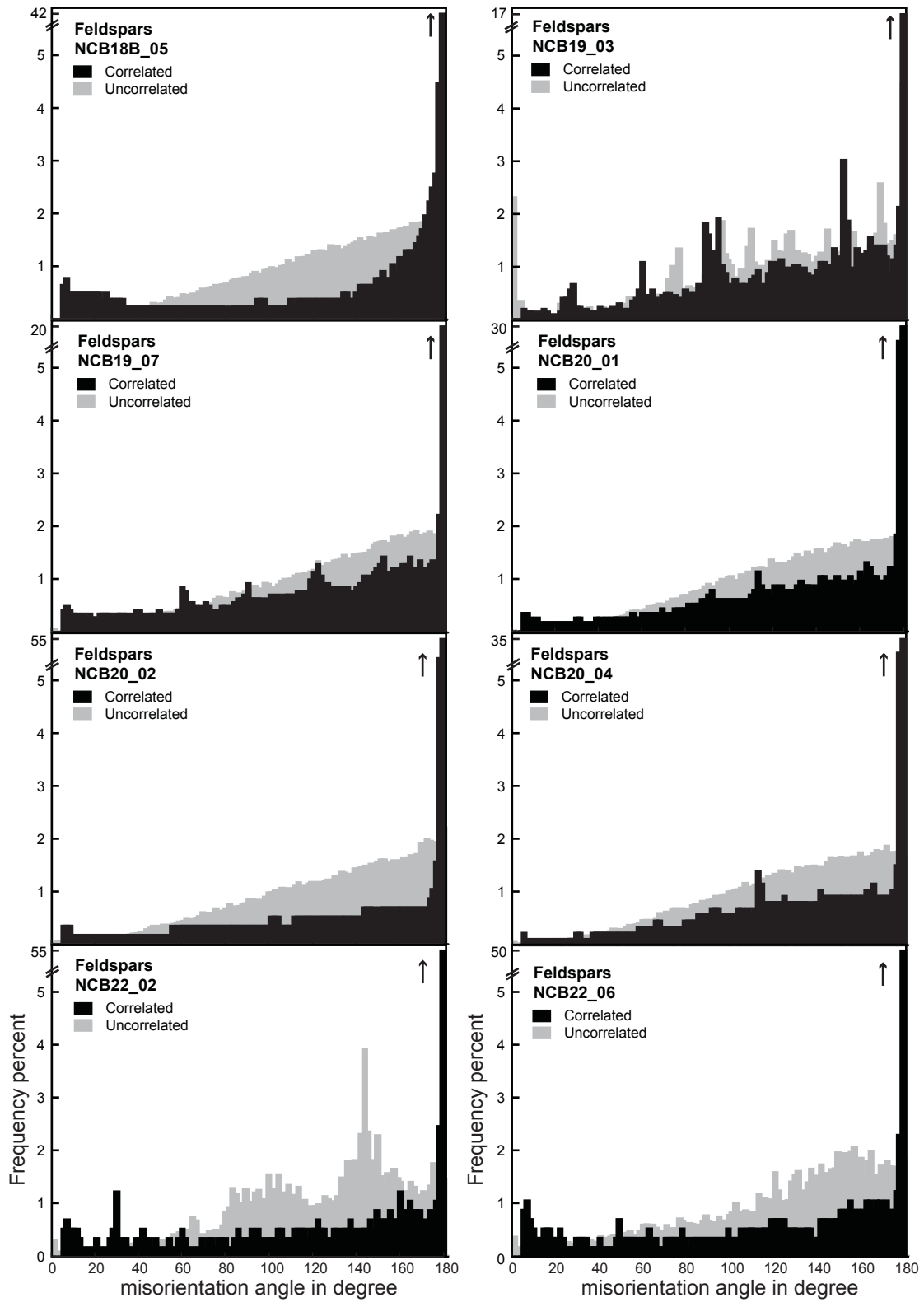


Figure F1: Grain boundary misorientation histograms of feldspars across the Dinnick Lake shear zone. Histograms show the recrystallized texture of feldspar with very few subgrains (misorientation at low angles, 5-15°).

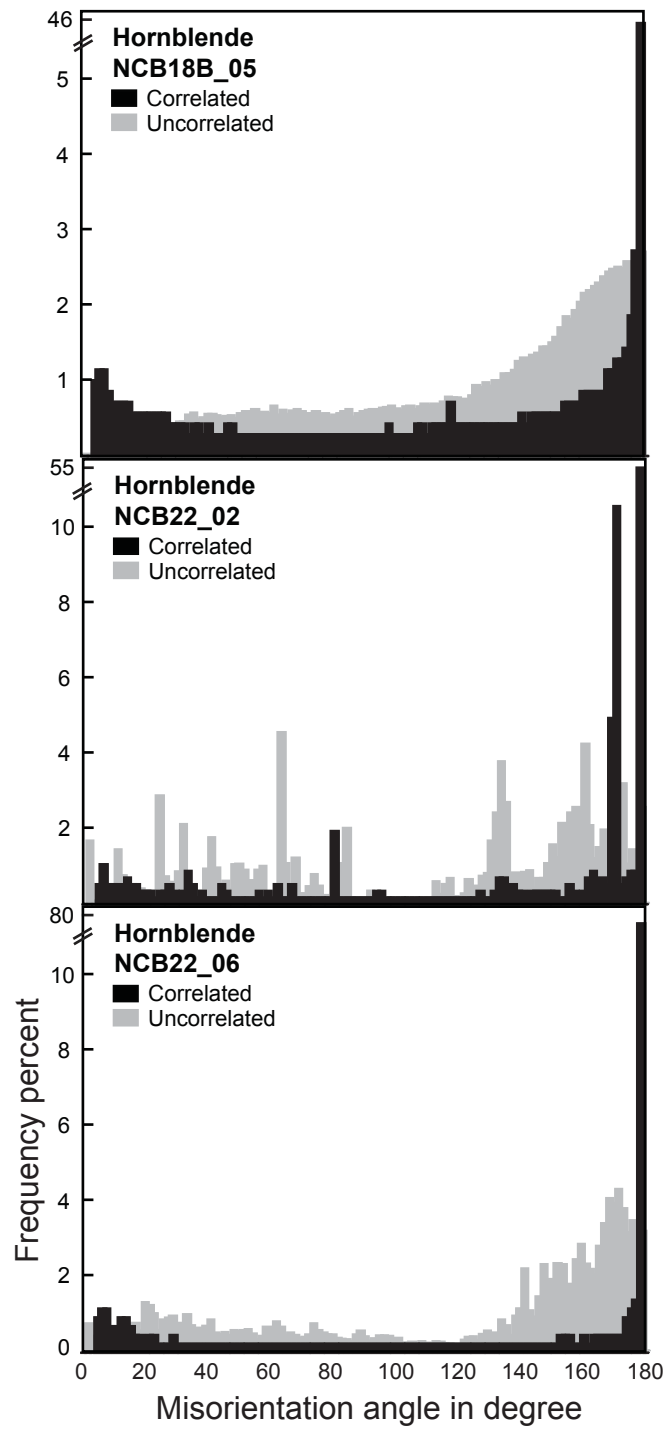


Figure F1: Grain boundary misorientation histograms of hornblende across the Dinnick Lake shear zone. Histograms show the recrystallized texture of hornblende with very few subgrains (misorientation at low angles, 5-15°).

Appendix G

Sample descriptions

Samples described here were collected over a four-year period, targeting specific areas across the greenstone belt (**Fig. 2.1B**). Samples from 2012 included a ~1 km traverse across the Dinnick Lake shear zone, which is located directly north of the Musselwhite mine. Approximately 20 samples were also acquired from a student working at the mine during the summer and represent a transect across the Akow Lake shear zone, which is also directly north of the mine and west of the Dinnick Lake shear zone. Due to outcrop availability, these were collected over a ~7 km N-S distribution, but ultimately represent a ~2 km traverse across stratigraphy. The rest of the samples were collected in the northwestern arm of the greenstone belt, targeting high T assemblages previously described by Breaks et al. (2001). In 2013, several samples were collected in the southeastern arm of the belt to complement samples previously collected by Kalbfleisch, Van Lankvelt and Duff. A few were collected from the northwestern part as well in order to have a representative spread across the whole belt. Additional sample descriptions from Kalbfleisch 2012 are included for samples used for analyses in this paper.

NCB12-10

This sample is a metaconglomerate collected near Miskeesik Lake in the northwestern most edge of the belt. Abundant biotite defines a moderate fabric that wraps around quartz and plagioclase pebbles. A few randomly oriented biotite grains are also present, suggesting another growth episode. The matrix is composed of fine-grained and pebble quartz + plagioclase. One cluster of euhedral garnets is found nested in biotite, indicating hydrothermal origin. Chlorite is a minor alteration phase replacing some biotite grains.

NCB12-11A

This sample was also collected near Miskeesik Lake in the northwestern portion of the NCGB. It is a metaconglomerate that has been intensely strained, evidenced by abundant very-fine grained recrystallized quartz. This unit displays a very weak fabric defined by radiating amphibole clusters. Minor biotite is also present, although not preferentially aligned to form a foliation.

NCB12-12

This sample was collected in the same area as previous two samples, at proximity to Miskeesik Lake in the northwestern arm of the belt. It is a metasediment comprised of pervasive white mica intergrown with chlorite in a sinuous foliation. Crenulations and S-C fabrics indicating a dominant sinistral movement are visible. High strain is evidenced by abundant very fine-grained recrystallized quartz in the matrix. Few quartz ribbons are also present. Broken and corroded staurolite porphyroblasts indicate sinistral displacement where white micas are wrapping around them.

NCB12-18

This sample is a metabasalt from the western side of the Dinnick Lake shear zone, which projects along strike to the Musselwhite mine Au deposit. It is composed of 60% hornblende, 30% plagioclase and 10% quartz, with trace micas and chlorite. Hbl in the sample define the main fabric and is found in a matrix of recrystallized quartz + plagioclase. They can be categorized into two groups; the first one consisting of larger porphyroclasts that are rounded and corroded, exhibiting undulose extinction, twinning and lower interference colors under crossed-polarized light. The other group consists of elongated to weakly radiating Hbl crystals defining the main fabric. These are less corroded and show very little undulose extinction. Most of the quartz is present in α or δ -shaped veins, indicating recrystallization product during strain.

Strong undulose extinction and many subgrains are visible. These augens, along with Hbl fish, tend to indicate a dominant sinistral shear sense, but both motion directions can be observed. Other deformation features include micro shear zones displaying localized S-C fabric defined by Hbl.

NCB12-21

This sample is similar to 18, but is slightly coarser and found on the eastern side of the shear zone. It contains 45% Hbl, 40% plag and 15% Qz, with minor chlorite. Foliation is defined by the segregation of hornblende and quartz + plagioclase bands. Distinction between the two types of Hbl is less clear in these; however we can observe coarse diamond-shaped Hbl fish that display dominant sinistral shear sense. Most Hbl grains are moderately corroded and some display weak undulose extinction. Qz is found dispersed in the plagioclase bands, and show many subgrains and undulose extinction.

NCB12-19, 20

These samples are from the core of the Dinnick Lake shear zone and exhibit L-tectonite fabrics. They display strong, shallow dipping lineations consisting of recrystallized quartz rods, which are locally folded in tight cm-scale isoclinal folds. Composition is 60% Qz, 35% K-Fsp and 5% muscovite, with accessory epidote and titanite. Quartz displays strong undulose extinction and many subgrains indicating recrystallization through crystal plastic processes. Some quartz crystals display a shape preferred orientation that is at $>45^\circ$ angle from fabric. Potassic feldspars are segregated into smaller bands between the Qz rods and are strongly sericitized. The few muscovite and biotite grains that are present are likely a product of alteration. They are very corroded and located preferentially in the Fsp bands.

JAC1

This sample is a mafic metavolcanic from the Akow Lake shear zone that consist of 70% hornblende, 25% plagioclase and 5% quartz, with minor chlorite alteration. Similarly to Dinnick Lake hornblende, these can be separated into two categories: Elongated crystals which define the fabric and coarser diamond-shape porphyroclasts, suggesting at least two growth periods. Finer, elongated grains seem to "flow" around the porphyroclasts. Porphyroclasts are in the form of fish that seem to display dominant dextral shear sense. In some areas, Hbl 'bands' seem to be boudinaged and surrounded by recrystallized Qz.

JAC5

This sample was identified by samplers as a mafic dyke, although it is very similar in appearance to the rest of mafic volcanics. It contains prismatic hornblende crystals that are fine-grained and define a moderate foliation. The matrix is composed of very fine-grained plagioclase and quartz, likely recrystallized indicating high strain.

JAC7, 11

These two samples from the Akow Lake traverse are metasedimentary units. They contain euhedral to subhedral garnet porphyroblasts in a matrix of quartz and plagioclase. A moderate fabric is defined by biotite and chlorite intergrown in sinuous bundles wrapping around porphyroblasts. Some garnets are also found in clusters nested in biotite and chlorite, suggesting a hydrothermal origin. Some alteration chlorite pods are suggesting pseudomorphic reactions after garnet replacement.

JAC15

This sample is mafic metavolcanic similar to previously described samples. It however has a few fracture-filling alteration phases such as calcite and a radiating fibrous mineral, perhaps actinolite.

13NCGB-1

This sample represents a thinly layered metasedimentary unit intercalated with thin green mafic volcanics from the northern arm of the belt. The sample contains abundant garnets (up to 1mm in size) that are peppered evenly throughout a very fine-grained matrix of quartz + plagioclase. Garnets are very corroded, fractured and contain abundant inclusions that are mostly at an oblique angle from main foliation. A moderate fabric is defined by white mica and biotite in metasedimentary portions, whereas prismatic to radiating amphiboles and chlorite define the foliation in mafic portions. Some amphiboles are also found in metasediments near contacts with metavolcanics. The main foliation is moderate and pervasive throughout, but it is primary layering that is the dominant feature.

13NCGB-3B

This sample is a coarse-grained metaconglomerate from the south portion of the belt, near the MSZ-NCT transition. It contains mostly quartz and plagioclase fine to pebble size grains. A moderate foliation, which might be controlled by primary layering or bedding, is defined by biotite and chlorite that wrap around coarser clasts. White micas are present as alteration phase and are found mostly in between quartz and plagioclase grains. Strain is evidenced by segregation of fine-grained matrix from coarse-grained domains.

13NCGB-6

This sample was collected a few km east of 3B and is a metasedimentary unit. It contains medium-grained quartz and plagioclase as a matrix, which is very uniform in size. A strong foliation is defined by biotite, white micas and chlorite. Evidence of strain can be seen with segregation of finer-grained quartz from the rest of the unit.

NCTK10-12B and 15

These samples consist of highly deformed metasediments (mica schists) from within the MSZ that contain both coarse-grained quartz ribbons and dynamically recrystallized finer-grained quartz. Plagioclase is full of inclusions and likely porphyroblastic, while white micas are aligned in the foliation. Chlorite appears to have formed as retrograde alteration as it is locally replacing biotite in NCTK10-15. White micas are dominant in both samples and segregated by grain size (coarse versus finer-grained domains). Good kinematic indicators are present at the outcrop-scale, represented by sigmoidal quartz sweats, deformed veinlets and transposed bedding that display dextral displacement. Sample NCTK10-15 bears calcite that could be remnant of diagenetic calcite or fracture-filling by hydrothermal fluids. These samples were selected for geochemistry of phyllosilicate minerals that define the regional fabric.

NCTK10-16A/B

NCTK10-16 is a staurolite-chloritoid schist situated within the MSZ and marked by tight mesoscopic folds that plunge 35° to the ENE. The limbs and hinge zones of the folds are host to quartz sweats associated with poikilitic garnets that was collected for geochemical analyses. One garnet in the thin section is at least 5 mm in diameter and full of quartz inclusions. This sample is peppered with fine-grained chlorite that defines a fairly heterogeneous foliation through a matrix of mostly fine-grained quartz. Chloritoid and staurolite porphyroblasts occur

locally. Cumulates of randomly oriented coarse-grained white mica are potential pseudomorphs after staurolite. Opaque minerals are accessory phases in this sample.

NCTK10-19

This sample is an albite schist situated within the MSZ, characterized by a weak SC-fabric and sigmoidal strain shadows cast by albite porphyroblasts that indicate dextral kinematics. Quartz is abundant and dynamically recrystallized through grain bulging migration and subgrain rotation. Apatite, rutile, monazite, and opaque minerals (ilmenite $\pm$ ilmenite) are present as accessories alongside altered plagioclase, potassic feldspar, local coarse-grained white mica, and fine-grained pervasive biotite. This sample presents potential for dating deformation in the Markop Lake deformation zone and was chosen for U-Th-total Pb age determination. Monazites are 40-70 μm -long, have diffuse boundaries, and are surrounded by a combination of allanite and clay minerals. The thin section contains a group of three monazite grains that align parallel to the foliation, and is found at the boundary between a plagioclase matrix and a foliation sub-parallel quartz ribbon.

NCTK10-20A/B

This sample is a highly strained schist situated within the MSZ at the contact with an amphibolite. It is strongly foliated through the alignment of white mica and chlorite segregated from quartz + plagioclase domains. This sample was chosen to investigate the geochemistry of phyllosilicates defining the regional fabric in a high strain zone.

NCTK10-26A/B

NCTK10-26 is situated just north of the main strand of the MSZ and constitutes a garnet-biotite schistose granule to cobble conglomerate that is highly strained, evidenced in 3:1 length to width flattening of cobbles, and metamorphism in the garnet zone (upper greenschist facies). Coarse-

grained biotite is aligned in continuous foliation planes and there is a distinct compositional segregation between more quartz + feldspar rich domains and phyllosilicate. The matrix is dominantly plagioclase and accessory phases consist of monazite, ilmenite, $\pm$ magnetite. Within this outcrop is a dilation structure filled with coarse-grained minerals that appear to have crystallized from a hydrothermal fluid, broadly undeformed and somewhat controlled by the more porous matrix surrounding abundant flattened cobbles. Euhedral garnet grains range in size from 500 μm to >5 mm and are contained mostly within nests of randomly oriented coarse-grained biotite. This sample was chosen for U-Th-total Pb dating of monazite. Monazite grains are abundant, most of which are fabric-elongate, range in size from 25 x 20 μm to 80 x 50 μm , and found either at the boundary between albite grains in the matrix or surrounded by clay minerals, and sometimes in contact with or proximity to fabric-forming biotite $\pm$ chlorite. Grains in the matrix are fairly euhedral and free of inclusions.

NCTK10-38

A sample of biotite schist is highly deformed and situated in the region of the ASZ that parallels the eastern contact of the ELS with the NRV north of Opapimiskan Lake. The level of strain is indicated by dynamically recrystallized quartz isolated with plagioclase in microlithons from penetrative SC-fabric defined by biotite and chlorite. The thin section contains three small foliation-elongate monazite grains that reside either at the boundary between quartz and plagioclase or in contact with biotite $\pm$ ilmenite and this sample contains monazite as an accessory phase which was chosen for geochronological investigation of the Akow Lake fault zone.

NCTK10-44A/B and Akow

These samples are andalusite-staurolite schists situated 4 km to the north of NCTK10-38 in the ASZ. On the outcrop scale, porphyroblastic staurolite and andalusite are localized in tightly folded bands that crosscut bedding and/or axial-planar foliation. Andalusite is poikiloblastic, containing many small inclusions of quartz, and locally books of biotite and euhedral staurolite. Biotite is the dominant phyllosilicate in this sample, followed by white mica and both define the foliation that for the most part wraps around poikiloblasts. Chlorite is very minor and slightly replacing biotite in the foliation, and rare fibrolite wraps around euhedral matrix-bound staurolite poikiloblasts. Coarser-grained quartz appear more strained and has sutured grain boundaries, and these are isolated amongst finer-grained quartz and plagioclase in the matrix. Accessory minerals in this sample include zircon, monazite, tourmaline, and opaque minerals such as ilmenite $\pm$ magnetite. Zircons are dominantly euhedral and oscillatory-zoned zircon and where the c-axis is not perpendicular to the direction of principal strain, it is often fractured and slightly displaced in the plane of foliation. Sample NCTK10-44A was selected for geochronology of monazite and is representative of amphibolite facies metamorphism within a crustal-scale deformation zone. Monazites are 30-40 μm in size, most are found in the matrix of plagioclase $\pm$ quartz, often in contact with (and more rarely embedded in) fabric forming micas (biotite $\pm$ muscovite or chlorite), and one is an inclusion in poikiloblastic andalusite.

NCTK10-51A

This sample consists of a high-strain biotite schist from the ELS at the eastern extremity in the NCT. Alignment of blocky biotite is a pervasive feature and long sinuous dextral bundles of biotite, chlorite, and muscovite weave between dynamically recrystallized microlithons of quartz and plagioclase among swarms of recovered quartz. Magnetite, ilmenite and monazite are

accessory phases in this sample. Small (~20 µm) monazite grains are situated at the junction between plagioclase grains and somewhat elongated in the direction of foliation and in contact with biotite. This sample was selected for monazite dating because it was deformed in the poorly understood North Caribou-Totogan shear zone at the most eastern extremity of the NCGB.

NCTK10-74A

This sample is a biotite schist located northwest of the MSZ, near Opapimiskan Lake. It is fine-grained, foliated and bears dynamically recrystallized quartz. Plagioclase is moderately altered by sericite. White mica is dominant in foliation planes although sometimes found at an angle oblique to the foliation. Biotite is also present in the foliation but is finer-grained and underwent some retrograde alteration by chlorite. This sample was collected near the contact with metavolcanics and as such is of interest in terms of geochemistry of fabric-forming minerals

NCTK10-75 and 76

These samples are two-mica schists from the North Caribou-Totogan shear zone and similar in terms of mineralogy and fabric. Foliation planes are defined by sinuous bundles of white mica, biotite and chlorite. Blocky micas are also found in quartz + plagioclase (sericitized) rich domains, segregated from fabric-forming phyllosilicate, in some cases constituting coarser-grained quartz ribbons. Zircon and opaques are accessory phases in both samples, whereas monazite is only found in NCTK10-76. Certain monazite grains are small (~20 µm) with fairly smooth grain boundaries and some are larger (~40-100 µm) with resorbed boundaries. One large monazite grain is oriented normal to the fabric and completely immersed in a bundle of biotite and muscovite. These samples were chosen for geochemistry of fabric-forming phyllosilicate and NCTK10-76 for monazite geochronology.

NCB11-24 and 28

These two garnet-bearing samples (biotite schist and hornblende schist) are part of the ELS, located near the NRF at the regional contact with the NRV. The rocks are highly deformed and lithological contacts and bedding planes are obvious focal points for strain. In the biotite schist (NCB11-24), fabric-elongate subhedral garnets are fractured and have been displaced along slip planes. Commonly accompanied by aggregates of smaller euhedral crystals, the garnets appear to have grown preferentially and been brittily deformed or boudinaged. The grains or fragments range in size from 1 to 3 mm. Very fine-grained biotite defined the foliation in a matrix of fine-grained quartz, and also occurs as randomly oriented grains. Blue-green needle-like amphiboles are sometimes found in regions surrounding garnet porphyroblasts. Bundles of sericite locally radiate from garnet fragments, commonly in proximity to carbonate-altered domains within shear bands. In the hornblende schist (NCB11-28), one garnet is euhedral and relatively inclusion-free. It is situated among abundant, potentially hydrothermal, coarse-grained green amphiboles within a fabric-parallel dilation crack. These samples were chosen for geochemistry of garnet.

NCB11-34

This sample is a meta-granule conglomerate near the contact of the ELS with the SRV on the southern shore of Eyapamikama Lake. The strain is localized along bedding planes and zones of lithological contrast in very coarse-grained and thick-bedded metasediments. Much finer grains in the matrix are found in tightly spaced microlithons segregated from pervasive foliation planes dominated by fine-grained micas that wrap around granules of plagioclase $\pm$ quartz. Ribbon quartz is highly strained and partially dynamically recrystallized. This sample bears abundant zircon and lesser monazite as well as allanite. This sample was chosen as it is the only sample from the northwestern arm from which a monazite age could be obtained. The monazite grains

are 50-60 μm long and only 10 μm wide, often kinked but roughly parallel to the very fine-grained foliation, and they have convoluted edges and sieve textures.

E591 479

This sample is a schist peppered with round to ellipsoid euhedral garnet porphyroblasts within a very fine-grained quartz + plagioclase matrix. Abundant phyllosilicate minerals (chlorite and biotite) define a strong foliation. The long axes of garnets roughly parallel foliation and garnets present in strain shadows are oriented more randomly with respect to principal strain. Foliation wraps around some porphyroblasts, on occasion with a sigmoidal shape. Collected from the northern bend of the NCGB, this high-strain sample contains local quartz ribbons or sweats of coarser grains that have partially recrystallized through grain boundary migrations or subgrain rotation. This sample was chosen for geochemical analysis of garnets.

Table G1: Sample locations

Sample	Easting	Northing	Sample	Easting	Northing
NCB12-10	619828	5872755	NCTK10-15	690680	5821722
NCB12-11	619814	5873147	NCTK10-16	690904	5821552
NCB12-12	620448	5872240	NCTK10-19	692153	5821302
NCB12-17	673939	5846129	NCTK10-20	692076	5821726
NCB12-18	673857	5846055	NCTK10-26	694428	5823783
NCB12-19	674233	5846078	NCTK10-38	673555	5843971
NCB12-20	674256	5846336	NCTK10-44	670289	5850342
NCB12-21	674355	5846417	NCTK10-51	312525	5819101
NCB12-22	674403	5846625	NCTK10-74	686874	5827529
JAC1	672421	5844278	NCTK10-75	306991	5820283
JAC5	672610	5844079	NCTK10-76	702814	5821120
JAC7	672973	5844106	254936	674678	5844472
JAC15	674372	5842618	254937	674711	5844214
JAC16	674264	5842723	254938	674521	5843961
JAC17	674224	5842814	438519	674891	5844343
Akow	670288	5850306	619688	673195	5845728
13NCGB-1	648708	5871865	619689	673338	5845723
13NCGB-3	300911	5820933	E438515	677700	5838363
13NCGB-6	300551	5820948	E438517	676940	5839927
NCB11-24	646720	5871092	E468976	677762	5845400
NCB11-28	638553	5871489	E468977	682256	5843192
NCB11-34	649138	5867215	E468979	681085	5839164
NCTK10-12	690491	5821669	E438520	673696	5847167

Appendix H

Methodology for major element EMPA and x-ray mapping

In situ major element EMPA of phyllosilicates and amphiboles

The JEOL JXA-8230 SuperProbe at the University of Ottawa (Ottawa, Canada) was used for *in situ* EMPA of phyllosilicates defining a moderate to strong fabric, and amphibole present in abundance in mafic metavolcanic units. Individual grain of chlorite in 21 samples, white micas in 15 samples, biotite in 14 samples and amphiboles in 6 samples were analyzed with an accelerating voltage of 15 or 20 kV and probe current of 20 nA to focus the electron beam to a minimum of 5 μm . Composition of all three phyllosilicates is plotted in ternary plots of **Fig. 2.4A** showing variability in atoms of Al, Mg, Fe and K per formula unit for each sample. EMPA results are summarized in **Appendix I1-3**.

Fabric-forming minerals include chlorite, biotite and white micas, which are present in most metasedimentary units, whereas mafic volcanic units only contain chlorite and minor biotite in the lowest metamorphic assemblages. End-member components used in white mica calculations include muscovite, paragonite, Fe-Al celadonite and pyrophyllite (Parra et al. 2002). Biotite chemistry comprises annite, phlogopite and Fe-Al celadonite end-members. Lastly, chlorite compositions were calculated using a combination of four end-members from Vidal et al. (2001). Our data as well as a compilation of data from Otto (2002), Isaac (2008), and Kalbfleisch (2012) reflects a consistent composition of muscovite, biotite and chlorite throughout the belt (**Fig. 2.4A**). Amphibole end-member calculations were done using a spreadsheet designed by Hawthorne and Oberti et al. (2012).

In situ major element EMPA of garnet

In this study, garnets in three samples from the Akow Lake region and the northwestern end of the belt (JAC7, JAC11 and NCB12-10) were analysed via *in situ* major element EMPA in order to determine their composition. Additionally, data acquired on five samples from Kalbfleisch (2012) were included (NCTK10-26B, 16B, E591 479, NCB11-24, 28). These samples represent garnet-bearing metasediments from upper greenschist to lower amphibolite metamorphic grades that display syn-tectonic

deformation textures such as cobble flattening, spatial association with fold hinges/limbs and micro-shear zones (detailed sample descriptions are available in **Appendix G**).

Garnets from six samples were analyzed *in situ* at the University of Ottawa (Ottawa, Canada) using the JEOL JXA-8230 SuperProbe. The probe is equipped with high-speed, backscatter electron detectors and 3 wavelength dispersive spectrometers (WDS), each outfitted with multiple analyzing crystals, for precise quantitative analysis of a wide range of elemental abundances. Polished thin sections (~100 µm thick) were prepared and treated with a conductive carbon coating to prevent charging during electron bombardment. During analysis, heating of a tungsten filament held at negative potential produced and accelerated electrons toward the sample. A series of magnetic electron lenses focused a 20 kV, 20 nA electron beam to a minimum resolution of 1 µm. Garnets in the other two samples were analyzed *in situ* by EMPA with a Cameca SX-100 operated by the Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology (Socorro, USA), which operates in a similar fashion, but with an accelerating voltage of 15 kV and beam current of 15 nA to focus the electron beam to a minimum of 1 µm.

Furthermore, four x-ray maps of Fe, Mg, Mn, Ca and Y were acquired on garnets of probable metamorphic origin (JAC11 and 13NCGB-1) and hydrothermal origin (alteration pod in NCTK10-26B) using the WDS as well as the energy dispersive spectrometer (EDS) of the JEOL JXA-8230 SuperProbe at the University of Ottawa (Ottawa, Canada). An accelerating voltage of 20 kV and a beam current of 200 nA combined with a spot size of 1 µm to produce maps, each with a 20 µm pixel size and 200 ms dwell time on each pixel. Two garnets from NCTK10-26B produced a 400 X 400 pixel and 500 X 500 pixel maps, whereas JAC11 and 13NCGB-1 produced a 950 X 950 pixel and 600 X 600 pixel maps respectively.

Results of *in situ* EMPA major elements are summarized in **Table I4** as wt% oxide, atom per formula units and end-member % for each of the eight samples. Data from samples NCTK10-26B, 16B, E591 479, NCB11-24 and 28 are reported for core, mean and rim analyses for individual garnet, whereas JAC7, JAC11 and NCB12-10 are reported as minimum, mean and maximum of all analyzed garnets in

the sample. Mean values for rims and cores were also included for JAC7 and JAC11. These were averaged from few single spots near rims and cores of several garnets. Relative end-member compositions as well as x-ray maps were compiled in **Fig. IC-5** (along with currently available data from Otto 2002 and Duff 2014).

Appendix I

Major element EMPA of biotite, white mica, chlorite, amphibole and garnet

Table I1: Major element EMPA of biotite

	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Wt%	JAC7 (n: 58)			JAC11 (n: 37)			JAC15 (n:8)			NCB12-10 (n:46)		
SiO ₂	31.035	35.269	39.737	26.692	34.830	35.787	35.524	35.912	36.567	35.304	36.783	37.442
TiO ₂	0.741	1.776	2.686	1.229	1.714	2.192	1.320	1.408	1.531	1.053	1.449	1.799
Al ₂ O ₃	17.299	18.526	21.460	17.165	17.965	19.245	16.763	16.949	17.146	16.844	17.877	18.341
FeOT	15.997	18.408	20.089	17.857	20.330	21.788	18.267	18.671	19.329	14.366	14.968	17.082
MnO	0.015	0.070	0.139	0.000	0.009	0.035	0.049	0.063	0.082	0.073	0.113	0.152
MgO	7.210	10.038	11.299	6.467	9.039	9.593	10.934	11.574	12.251	12.796	13.312	13.666
CaO	0.004	0.083	0.461	0.000	0.049	0.250	0.041	0.072	0.153	0.003	0.044	0.193
Na ₂ O	0.092	0.175	0.420	0.092	0.148	0.331	0.051	0.085	0.114	0.204	0.286	0.358
K ₂ O	7.141	9.109	9.489	7.976	8.944	9.278	8.286	8.659	9.082	7.765	8.566	8.882
F	0.000	0.076	0.238	0.000	0.037	0.194	0.000	0.034	0.108	0.000	0.115	0.291
Cl	0.006	0.016	0.033	0.000	0.006	0.016	0.087	0.097	0.104	0.002	0.012	0.018
Total	90.318	93.546	95.426	79.680	93.072	95.025	92.962	93.524	94.339	90.661	93.525	94.565
Ions on the basis of 22 positive charges												
Si	2.503	2.723	2.977	2.483	2.728	2.780	2.748	2.772	2.802	2.710	2.779	2.804
Ti	0.044	0.103	0.163	0.072	0.101	0.126	0.077	0.082	0.089	0.060	0.082	0.102
Al	1.545	1.686	2.039	1.581	1.660	1.993	1.510	1.542	1.563	1.547	1.592	1.630
Fe	1.002	1.189	1.310	1.150	1.333	1.436	1.170	1.205	1.253	0.908	0.946	1.097
Mn	0.001	0.005	0.009	0.000	0.001	0.003	0.003	0.004	0.005	0.005	0.007	0.010
Mg	0.867	1.155	1.305	0.897	1.055	1.113	1.264	1.332	1.393	1.455	1.499	1.541
Ca	0.000	0.007	0.037	0.000	0.004	0.021	0.003	0.006	0.013	0.000	0.004	0.016
Na	0.013	0.026	0.061	0.014	0.023	0.049	0.008	0.013	0.017	0.030	0.042	0.052
K	0.706	0.897	0.936	0.795	0.894	1.000	0.818	0.853	0.888	0.760	0.825	0.852
F	7.547	7.792	7.845	7.688	7.799	7.924	7.786	7.808	7.827	7.748	7.776	7.798
Cl	0.000	0.018	0.057	0.000	0.009	0.048	0.000	0.008	0.026	0.000	0.027	0.069
Cation site distribution												
Si	2.503	2.723	2.977	2.483	2.728	2.780	2.748	2.772	2.802	2.710	2.779	2.804
Ti	0.044	0.103	0.163	0.072	0.101	0.126	0.077	0.082	0.089	0.060	0.082	0.102
Al(IV)	0.932	1.174	1.334	1.107	1.171	1.407	1.114	1.146	1.174	1.103	1.139	1.207
Al(VI)	0.423	0.513	0.705	0.447	0.490	0.592	0.375	0.396	0.416	0.409	0.453	0.481
Mg(M2)	0.529	0.731	0.791	0.551	0.667	0.698	0.798	0.840	0.875	0.908	0.944	0.975
Fe(M2)	0.655	0.752	0.827	0.728	0.843	0.906	0.745	0.760	0.791	0.574	0.595	0.673
(M2)	1.291	1.483	1.573	1.408	1.510	1.551	1.581	1.600	1.620	1.510	1.540	1.581
Mn(M2)	0.001	0.005	0.009	0.000	0.001	0.003	0.003	0.004	0.005	0.005	0.007	0.010
Mg(M1)	0.337	0.425	0.524	0.346	0.388	0.418	0.466	0.492	0.518	0.533	0.555	0.585
Fe(M1)	0.348	0.437	0.495	0.422	0.490	0.545	0.423	0.445	0.463	0.333	0.350	0.424
v(M1)	-0.013	0.138	0.265	0.037	0.122	0.185	0.037	0.063	0.106	0.005	0.095	0.124
K(A)	0.706	0.897	0.936	0.795	0.894	1.000	0.818	0.853	0.888	0.760	0.825	0.852
Na(A)	0.013	0.026	0.061	0.014	0.023	0.049	0.008	0.013	0.017	0.030	0.042	0.052
v(A)	0.039	0.076	0.273	-0.027	0.083	0.186	0.099	0.135	0.168	0.100	0.133	0.201
End-member composition												
Fe-Al-celadonite	24%	33%	54%	25%	33%	41%	23%	25%	28%	20%	23%	25%
Annite	19%	35%	49%	33%	45%	59%	29%	32%	36%	14%	15%	23%
Phlogopite	16%	32%	41%	15%	22%	28%	37%	43%	47%	57%	62%	64%

Table 11: Major element EMPA of biotite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCB12-11A (n:11)			NCB12-19 (n:79)			NCB12-20 (n:43)		
SiO ₂	36.327	37.109	37.686	34.478	35.388	36.165	32.676	35.062	42.670
TiO ₂	0.922	1.933	2.295	1.306	1.997	2.851	1.765	2.510	3.406
Al ₂ O ₃	15.630	16.048	16.418	16.300	16.873	17.470	15.524	16.579	17.241
FeOT	13.997	14.727	15.462	19.905	21.047	22.016	20.634	22.621	26.187
MnO	0.124	0.155	0.201	0.273	0.315	0.524	0.289	0.406	0.537
MgO	12.218	13.230	14.050	7.669	8.292	8.965	6.280	6.995	8.458
CaO	0.000	0.000	0.000	0.000	0.120	0.723	0.000	0.069	0.498
Na ₂ O	0.034	0.104	0.277	0.014	0.050	0.294	0.000	0.044	0.465
K ₂ O	8.997	9.332	9.526	7.201	9.384	9.963	6.837	9.173	9.788
F	0.140	0.271	0.405	0.022	0.169	0.612	0.117	0.308	0.545
Cl	0.025	0.036	0.051	0.020	0.035	0.065	0.005	0.015	0.033
Total	92.408	92.944	93.280	91.672	93.670	94.892	92.041	93.782	98.366
Ions on the basis of 22 positive charges									
Si	2.805	2.840	2.887	2.748	2.781	2.851	2.655	2.776	3.115
Ti	0.053	0.111	0.132	0.077	0.118	0.168	0.103	0.150	0.205
Al	1.408	1.448	1.483	1.510	1.562	1.611	1.346	1.548	1.601
Fe	0.897	0.943	0.992	1.302	1.383	1.462	1.292	1.499	1.779
Mn	0.008	0.010	0.013	0.018	0.021	0.035	0.019	0.027	0.037
Mg	1.395	1.510	1.601	0.898	0.971	1.048	0.747	0.827	1.025
Ca	0.000	0.000	0.000	0.000	0.010	0.061	0.000	0.006	0.042
Na	0.005	0.015	0.041	0.002	0.008	0.044	0.000	0.007	0.070
K	0.873	0.911	0.929	0.719	0.940	1.000	0.709	0.927	0.995
F	7.746	7.788	7.832	7.664	7.794	7.854	7.485	7.767	7.832
Cl	0.034	0.066	0.099	0.006	0.042	0.152	0.029	0.077	0.137
Cation site distribution									
Si	2.805	2.840	2.887	2.748	2.781	2.851	2.655	2.776	3.115
Ti	0.053	0.111	0.132	0.077	0.118	0.168	0.103	0.150	0.205
Al(IV)	1.008	1.048	1.121	1.044	1.101	1.162	0.747	1.074	1.227
Al(VI)	0.362	0.399	0.454	0.417	0.461	0.495	0.272	0.474	0.603
Mg(M2)	0.916	0.979	1.027	0.590	0.626	0.671	0.485	0.533	0.618
Fe(M2)	0.586	0.612	0.642	0.846	0.892	0.938	0.872	0.966	1.073
(M2)	1.533	1.591	1.630	1.487	1.518	1.563	1.374	1.499	1.692
Mn(M2)	0.008	0.010	0.013	0.018	0.021	0.035	0.019	0.027	0.037
Mg(M1)	0.479	0.530	0.581	0.307	0.345	0.381	0.243	0.294	0.406
Fe(M1)	0.311	0.331	0.350	0.454	0.491	0.547	0.420	0.533	0.706
v(M1)	0.073	0.139	0.197	0.094	0.164	0.218	-0.112	0.173	0.337
K(A)	0.873	0.911	0.929	0.719	0.940	1.000	0.709	0.927	0.995
Na(A)	0.005	0.015	0.041	0.002	0.008	0.044	0.000	0.007	0.070
v(A)	0.052	0.073	0.113	-0.009	0.052	0.269	-0.003	0.066	0.291
End-member composition									
Fe-Al-celadonite	18%	24%	32%	31%	36%	40%	14%	36%	67%
Annite	13%	15%	18%	43%	48%	53%	28%	54%	72%
Phlogopite	52%	61%	67%	13%	17%	21%	5%	9%	14%

Table II: Major element EMPA of biotite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-12B (n: 5)			NCTK10-20A (N: 25)			NCTK10-26A (N: 26)		
SiO ₂	34.44	35.49	36.84	29.97	36.05	36.87	35.29	35.96	36.36
TiO ₂	0.84	1.68	2.22	1.42	1.77	4.63	1.04	1.58	2.07
Al ₂ O ₃	18.19	18.69	18.94	16.29	18.97	19.47	18.74	19.41	20.03
FeO _T	18.16	19.06	20.04	9.77	15.78	17.62	16.31	17.29	18.19
MnO	0.23	0.31	0.40	0.13	0.18	0.27	0.13	0.23	0.32
MgO	10.44	11.02	11.52	10.22	11.70	12.15	10.99	11.33	11.87
CaO	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na ₂ O	0.04	0.05	0.07	0.05	0.12	0.22	0.21	0.29	0.39
K ₂ O	5.24	7.94	9.48	6.69	9.31	9.79	8.43	8.83	9.17
F	0.15	0.20	0.25	0.20	0.27	0.39	0.16	0.24	0.34
Cl	0.02	0.02	0.03	0.01	0.01	0.02	BDL	0.01	0.03
Total	92.45	93.94	95.09	77.74	93.40	95.38	92.93	94.46	95.24
Ions on the basis of 22 positive charges									
Si	2.657	2.706	2.813	2.647	2.732	2.760	2.679	2.708	2.737
Ti	0.048	0.096	0.127	0.081	0.102	0.310	0.059	0.090	0.118
Al	1.637	1.679	1.705	1.666	1.695	1.774	1.675	1.722	1.769
Fe	1.146	1.216	1.279	0.726	0.998	1.104	1.022	1.089	1.145
Mn	0.015	0.020	0.026	0.008	0.011	0.020	0.008	0.015	0.020
Mg	1.181	1.252	1.325	1.266	1.322	1.400	1.239	1.272	1.332
Ca	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na	0.006	0.007	0.010	0.008	0.017	0.032	0.031	0.042	0.057
K	0.510	0.772	0.918	0.758	0.899	0.932	0.816	0.848	0.876
F	0.035	0.049	0.062	0.047	0.066	0.111	0.039	0.057	0.081
Cl	0.002	0.003	0.004	0.001	0.002	0.003	BDL	0.001	0.004
Cation site distribution									
Si	2.657	2.706	2.813	2.647	2.732	2.760	2.679	2.708	2.737
Ti	0.048	0.096	0.127	0.081	0.102	0.310	0.059	0.090	0.118
Al(IV)	1.139	1.198	1.275	1.025	1.166	1.270	1.172	1.202	1.232
Al(VI)	0.423	0.481	0.508	0.489	0.529	0.682	0.489	0.520	0.555
Mg(M2)	0.735	0.761	0.792	0.797	0.832	0.850	0.772	0.789	0.825
Fe(M2)	0.714	0.738	0.764	0.453	0.628	0.695	0.635	0.676	0.705
Mn(M2)	0.015	0.020	0.026	0.008	0.011	0.020	0.008	0.015	0.020
Mg(M1)	0.438	0.491	0.533	0.469	0.490	0.556	0.464	0.483	0.508
Fe(M1)	0.432	0.477	0.535	0.273	0.370	0.422	0.387	0.413	0.440
v(M1)	0.000	0.053	0.128	0.023	0.140	0.217	0.053	0.104	0.129
K(A)	0.510	0.772	0.918	0.758	0.899	0.932	0.816	0.848	0.876
Na(A)	0.006	0.007	0.010	0.008	0.017	0.032	0.031	0.042	0.057
v(A)	0.075	0.221	0.484	0.046	0.084	0.223	0.081	0.110	0.151
End-member composition									
Fe-Al-cel	20.79%	27.90%	31.91%	22.43%	29.95%	32.30%	25.79%	29.71%	31.83%
Annite	30.66%	34.40%	37.53%	9.04%	21.18%	28.00%	23.17%	27.12%	30.90%
Phlogopite	33.70%	37.69%	41.68%	42.29%	48.87%	58.66%	39.84%	43.17%	49.36%

Table II: Major element EMPA of biotite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-51A (n: 18)			NCTK10-74A (n: 4)			NCTK10-75 (n: 26)		
SiO ₂	34.33	35.64	36.21	35.44	36.14	37.19	33.48	34.85	37.66
TiO ₂	1.51	1.72	1.87	0.49	1.28	2.22	1.74	2.04	2.46
Al ₂ O ₃	18.59	19.07	19.40	19.24	19.62	20.13	17.76	18.49	19.23
FeO _T	17.50	18.22	19.63	12.77	14.83	15.86	19.74	21.11	22.53
MnO	0.24	0.27	0.33	0.39	0.42	0.44	0.18	0.23	0.27
MgO	10.49	10.72	11.04	12.46	13.62	14.68	7.44	8.58	8.99
CaO	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na ₂ O	0.03	0.09	0.18	0.04	0.06	0.08	0.03	0.12	1.06
K ₂ O	8.52	9.66	10.07	7.58	8.51	9.35	8.16	9.14	9.87
F	0.06	0.13	0.20	0.03	0.09	0.22	0.01	0.10	0.16
Cl	BDL	0.01	0.02	0.01	0.02	0.04	BDL	0.01	0.06
Total	93.27	94.81	95.71	93.33	94.06	94.91	91.20	94.05	96.85
Ions on the basis of 22 positive charges									
Si	2.639	2.699	2.721	2.672	2.696	2.734	2.643	2.699	2.805
Ti	0.088	0.098	0.106	0.027	0.072	0.124	0.102	0.119	0.145
Al	1.661	1.702	1.729	1.687	1.725	1.743	1.643	1.687	1.720
Fe	1.106	1.154	1.262	0.785	0.926	1.000	1.280	1.367	1.459
Mn	0.015	0.017	0.021	0.025	0.027	0.028	0.012	0.015	0.018
Mg	1.183	1.210	1.261	1.382	1.514	1.608	0.827	0.991	1.035
Ca	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na	0.004	0.014	0.026	0.006	0.009	0.012	0.005	0.017	0.153
K	0.839	0.933	0.971	0.729	0.809	0.877	0.807	0.903	0.969
F	0.014	0.032	0.049	0.006	0.020	0.051	0.002	0.024	0.039
Cl	BDL	0.001	0.002	BDL	0.001	0.001	BDL	0.002	0.008
Cation site distribution									
Si	2.639	2.699	2.721	2.672	2.696	2.734	2.643	2.699	2.805
Ti	0.088	0.098	0.106	0.027	0.072	0.124	0.102	0.119	0.145
Al(IV)	1.182	1.203	1.270	1.172	1.232	1.260	1.076	1.182	1.249
Al(VI)	0.438	0.498	0.539	0.474	0.493	0.514	0.432	0.505	0.612
Mg(M2)	0.747	0.760	0.778	0.860	0.919	0.987	0.536	0.622	0.651
Fe(M2)	0.699	0.725	0.772	0.481	0.562	0.599	0.798	0.858	0.917
Mn(M2)	0.015	0.017	0.021	0.025	0.027	0.028	0.012	0.015	0.018
Mg(M1)	0.436	0.450	0.490	0.522	0.596	0.622	0.290	0.369	0.399
Fe(M1)	0.408	0.429	0.490	0.303	0.364	0.406	0.452	0.509	0.545
v(M1)	0.020	0.121	0.157	0.000	0.048	0.115	0.071	0.122	0.258
K(A)	0.839	0.933	0.971	0.729	0.809	0.877	0.807	0.903	0.969
Na(A)	0.004	0.014	0.026	0.006	0.009	0.012	0.005	0.017	0.153
v(A)	0.021	0.053	0.157	0.112	0.181	0.264	0.015	0.080	0.179
End-member composition									
Fe-Al-cel	22.60%	30.22%	33.53%	17.56%	20.28%	26.37%	25.10%	33.16%	48.92%
Annite	29.92%	32.43%	38.74%	8.58%	15.20%	18.60%	39.70%	48.34%	55.56%
Phlogopite	35.43%	37.35%	40.14%	55.02%	64.53%	73.86%	10.67%	18.50%	21.38%

Table I1: Major element EMPA of biotite

	min	mean	max
Wt%	NCTK10-76 (n: 17)		
SiO ₂	34.89	35.52	36.69
TiO ₂	1.71	2.09	2.64
Al ₂ O ₃	17.57	18.15	18.81
FeO _T	18.61	19.48	20.18
MnO	0.20	0.25	0.31
MgO	9.16	9.82	10.44
CaO	BDL	BDL	BDL
Na ₂ O	0.01	0.05	0.10
K ₂ O	8.90	9.54	9.87
F	BDL	0.07	0.13
Cl	BDL	0.01	0.07
Total	93.07	94.29	94.97
Ions on the basis of 22+ charges			
Si	2.693	2.722	2.772
Ti	0.099	0.121	0.153
Al	1.589	1.639	1.688
Fe	1.187	1.249	1.298
Mn	0.013	0.016	0.020
Mg	1.048	1.122	1.199
Ca	BDL	BDL	BDL
Na	0.001	0.007	0.014
K	0.874	0.933	0.962
F	BDL	0.017	0.030
Cl	BDL	0.001	0.009
Cation site distribution			
Si	2.693	2.722	2.772
Ti	0.099	0.121	0.153
Al(IV)	1.118	1.157	1.199
Al(VI)	0.435	0.482	0.526
Mg(M2)	0.671	0.711	0.745
Fe(M2)	0.748	0.791	0.818
Mn(M2)	0.013	0.016	0.020
Mg(M1)	0.377	0.411	0.454
Fe(M1)	0.430	0.457	0.480
v(M1)	0.069	0.132	0.165
K(A)	0.874	0.933	0.962
Na(A)	0.001	0.007	0.014
v(A)	0.030	0.060	0.119
End-member composition			
Fe-Al-cel	27.55%	32.48%	37.36%
Annite	34.23%	39.10%	42.41%
Phlogopite	22.93%	28.43%	33.53%

BDL: below detection limit.

Table I2: Major element EMPA of white mica

	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-44A (n: 21)			NCTK10-44B (n: 18)			13-NCGB-6 (n: 21)			13-NCGB-3B (n: 19)		
SiO ₂	45.054	46.064	46.428	42.383	45.503	46.083	43.730	45.095	46.482	37.278	44.825	45.728
TiO ₂	0.305	0.455	0.564	0.135	0.348	0.700	0.268	0.320	0.421	0.230	0.323	0.439
Al ₂ O ₃	34.838	35.803	36.344	34.752	35.746	36.205	31.466	33.752	35.106	29.865	33.429	34.327
FeOT	0.677	0.865	2.005	0.565	0.916	3.992	2.178	2.758	5.007	2.371	3.222	12.455
MnO	0.000	0.009	0.046	0.000	0.011	0.050	0.000	0.027	0.173	0.000	0.027	0.194
MgO	0.451	0.562	0.866	0.441	0.684	3.022	0.484	0.633	0.935	0.516	0.925	5.007
CaO	0.000	0.014	0.037	0.000	0.015	0.034	0.000	0.012	0.028	0.000	0.007	0.021
Na ₂ O	0.941	1.291	1.477	1.020	1.225	1.398	0.401	0.553	0.731	0.321	0.465	0.577
K ₂ O	7.841	8.991	9.331	7.361	8.913	9.403	9.374	10.164	10.353	6.173	10.114	10.697
F	0.000	0.049	0.191	0.000	0.046	0.118	0.000	0.053	0.142	0.000	0.041	0.125
Cl	0.000	0.002	0.009	0.000	0.008	0.131	0.000	0.003	0.019	0.000	0.002	0.006
Total	92.093	94.106	94.803	92.344	93.415	94.188	91.310	93.371	94.197	91.624	93.381	94.220
Ions on the basis of 22 positive charges												
Si	3.056	3.077	3.101	2.907	3.063	3.094	3.037	3.088	3.166	2.734	3.076	3.125
Ti	0.015	0.023	0.028	0.007	0.018	0.036	0.014	0.016	0.022	0.013	0.017	0.023
Al	2.779	2.818	2.850	2.791	2.836	2.873	2.574	2.723	2.811	2.581	2.704	2.767
Fe	0.038	0.048	0.114	0.032	0.052	0.229	0.124	0.158	0.296	0.136	0.187	0.764
Mn	0.000	0.001	0.003	0.000	0.001	0.003	0.000	0.002	0.010	0.000	0.002	0.012
Mg	0.045	0.056	0.088	0.044	0.069	0.309	0.049	0.065	0.099	0.053	0.096	0.547
Ca	0.000	0.001	0.003	0.000	0.001	0.002	0.000	0.001	0.002	0.000	0.001	0.002
Na	0.124	0.167	0.191	0.133	0.160	0.182	0.054	0.073	0.097	0.045	0.062	0.076
K	0.682	0.766	0.790	0.644	0.765	0.808	0.846	0.888	0.908	0.577	0.885	0.928
F	6.907	6.957	6.978	6.905	6.964	7.068	6.998	7.014	7.033	6.972	7.029	7.274
Cl	0.000	0.010	0.040	0.000	0.010	0.025	0.000	0.011	0.031	0.000	0.009	0.027
Cation site distribution												
Si	3.056	3.077	3.101	2.907	3.063	3.094	3.037	3.088	3.166	2.734	3.076	3.125
Ti	0.015	0.023	0.028	0.007	0.018	0.036	0.014	0.016	0.022	0.013	0.017	0.023
Al(IV)	0.873	0.900	0.923	0.888	0.919	1.076	0.820	0.896	0.946	0.855	0.907	1.253
Al(VI)	1.896	1.918	1.932	1.733	1.916	1.944	1.731	1.828	1.865	1.328	1.797	1.849
Mg(M2)	0.034	0.044	0.051	0.031	0.048	0.152	0.035	0.050	0.074	0.040	0.067	0.276
Fe(M2)	0.030	0.037	0.059	0.024	0.035	0.112	0.098	0.121	0.200	0.106	0.135	0.385
(M2)	0.068	0.081	0.104	0.056	0.083	0.264	0.133	0.171	0.267	0.150	0.202	0.660
Mn(M2)	0.000	0.001	0.003	0.000	0.001	0.003	0.000	0.002	0.010	0.000	0.002	0.012
Mg(M1)	0.005	0.012	0.043	0.006	0.021	0.157	0.010	0.015	0.032	0.011	0.029	0.272
Fe(M1)	0.005	0.011	0.055	0.005	0.016	0.117	0.026	0.037	0.096	0.026	0.052	0.379
v(M1)	0.902	0.977	0.990	0.726	0.962	0.989	0.872	0.948	0.963	0.349	0.918	0.963
K(A)	0.682	0.766	0.790	0.644	0.765	0.808	0.846	0.888	0.908	0.577	0.885	0.928
Na(A)	0.124	0.167	0.191	0.133	0.160	0.182	0.054	0.073	0.097	0.045	0.062	0.076
v(A)	0.036	0.067	0.193	0.042	0.075	0.206	0.018	0.039	0.099	0.013	0.054	0.377
End-member composition												
Muscovite	76%	79%	81%	73%	79%	82%	79%	85%	86%	60%	84%	87%
Paragonite	14%	17%	19%	14%	17%	19%	5%	7%	9%	4%	6%	7%
Fe-Al-celadonite	1%	2%	3%	1%	2%	5%	5%	7%	13%	6%	9%	29%
Pyrophyllite	1%	2%	6%	1%	2%	5%	1%	1%	3%	0%	1%	6%

Table I2: Major element EMPA of white mica

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCB12-12 (n: 24)			NCTK10-16B (n: 27)			NCB12-19 (n: 9)		
SiO ₂	45.768	46.658	47.695	22.413	44.632	46.642	45.336	46.717	47.869
TiO ₂	0.212	0.354	0.487	0.077	0.196	0.293	0.267	0.453	0.621
Al ₂ O ₃	35.111	36.273	37.697	21.836	34.992	36.266	29.454	30.223	30.823
FeOT	0.761	1.135	2.289	1.645	3.177	35.574	4.834	5.291	6.131
MnO	0.000	0.009	0.028	0.000	0.008	0.083	0.011	0.040	0.062
MgO	0.352	0.480	0.595	0.316	0.653	6.306	1.409	1.655	1.942
CaO	0.000	0.020	0.053	0.000	0.048	0.498	0.000	0.006	0.026
Na ₂ O	0.743	0.811	1.027	0.000	0.615	0.713	0.117	0.143	0.176
K ₂ O	9.557	9.903	10.078	0.000	9.409	9.876	10.859	10.953	11.084
F	0.000	0.078	0.178	0.000	0.128	0.242	0.000	0.060	0.124
Cl	0.000	0.003	0.012	0.000	0.002	0.017	0.000	0.002	0.008
Total	94.586	95.724	96.789	86.295	93.860	95.068	94.223	95.541	96.521

Ions on the basis of 22 positive charges

Si	3.016	3.078	3.120	2.008	3.027	3.109	3.138	3.180	3.222
Ti	0.011	0.018	0.024	0.005	0.010	0.015	0.014	0.023	0.032
Al	2.761	2.820	2.915	2.306	2.801	2.870	2.379	2.425	2.465
Fe	0.042	0.063	0.128	0.092	0.204	2.665	0.271	0.301	0.353
Mn	0.000	0.001	0.002	0.000	0.001	0.006	0.001	0.002	0.004
Mg	0.034	0.047	0.059	0.031	0.073	0.842	0.145	0.168	0.199
Ca	0.000	0.001	0.004	0.000	0.003	0.036	0.000	0.000	0.002
Na	0.094	0.104	0.134	0.000	0.080	0.092	0.016	0.019	0.024
K	0.813	0.833	0.850	0.000	0.809	0.857	0.936	0.951	0.973
F	6.945	6.964	7.001	6.945	7.008	7.834	7.043	7.070	7.116
Cl	0.000	0.016	0.037	0.000	0.027	0.052	0.000	0.013	0.027

Cation site distribution

Si	3.016	3.078	3.120	2.008	3.027	3.109	3.138	3.180	3.222
Ti	0.011	0.018	0.024	0.005	0.010	0.015	0.014	0.023	0.032
Al(IV)	0.866	0.905	0.970	0.880	0.963	1.986	0.764	0.797	0.829
Al(VI)	1.866	1.915	1.945	0.319	1.837	1.912	1.578	1.628	1.653
Mg(M2)	0.027	0.037	0.050	0.021	0.044	0.402	0.113	0.133	0.160
Fe(M2)	0.027	0.048	0.090	0.063	0.118	1.272	0.217	0.238	0.272
(M2)	0.055	0.085	0.133	0.087	0.162	1.674	0.345	0.370	0.418
Mn(M2)	0.000	0.001	0.002	0.000	0.001	0.006	0.001	0.002	0.004
Mg(M1)	0.005	0.011	0.023	0.006	0.030	0.440	0.028	0.035	0.043
Fe(M1)	0.004	0.015	0.039	0.012	0.085	1.393	0.054	0.064	0.081
v(M1)	0.946	0.975	0.991	-0.834	0.885	0.982	0.876	0.901	0.918
K(A)	0.813	0.833	0.850	0.000	0.809	0.857	0.936	0.951	0.973
Na(A)	0.094	0.104	0.134	0.000	0.080	0.092	0.016	0.019	0.024
v(A)	0.046	0.063	0.086	0.059	0.111	1.000	0.008	0.030	0.045

End-member composition

Muscovite	81%	85%	86%	0%	82%	87%	77%	79%	80%
Paragonite	10%	11%	13%	0%	8%	9%	1%	2%	2%
Fe-Al-celadonite	1%	3%	5%	0%	4%	5%	17%	19%	21%
Pyrophyllite	1%	2%	3%	2%	6%	100%	0%	1%	1%

Table I2: Major element EMPA of white mica

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-12B (n: 36)			NCTK10-15 (n: 31)			NCTK10-16A (n: 23)		
SiO ₂	42.46	45.21	46.70	44.65	46.97	49.02	41.71	45.64	47.04
TiO ₂	0.26	0.40	2.28	0.33	0.90	1.88	0.13	0.23	0.34
Al ₂ O ₃	31.08	34.11	35.51	31.33	33.09	34.51	33.87	35.88	37.03
Al ₂ O ₃	2.00	3.21	8.15	1.54	1.92	4.38	1.26	1.98	7.54
FeO _T	BDL	0.02	0.08	BDL	0.19	1.92	BDL	0.01	0.05
MgO	0.47	0.77	1.89	0.96	1.43	2.52	0.25	0.40	1.38
CaO	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na ₂ O	0.27	0.53	0.68	0.20	0.26	0.33	0.58	0.83	1.15
K ₂ O	9.32	10.09	10.60	9.62	10.61	11.08	8.23	9.42	10.01
F	BDL	0.03	0.10	BDL	0.07	0.16	0.06	0.14	0.31
Cl	BDL	0.01	0.07	BDL	0.00	0.02	BDL	0.00	0.02
Total	91.40	94.38	95.38	93.68	95.44	96.34	92.95	94.54	95.79
Ions on the basis of 22 positive charges									
Si	2.952	3.067	3.152	3.022	3.137	3.228	2.907	3.058	3.125
Ti	0.013	0.020	0.117	0.017	0.045	0.094	0.006	0.012	0.017
Al	2.550	2.727	2.860	2.483	2.604	2.701	2.761	2.834	2.937
Fe	0.111	0.183	0.474	0.085	0.107	0.248	0.072	0.112	0.440
Mn	BDL	0.001	0.005	BDL	0.011	0.110	BDL	0.001	0.003
Mg	0.047	0.079	0.196	0.095	0.143	0.255	0.025	0.040	0.143
Ca	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Na	0.036	0.070	0.091	0.026	0.033	0.042	0.078	0.108	0.149
K	0.821	0.873	0.910	0.830	0.904	0.953	0.732	0.805	0.855
F	BDL	0.006	0.021	BDL	0.015	0.034	0.000	0.000	0.000
Cl	BDL	0.001	0.008	BDL	0.000	0.002	BDL	0.000	0.000
Cation site distribution									
Si	2.952	3.067	3.152	3.022	3.137	3.228	2.907	3.058	3.125
Ti	0.013	0.020	0.117	0.017	0.045	0.094	0.006	0.012	0.017
Al(IV)	0.848	0.932	1.048	0.772	0.862	0.978	0.875	0.941	1.082
Al(VI)	1.560	1.795	1.870	1.630	1.743	1.824	1.700	1.893	1.942
Mg(M2)	0.031	0.056	0.135	0.073	0.116	0.159	0.014	0.025	0.073
Fe(M2)	0.082	0.129	0.295	0.059	0.087	0.155	0.034	0.070	0.224
Mn(M2)	0.000	0.001	0.005	0.000	0.011	0.110	0.000	0.001	0.003
Mg(M1)	0.009	0.023	0.067	0.010	0.027	0.096	0.007	0.015	0.070
Fe(M1)	0.023	0.054	0.179	0.007	0.021	0.093	0.020	0.042	0.216
v(M1)	0.754	0.923	0.966	0.811	0.953	0.983	0.714	0.944	0.972
K(A)	0.821	0.873	0.910	0.830	0.904	0.953	0.732	0.805	0.855
Na(A)	0.036	0.070	0.091	0.026	0.033	0.042	0.078	0.108	0.149
v(A)	0.011	0.057	0.113	0.017	0.063	0.136	0.047	0.086	0.190
End-member composition									
Muscovite	75.18%	84.12%	87.34%	82.99%	88.56%	91.78%	75.98%	82.70%	85.65%
Paragonite	3.31%	6.74%	9.20%	2.48%	3.25%	4.24%	8.14%	11.12%	15.49%
Fe-Celadonite	4.24%	7.57%	17.14%	4.06%	6.12%	10.15%	1.56%	3.69%	11.75%
Pyrophyllite	0.29%	1.56%	2.98%	0.51%	2.07%	3.90%	1.29%	2.48%	4.13%

Table I2: Major element EMPA of white mica

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-20A (n: 28)			NCTK10-51A (n: 23)			NCTK10-74A (n: 17)		
SiO ₂	44.00	46.39	47.71	44.29	45.39	46.17	44.41	47.09	49.65
TiO ₂	0.43	0.49	0.62	0.33	0.40	0.57	0.11	0.65	2.02
Al ₂ O ₃	33.74	35.06	35.93	32.86	35.22	36.15	27.77	33.34	35.27
FeO _T	0.90	1.47	3.50	1.27	1.90	3.69	0.99	1.83	4.83
MnO	BDL	0.02	0.04	BDL	0.02	0.04	0.00	0.03	0.11
MgO	0.71	1.08	2.78	0.39	0.75	1.54	1.06	1.93	5.77
CaO	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.04	0.63
Na ₂ O	0.49	0.59	0.84	0.47	0.70	0.96	0.05	0.22	0.29
K ₂ O	7.88	9.83	10.50	9.25	9.99	10.38	8.45	10.45	11.13
F	BDL	0.04	0.15	BDL	0.03	0.09	BDL	0.06	0.13
Cl	BDL	0.01	0.16	BDL	0.00	0.01	BDL	0.00	0.01
Total	93.40	94.97	95.89	93.17	94.36	94.81	94.16	95.66	96.31
Ions on the basis of 22 positive charges									
Si	2.998	3.089	3.137	3.014	3.055	3.099	3.040	3.131	3.322
Ti	0.022	0.025	0.031	0.017	0.020	0.029	0.006	0.032	0.102
Al	2.691	2.751	2.805	2.671	2.794	2.858	2.190	2.611	2.748
Fe	0.050	0.082	0.199	0.071	0.107	0.213	0.054	0.103	0.273
Mn	BDL	0.001	0.003	BDL	0.001	0.002	BDL	0.002	0.007
Mg	0.070	0.108	0.282	0.039	0.076	0.158	0.105	0.193	0.589
Ca	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.003	0.045
Na	0.063	0.076	0.107	0.061	0.091	0.124	0.007	0.029	0.037
K	0.681	0.835	0.889	0.800	0.858	0.887	0.737	0.886	0.935
F	BDL	0.009	0.031	BDL	0.006	0.018	BDL	0.013	0.027
Cl	BDL	0.001	0.018	BDL	0.000	0.001	BDL	0.000	0.001
Cation site distribution									
Si	2.998	3.089	3.137	3.014	3.055	3.099	3.040	3.131	3.322
Ti	0.022	0.025	0.031	0.017	0.020	0.029	0.006	0.032	0.102
Al(IV)	0.849	0.910	1.002	0.901	0.944	0.986	0.678	0.863	0.960
Al(VI)	1.720	1.841	1.881	1.726	1.850	1.914	1.476	1.748	1.847
Mg(M2)	0.055	0.076	0.150	0.030	0.054	0.105	0.079	0.146	0.361
Fe(M2)	0.037	0.058	0.106	0.048	0.076	0.142	0.046	0.078	0.171
Mn(M2)	0.000	0.001	0.003	0.000	0.001	0.002	0.000	0.002	0.007
Mg(M1)	0.006	0.031	0.133	0.008	0.022	0.058	0.005	0.047	0.242
Fe(M1)	0.004	0.024	0.094	0.012	0.031	0.079	0.002	0.025	0.112
v(M1)	0.774	0.945	0.990	0.863	0.947	0.979	0.646	0.929	0.993
K(A)	0.681	0.835	0.889	0.800	0.858	0.887	0.737	0.886	0.935
Na(A)	0.063	0.076	0.107	0.061	0.091	0.124	0.007	0.029	0.037
v(A)	0.033	0.089	0.252	0.023	0.051	0.107	0.033	0.085	0.245
End-member composition									
Muscovite	78.08%	85.97%	88.20%	81.54%	85.35%	88.03%	77.16%	88.34%	92.67%
Paragonite	6.45%	7.83%	10.68%	6.10%	9.03%	12.51%	0.60%	2.87%	3.76%
Fe-Celadonite	2.07%	3.45%	6.32%	2.48%	4.20%	8.64%	3.00%	6.00%	14.57%
Pyrophyllite	1.00%	2.76%	7.95%	0.65%	1.42%	2.80%	1.06%	2.79%	6.94%

Table I2: Major element EMPA of white mica

	min	mean	max	min	mean	max
Wt%	NCTK10-75 (n: 38)			NCTK10-76 (n: 37)		
SiO ₂	42.46	45.17	46.70	44.97	45.98	48.76
TiO ₂	0.26	0.39	2.28	0.51	0.62	0.74
Al ₂ O ₃	31.08	34.06	35.51	32.47	34.44	35.44
FeO _T	2.00	3.24	8.15	1.55	1.89	2.90
MnO	BDL	0.02	0.08	BDL	0.01	0.04
MgO	0.47	0.78	1.89	0.59	0.81	1.37
CaO	BDL	BDL	BDL	BDL	BDL	BDL
Na ₂ O	0.27	0.54	0.83	0.38	0.55	0.71
K ₂ O	9.32	10.08	10.60	9.87	10.33	10.71
F	BDL	0.03	0.10	BDL	0.03	0.11
Cl	BDL	0.01	0.16	BDL	0.00	0.03
Total	91.40	94.32	95.38	94.00	94.62	95.72
Ions on the basis of 22 positive charges						
Si	2.952	3.068	3.152	3.052	3.090	3.240
Ti	0.013	0.020	0.117	0.025	0.032	0.038
Al	2.550	2.725	2.860	2.543	2.727	2.796
Fe	0.111	0.185	0.474	0.087	0.106	0.164
Mn	BDL	0.001	0.005	BDL	0.001	0.002
Mg	0.047	0.079	0.196	0.059	0.081	0.138
Ca	BDL	BDL	BDL	BDL	BDL	BDL
Na	0.036	0.071	0.110	0.049	0.072	0.093
K	0.821	0.873	0.910	0.849	0.885	0.925
F	BDL	0.006	0.021	BDL	0.007	0.024
Cl	BDL	0.001	0.019	BDL	0.001	0.003
Cation site distribution						
Si	2.952	3.068	3.152	3.052	3.090	3.240
Ti	0.013	0.020	0.117	0.025	0.032	0.038
Al(IV)	0.848	0.932	1.048	0.760	0.909	0.948
Al(VI)	1.560	1.793	1.870	1.755	1.818	1.853
Mg(M2)	0.031	0.056	0.135	0.045	0.065	0.105
Fe(M2)	0.082	0.130	0.295	0.068	0.085	0.122
Mn(M2)	0.000	0.001	0.005	0.000	0.001	0.002
Mg(M1)	0.009	0.023	0.067	0.005	0.016	0.035
Fe(M1)	0.023	0.055	0.179	0.006	0.021	0.044
v(M1)	0.754	0.922	0.966	0.921	0.963	0.989
K(A)	0.821	0.873	0.910	0.849	0.885	0.925
Na(A)	0.036	0.071	0.110	0.049	0.072	0.093
v(A)	0.011	0.056	0.113	0.018	0.043	0.096
End-member composition						
Muscovite	75.18%	83.97%	87.34%	83.41%	86.57%	88.67%
Paragonite	3.31%	6.82%	10.34%	4.76%	7.03%	9.00%
Fe-Celadonite	4.24%	7.65%	17.14%	3.75%	5.11%	8.02%
Pyrophyllite	0.29%	1.55%	2.98%	0.49%	1.29%	3.81%

BDL: below detection limit.

Table 13: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Wt%	JAC1 (n: 25)			JAC5 (n: 3)			JAC7 (n:27)			JAC11 (n:2)		
SiO ₂	25.228	26.462	39.954	25.827	26.359	27.019	24.268	24.709	24.985	24.679	24.739	24.798
TiO ₂	0.052	0.080	0.209	0.077	0.092	0.117	0.046	0.078	0.096	0.096	0.115	0.134
Al ₂ O ₃	13.833	21.052	22.287	19.594	19.711	19.798	21.059	21.934	22.386	20.739	20.913	21.087
FeOT	15.830	18.852	20.541	21.313	22.235	23.061	21.711	22.924	24.134	26.416	26.551	26.685
MnO	0.092	0.132	0.185	0.212	0.231	0.269	0.095	0.121	0.138	0.003	0.010	0.016
MgO	13.494	18.116	19.130	16.026	16.308	16.724	14.422	15.140	15.739	12.954	12.957	12.960
CaO	0.005	0.444	8.384	0.041	0.067	0.083	0.006	0.028	0.043	0.007	0.017	0.026
Na ₂ O	0.000	0.034	0.671	0.003	0.011	0.017	0.000	0.003	0.014	0.010	0.011	0.011
K ₂ O	0.000	0.008	0.074	0.013	0.118	0.324	0.012	0.051	0.119	0.032	0.079	0.125
F	0.000	0.004	0.039	0.000	0.015	0.032	0.000	0.006	0.035	0.000	0.021	0.042
Cl	0.000	0.004	0.028	0.002	0.003	0.004	0.000	0.005	0.010	0.001	0.002	0.003
Total	83.052	85.189	92.678	84.965	85.151	85.477	83.261	84.998	85.626	85.401	85.412	85.423
Ions on the basis of 28 positive charges												
Si	2.684	2.767	3.783	2.783	2.818	2.860	2.618	2.657	2.694	2.693	2.701	2.709
Ti	0.004	0.006	0.015	0.006	0.007	0.009	0.004	0.006	0.008	0.008	0.009	0.011
Al	1.543	2.604	2.763	2.463	2.483	2.499	2.725	2.779	2.849	2.670	2.691	2.712
Fe ²⁺	1.253	1.653	1.809	1.886	1.988	2.078	1.943	2.061	2.177	2.411	2.424	2.437
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn	0.008	0.012	0.015	0.019	0.021	0.025	0.009	0.011	0.013	0.000	0.001	0.001
Mg	1.905	2.833	2.989	2.575	2.599	2.639	2.319	2.427	2.512	2.108	2.109	2.111
Ca	0.001	0.046	0.850	0.005	0.008	0.010	0.001	0.003	0.005	0.001	0.002	0.003
Na	0.000	0.006	0.123	0.001	0.002	0.003	0.000	0.001	0.003	0.002	0.002	0.002
K	0.000	0.001	0.009	0.002	0.016	0.044	0.002	0.007	0.016	0.004	0.011	0.017
F	9.497	9.929	9.967	9.926	9.942	9.967	9.938	9.951	9.966	9.949	9.951	9.953
Cl	0.000	0.001	0.013	0.000	0.005	0.011	0.000	0.002	0.012	0.000	0.007	0.014
Cation site distribution												
Si(T1)	1.789	1.845	2.522	1.856	1.878	1.907	1.745	1.771	1.796	1.796	1.801	1.806
Si(T2)	0.895	0.922	1.261	0.928	0.939	0.953	0.873	0.886	0.898	0.898	0.900	0.903
Al(T2) (IV)	0.217	1.233	1.316	1.140	1.182	1.217	1.306	1.343	1.382	1.291	1.299	1.307
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.182	0.240	0.262	0.274	0.288	0.301	0.282	0.299	0.316	0.350	0.351	0.353
Mg(M1)	0.276	0.411	0.433	0.373	0.377	0.383	0.336	0.352	0.364	0.306	0.306	0.306
Al(M1) (VI)	-0.974	0.206	0.282	0.192	0.223	0.250	0.258	0.273	0.293	0.267	0.268	0.269
v(M1)	0.054	0.143	1.516	0.075	0.112	0.152	0.051	0.077	0.093	0.074	0.075	0.076
Mg(M2+M3)	1.629	2.422	2.556	2.202	2.222	2.256	1.983	2.075	2.148	1.802	1.803	1.804
Fe(M2+M3)	1.072	1.413	1.547	1.613	1.700	1.777	1.662	1.762	1.861	2.061	2.073	2.084
Al(M2+M3)	0.072	0.164	1.300	0.022	0.078	0.131	0.131	0.163	0.194	0.112	0.124	0.137
End-member composition												
Daphnite	0%	5%	9%	14%	18%	22%	18%	25%	35%	59%	60%	61%
Clinochlore	2%	73%	80%	64%	68%	74%	48%	57%	63%	30%	30%	30%
Mg-Amesite	0%	16%	19%	11%	13%	14%	15%	17%	19%	9%	9%	10%
Mg-Sudoite	0%	6%	98%	0%	1%	2%	1%	1%	2%	0%	1%	1%

Table 13: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Wt%	NCB12-10 (n:12)			NCB12-11A (n:9)			NCTK10-44A (n:21)			NCTK10-44B (n:19)		
SiO ₂	25.331	25.640	26.305	26.049	26.649	28.027	24.499	24.894	26.182	24.594	24.927	25.316
TiO ₂	0.074	0.097	0.138	0.048	0.079	0.107	0.085	0.102	0.143	0.069	0.090	0.121
Al ₂ O ₃	21.333	22.047	22.517	19.682	20.176	20.666	22.713	23.044	23.355	22.831	23.124	23.526
FeOT	17.271	18.009	19.999	17.297	18.042	18.776	20.074	20.645	21.374	19.181	19.544	20.102
MnO	0.175	0.191	0.211	0.203	0.264	0.305	0.217	0.256	0.291	0.224	0.256	0.296
MgO	18.273	18.778	19.204	17.383	19.037	19.851	14.282	16.314	16.764	16.814	17.142	17.392
CaO	0.002	0.024	0.090	0.010	0.030	0.061	0.000	0.014	0.113	0.000	0.009	0.033
Na ₂ O	0.000	0.006	0.021	0.000	0.006	0.017	0.000	0.009	0.037	0.000	0.006	0.024
K ₂ O	0.000	0.048	0.221	0.000	0.008	0.023	0.001	0.061	0.266	0.000	0.039	0.371
F	0.000	0.022	0.099	0.000	0.024	0.126	0.000	0.028	0.124	0.000	0.039	0.126
Cl	0.000	0.003	0.009	0.001	0.007	0.013	0.000	0.003	0.012	0.000	0.002	0.009
Total	83.957	84.865	85.916	82.242	84.323	85.407	84.395	85.370	86.181	84.579	85.177	85.942

Ions on the basis of 28 positive charges

Si	2.649	2.685	2.728	2.757	2.809	2.928	2.595	2.630	2.787	2.590	2.623	2.651
Ti	0.006	0.008	0.011	0.004	0.006	0.009	0.007	0.008	0.011	0.005	0.007	0.010
Al	2.647	2.721	2.775	2.451	2.506	2.564	2.828	2.869	2.915	2.836	2.868	2.896
Fe ²⁺	1.507	1.577	1.752	1.535	1.591	1.655	1.769	1.823	1.886	1.689	1.720	1.769
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn	0.016	0.017	0.019	0.018	0.024	0.028	0.020	0.023	0.026	0.020	0.023	0.026
Mg	2.854	2.932	2.987	2.807	2.991	3.137	2.266	2.569	2.638	2.617	2.690	2.730
Ca	0.000	0.003	0.010	0.001	0.003	0.007	0.000	0.002	0.013	0.000	0.001	0.004
Na	0.000	0.001	0.004	0.000	0.001	0.004	0.000	0.002	0.008	0.000	0.001	0.005
K	0.000	0.006	0.030	0.000	0.001	0.003	0.000	0.008	0.036	0.000	0.005	0.049
F	9.919	9.950	9.997	9.843	9.933	9.974	9.789	9.933	9.954	9.905	9.939	9.965
Cl	0.000	0.007	0.033	0.000	0.008	0.042	0.000	0.009	0.042	0.000	0.013	0.042

Cation site distribution

Si(T1)	1.766	1.790	1.819	1.838	1.873	1.952	1.730	1.753	1.858	1.726	1.749	1.767
Si(T2)	0.883	0.895	0.909	0.919	0.936	0.976	0.865	0.877	0.929	0.863	0.874	0.884
Al(T2) (IV)	1.272	1.315	1.351	1.072	1.191	1.243	1.213	1.370	1.405	1.349	1.377	1.410
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.219	0.229	0.254	0.223	0.231	0.240	0.257	0.264	0.273	0.245	0.249	0.257
Mg(M1)	0.414	0.425	0.433	0.407	0.434	0.455	0.329	0.372	0.382	0.379	0.390	0.396
Al(M1) (VI)	0.219	0.262	0.278	0.164	0.233	0.258	0.137	0.254	0.273	0.225	0.262	0.284
v(M1)	0.063	0.085	0.139	0.063	0.103	0.194	0.083	0.110	0.269	0.069	0.099	0.148
Mg(M2+M3)	2.440	2.507	2.554	2.400	2.558	2.682	1.938	2.196	2.255	2.237	2.300	2.334
Fe(M2+M3)	1.288	1.348	1.498	1.313	1.360	1.415	1.513	1.559	1.613	1.444	1.471	1.513
Al(M2+M3)	0.062	0.145	0.214	-0.002	0.083	0.215	0.195	0.245	0.498	0.185	0.230	0.302

End-member composition

Daphnite	3%	4%	7%	2%	4%	6%	10%	12%	15%	7%	8%	9%
Clinocllore	75%	78%	79%	79%	81%	83%	43%	66%	69%	68%	71%	72%
Mg-Amesite	14%	18%	19%	9%	14%	16%	6%	18%	20%	16%	19%	21%
Mg-Sudoite	0%	1%	3%	0%	1%	5%	2%	5%	37%	1%	3%	8%

Table 13: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max	min	mean	max
Wt%	13NCGB-06 (n:21)			13NCGB-03B (n:19)			NCB12-12 (n:24)			NCTK10-16B (n:26)		
SiO ₂	23.547	24.163	26.537	23.349	23.681	24.392	23.652	24.282	25.116	21.787	22.275	24.307
TiO ₂	0.052	0.082	0.254	0.056	0.076	0.165	0.046	0.067	0.095	0.032	0.065	0.127
Al ₂ O ₃	18.620	21.177	22.027	21.532	21.986	22.406	21.841	22.642	23.391	21.836	22.159	22.978
FeOT	25.851	26.614	27.708	25.631	26.487	27.007	24.693	26.013	27.199	30.599	35.525	36.239
MnO	0.273	0.458	0.551	0.435	0.485	0.542	0.113	0.215	0.372	0.066	0.115	0.182
MgO	11.297	12.318	12.907	12.001	12.449	12.795	11.896	13.010	14.423	5.638	6.301	9.182
CaO	0.000	0.014	0.055	0.000	0.016	0.225	0.000	0.011	0.040	0.000	0.093	2.165
Na ₂ O	0.000	0.008	0.020	0.000	0.015	0.182	0.000	0.006	0.016	0.000	0.007	0.034
K ₂ O	0.000	0.071	0.679	0.007	0.038	0.183	0.000	0.017	0.045	0.000	0.011	0.033
F	0.000	0.019	0.143	0.000	0.006	0.101	0.000	0.014	0.089	0.000	0.003	0.031
Cl	0.000	0.005	0.021	0.000	0.002	0.011	0.005	0.021	0.034	0.000	0.006	0.013
Total	83.733	84.931	85.574	84.633	85.241	86.199	84.828	86.298	87.624	85.533	86.561	87.475
Ions on the basis of 28 positive charges												
Si	2.592	2.665	2.914	2.571	2.600	2.653	2.558	2.614	2.672	2.492	2.533	2.698
Ti	0.004	0.007	0.021	0.005	0.006	0.014	0.004	0.005	0.008	0.003	0.006	0.011
Al	2.410	2.752	2.849	2.784	2.845	2.884	2.757	2.873	2.981	2.874	2.969	3.014
Fe ²⁺	2.385	2.454	2.613	2.331	2.432	2.465	2.207	2.342	2.483	2.836	3.378	3.448
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn	0.025	0.043	0.051	0.041	0.045	0.050	0.010	0.020	0.034	0.006	0.011	0.018
Mg	1.890	2.025	2.103	1.946	2.038	2.075	1.938	2.088	2.299	0.933	1.068	1.517
Ca	0.000	0.002	0.007	0.000	0.002	0.026	0.000	0.001	0.005	0.000	0.011	0.257
Na	0.000	0.002	0.004	0.000	0.003	0.038	0.000	0.001	0.003	0.000	0.001	0.008
K	0.000	0.010	0.095	0.001	0.005	0.026	0.000	0.002	0.006	0.000	0.002	0.005
F	9.898	9.958	9.985	9.932	9.976	9.991	9.927	9.946	9.972	9.860	9.979	10.000
Cl	0.000	0.007	0.050	0.000	0.002	0.035	0.000	0.005	0.030	0.000	0.001	0.011
Cation site distribution												
Si(T1)	1.728	1.776	1.943	1.714	1.733	1.769	1.705	1.743	1.781	1.661	1.688	1.798
Si(T2)	0.864	0.888	0.971	0.857	0.867	0.884	0.853	0.871	0.891	0.831	0.844	0.899
Al(T2) (IV)	1.086	1.335	1.408	1.347	1.400	1.429	1.328	1.386	1.442	1.302	1.467	1.508
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.346	0.356	0.379	0.338	0.353	0.357	0.320	0.340	0.360	0.411	0.490	0.500
Mg(M1)	0.274	0.294	0.305	0.282	0.295	0.301	0.281	0.303	0.333	0.135	0.155	0.220
Al(M1) (VI)	0.141	0.246	0.276	0.181	0.266	0.282	0.259	0.274	0.293	-0.002	0.303	0.327
v(M1)	0.071	0.105	0.212	0.068	0.086	0.199	0.056	0.084	0.103	0.019	0.052	0.421
Mg(M2+M3)	1.616	1.731	1.798	1.664	1.742	1.774	1.657	1.785	1.965	0.798	0.913	1.297
Fe(M2+M3)	2.039	2.098	2.234	1.993	2.079	2.108	1.887	2.002	2.123	2.424	2.889	2.948
Al(M2+M3)	0.127	0.170	0.231	0.126	0.179	0.343	0.147	0.213	0.267	0.147	0.199	0.574
End-member composition												
Daphnite	58%	65%	79%	59%	63%	66%	38%	55%	70%	93%	99%	100%
Clinochlore	16%	25%	31%	23%	26%	28%	20%	31%	46%	0%	0%	4%
Mg-Amesite	3%	8%	10%	6%	9%	10%	8%	11%	15%	0%	0%	2%
Mg-Sudoite	1%	2%	4%	1%	2%	11%	1%	2%	3%	0%	0%	6%

Table I3: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-12B (n: 26)			NCTK10-15 (n: 21)			NCTK10-16A (n: 24)		
SiO ₂	26.32	27.00	27.65	19.86	27.12	28.79	22.26	23.20	24.08
TiO ₂	0.00	0.12	0.36	0.02	0.16	0.82	0.03	0.09	0.24
Al ₂ O ₃	19.03	20.30	21.44	15.40	18.87	20.35	21.87	22.89	23.43
FeO _T	23.37	24.61	25.32	20.03	24.49	26.24	31.91	34.11	36.29
MnO	0.20	0.64	1.60	0.32	0.42	0.56	0.12	0.18	0.21
MgO	14.28	14.72	15.45	10.89	15.10	16.44	6.09	7.25	8.06
CaO	0.00	0.07	0.26	BDL	0.07	0.35	BDL	0.02	0.05
Na ₂ O	BDL	0.02	0.06	BDL	0.05	0.59	BDL	0.02	0.07
K ₂ O	0.00	0.09	0.45	0.01	0.14	0.93	BDL	0.03	0.08
F	BDL	0.04	0.14	BDL	0.04	0.20	BDL	0.01	0.07
Cl	BDL	0.01	0.03	BDL	0.03	0.31	BDL	0.02	0.05
Total	86.63	87.60	88.36	67.07	86.50	88.41	85.63	87.80	88.89
Ions on the basis of 28 positive charges									
Si	2.755	2.836	2.897	2.766	2.888	3.029	2.476	2.567	2.639
Ti	0.000	0.009	0.028	0.001	0.013	0.064	0.003	0.007	0.020
Al	2.354	2.513	2.642	2.199	2.372	2.529	2.860	2.985	3.071
Fe	2.036	2.162	2.219	2.051	2.183	2.332	2.999	3.156	3.381
Mn	0.017	0.057	0.143	0.029	0.038	0.050	0.011	0.017	0.020
Mg	2.237	2.305	2.412	2.243	2.396	2.553	1.010	1.195	1.343
Ca	0.000	0.007	0.029	BDL	0.008	0.040	BDL	0.002	0.006
Na	BDL	0.004	0.012	BDL	0.011	0.121	BDL	0.003	0.016
K	0.000	0.012	0.059	0.001	0.019	0.124	BDL	0.004	0.011
F	BDL	0.012	0.047	BDL	0.014	0.086	BDL	0.003	0.026
Cl	BDL	0.002	0.006	BDL	0.005	0.055	BDL	0.003	0.009
Cation site distribution									
Si(T1)	1.837	1.891	1.931	1.844	1.925	2.019	1.651	1.711	1.759
Si(T2)	0.918	0.945	0.966	0.922	0.963	1.010	0.825	0.856	0.880
Al(T2) (IV)	1.103	1.164	1.245	0.971	1.112	1.234	1.361	1.433	1.524
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.295	0.314	0.322	0.297	0.317	0.338	0.435	0.458	0.490
Mg(M1)	0.324	0.334	0.350	0.325	0.347	0.370	0.146	0.173	0.195
Al(M1) (VI)	0.111	0.169	0.227	0.042	0.175	0.223	0.237	0.272	0.316
v(M1)	0.123	0.183	0.235	0.102	0.161	0.313	0.041	0.097	0.141
Mg(M2+M3)	1.913	1.971	2.062	1.917	2.049	2.183	0.863	1.022	1.148
Fe(M2+M3)	1.740	1.849	1.898	1.754	1.867	1.994	2.565	2.698	2.891
Al(M2+M3)	0.112	0.180	0.241	0.012	0.085	0.217	0.210	0.280	0.351
End-member composition									
Daphnite	26.93%	37.13%	42.41%	22.79%	35.08%	48.61%	96.38%	97.96%	99.39%
Clinochlore	46.35%	51.00%	59.24%	41.57%	55.41%	68.16%	0.24%	0.88%	1.74%
Mg-Amesite	5.33%	7.94%	12.39%	1.85%	8.06%	10.64%	0.22%	0.54%	0.98%
Mg-Sudoite	1.79%	3.93%	8.26%	0.01%	1.46%	9.63%	0.07%	0.61%	1.19%

Table I3: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-20A (n: 40)			NCTK10-26A (n: 8)			NCTK10-51A (n: 29)		
SiO ₂	24.95	25.72	27.54	24.26	25.08	25.89	24.79	26.27	29.77
TiO ₂	0.04	0.11	0.32	0.07	0.07	0.07	0.05	0.12	0.54
Al ₂ O ₃	22.28	23.37	24.01	22.08	22.55	23.02	17.50	21.24	23.82
FeO _T	19.54	20.28	21.47	20.22	20.75	21.29	21.51	23.22	26.12
MnO	0.24	0.32	0.36	0.39	0.41	0.43	0.31	0.43	0.51
MgO	16.07	16.75	17.21	15.73	16.24	16.75	14.82	15.94	16.56
CaO	BDL	0.02	0.08	0.02	0.03	0.05	BDL	BDL	0.29
Na ₂ O	BDL	0.03	0.40	0.00	0.00	0.01	BDL	0.01	0.05
K ₂ O	0.00	0.16	0.70	0.11	0.17	0.23	BDL	0.16	0.74
F	BDL	0.02	0.09	0.09	0.09	0.09	BDL	0.01	0.07
Cl	BDL	0.02	0.33	0.00	0.01	0.01	BDL	0.00	0.01
Total	85.62	86.81	88.05	83.01	85.36	87.71	85.43	87.43	88.27
Ions on the basis of 28 positive charges									
Si	2.605	2.662	2.788	2.643	2.656	2.669	2.576	2.746	3.071
Ti	0.003	0.009	0.025	0.005	0.005	0.005	0.004	0.010	0.042
Al	2.736	2.850	2.955	2.795	2.815	2.835	2.213	2.615	2.917
Fe	1.686	1.755	1.876	1.834	1.838	1.842	1.881	2.030	2.314
Mn	0.021	0.028	0.032	0.034	0.037	0.039	0.028	0.038	0.045
Mg	2.478	2.584	2.649	2.555	2.564	2.573	2.341	2.483	2.571
Ca	BDL	0.002	0.008	0.002	0.004	0.005	BDL	0.003	0.033
Na	BDL	0.006	0.081	0.000	0.001	0.001	BDL	0.002	0.009
K	0.000	0.022	0.092	0.016	0.023	0.030	BDL	0.022	0.098
F	BDL	0.007	0.028	0.028	0.029	0.031	BDL	0.003	0.023
Cl	BDL	0.003	0.057	BDL	0.001	0.002	BDL	0.001	0.003
Cation site distribution									
Si(T1)	1.737	1.775	1.859	1.762	1.771	1.779	1.717	1.831	2.047
Si(T2)	0.868	0.887	0.929	0.881	0.885	0.890	0.859	0.915	1.024
Al(T2) (IV)	1.212	1.338	1.395	1.331	1.344	1.357	0.929	1.254	1.424
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.244	0.254	0.272	0.266	0.267	0.267	0.273	0.294	0.335
Mg(M1)	0.359	0.375	0.384	0.370	0.372	0.373	0.339	0.360	0.373
Al(M1) (VI)	0.132	0.222	0.265	0.233	0.235	0.238	0.083	0.220	0.273
v(M1)	0.095	0.149	0.260	0.124	0.126	0.128	0.073	0.126	0.282
Mg(M2+M3)	2.119	2.210	2.265	2.185	2.192	2.200	2.001	2.123	2.198
Fe(M2+M3)	1.442	1.500	1.604	1.568	1.572	1.575	1.608	1.735	1.978
Al(M2+M3)	0.219	0.290	0.414	0.231	0.236	0.240	0.010	0.141	0.253
End-member composition									
Daphnite	8.12%	9.73%	14.29%	11.78%	12.55%	13.68%	14.12%	24.57%	45.38%
Clinochlore	59.16%	67.01%	70.48%	65.25%	66.57%	67.66%	48.09%	60.60%	66.17%
Mg-Amesite	7.51%	15.10%	18.99%	15.57%	17.60%	19.18%	3.21%	12.92%	19.09%
Mg-Sudoite	2.70%	8.16%	25.21%	2.19%	3.29%	5.14%	0.01%	1.92%	12.07%

Table I3: Major element EMPA of chlorite

	min	mean	max	min	mean	max	min	mean	max
Wt%	NCTK10-74A (n: 13)			NCTK10-75 (n: 51)			NCTK10-76 (n: 39)		
SiO ₂	28.25	28.87	30.10	22.74	23.99	25.25	25.01	25.74	26.76
TiO ₂	0.00	0.09	0.45	0.04	0.08	0.20	0.03	0.12	0.48
Al ₂ O ₃	19.22	19.86	20.91	21.73	23.11	23.92	20.81	21.63	22.89
FeO _T	17.13	19.36	21.40	23.03	26.31	28.28	22.70	23.76	25.34
MnO	0.53	0.57	0.61	0.37	0.43	0.51	0.38	0.44	0.49
MgO	17.71	18.78	20.97	11.53	12.88	13.39	14.18	15.38	16.51
CaO	BDL	0.10	0.48	BDL	0.01	0.05	BDL	0.01	0.06
Na ₂ O	BDL	0.01	0.03	BDL	0.04	0.73	BDL	0.02	0.35
K ₂ O	BDL	0.12	0.80	0.00	0.10	0.85	0.01	0.09	0.88
F	BDL	0.05	0.17	BDL	0.00	0.05	BDL	0.00	0.06
Cl	BDL	0.01	0.02	BDL	0.01	0.19	BDL	0.01	0.06
Total	87.42	87.82	88.80	82.12	86.96	88.42	85.54	87.20	88.18
Ions on the basis of 28 positive charges									
Si	2.889	2.932	3.005	2.500	2.571	2.663	2.612	2.706	2.785
Ti	0.000	0.007	0.035	0.003	0.007	0.016	0.002	0.009	0.038
Al	2.285	2.377	2.459	2.762	2.919	3.035	2.575	2.680	2.814
Fe	1.438	1.645	1.830	2.157	2.357	2.528	1.979	2.089	2.260
Mn	0.045	0.049	0.053	0.033	0.039	0.046	0.034	0.039	0.043
Mg	2.635	2.842	3.139	1.837	2.058	2.148	2.254	2.411	2.571
Ca	BDL	0.011	0.052	BDL	0.001	0.005	BDL	0.001	0.006
Na	BDL	0.002	0.006	BDL	0.007	0.153	BDL	0.004	0.070
K	BDL	0.016	0.101	BDL	0.013	0.114	0.001	0.012	0.117
F	BDL	0.015	0.055	BDL	0.001	0.018	BDL	0.001	0.020
Cl	BDL	0.001	0.003	BDL	0.002	0.034	BDL	0.001	0.010
Cation site distribution									
Si(T1)	1.926	1.954	2.003	1.667	1.714	1.775	1.741	1.804	1.857
Si(T2)	0.963	0.977	1.002	0.833	0.857	0.888	0.871	0.902	0.928
Al(T2) (IV)	0.995	1.068	1.111	1.337	1.429	1.500	1.215	1.294	1.388
Al(M4)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe(M1)	0.208	0.239	0.265	0.313	0.342	0.367	0.287	0.303	0.328
Mg(M1)	0.382	0.412	0.455	0.266	0.298	0.311	0.327	0.350	0.373
Al(M1) (VI)	0.048	0.146	0.185	0.172	0.265	0.299	0.126	0.234	0.269
v(M1)	0.154	0.204	0.344	0.046	0.094	0.204	0.080	0.113	0.235
Mg(M2+M3)	2.253	2.430	2.683	1.571	1.760	1.837	1.927	2.062	2.198
Fe(M2+M3)	1.229	1.407	1.565	1.844	2.016	2.162	1.692	1.786	1.932
Al(M2+M3)	0.087	0.163	0.416	0.134	0.225	0.359	0.106	0.152	0.234
End-member composition									
Daphnite	1.80%	6.19%	10.96%	40.00%	57.16%	75.89%	18.20%	27.99%	44.14%
Clinochlore	62.70%	81.29%	89.08%	15.37%	29.14%	38.93%	43.60%	56.58%	66.84%
Mg-Amesite	1.96%	7.95%	10.35%	5.22%	10.83%	13.96%	6.85%	13.64%	17.20%
Mg-Sudoite	0.56%	4.56%	30.82%	0.37%	2.87%	11.50%	0.66%	1.79%	8.39%

BDL: below detection limit.

Table I4a: Major element EMPA of garnet

	min	mean	max	mean rim*	mean core*	min	mean	max	mean rim*	mean core*	min	mean	max
Wt%	JAC 7, n: 66					JAC11, n: 69					NCB12-10, n: 4		
SiO ₂	36.678	37.253	37.546	37.281	37.185	35.243	36.984	37.482	37.042	36.908	36.932	36.994	37.025
TiO ₂	0.007	0.045	0.110	0.045	0.054	0.008	0.031	0.063	0.034	0.039	0.021	0.036	0.052
Al ₂ O ₃	20.443	20.784	21.146	20.772	20.735	20.328	20.701	21.016	20.643	20.601	20.946	21.005	21.089
Cr ₂ O ₃	0.000	0.009	0.047	0.009	0.012	0.000	0.033	0.097	0.035	0.016	0.032	0.108	0.151
Fe ₂ O ₃	0.000	0.199	0.914	0.168	0.237	0.000	0.188	1.839	0.081	0.144	0.121	0.523	0.901
FeO	28.874	32.416	34.538	32.830	31.171	34.151	36.742	38.498	37.119	37.234	27.463	27.929	28.445
MnO	2.390	4.204	7.628	3.730	5.592	0.000	0.139	2.612	0.178	0.415	6.780	7.296	7.714
MgO	1.810	2.690	3.360	2.832	2.376	1.475	2.595	3.182	2.424	1.964	3.645	3.724	3.777
CaO	1.597	2.409	3.657	2.288	2.672	1.612	2.113	2.781	2.076	2.339	1.747	1.803	1.861
Number of atoms in formulae (oxygen basis 12)													
Si	2.979	3.004	3.023	3.006	3.003	2.939	3.002	3.020	3.008	3.005	2.973	2.981	2.992
Ti	0.000	0.003	0.007	0.003	0.003	0.000	0.002	0.004	0.002	0.002	0.001	0.002	0.003
Al	1.960	1.975	2.000	1.974	1.974	1.961	1.981	2.006	1.976	1.977	1.985	1.995	2.002
Cr	0.000	0.001	0.003	0.001	0.001	0.000	0.002	0.006	0.002	0.001	0.002	0.007	0.010
Fe ³⁺	0.000	0.012	0.055	0.010	0.014	0.000	0.012	0.115	0.005	0.009	0.007	0.032	0.054
Fe ²⁺	1.940	2.186	2.335	2.214	2.105	2.340	2.494	2.619	2.521	2.535	1.844	1.882	1.916
Mn	0.163	0.287	0.524	0.255	0.383	0.000	0.010	0.179	0.012	0.029	0.462	0.498	0.528
Mg	0.219	0.323	0.401	0.340	0.286	0.179	0.314	0.386	0.293	0.238	0.438	0.447	0.452
Ca	0.138	0.208	0.313	0.198	0.231	0.140	0.184	0.242	0.181	0.204	0.151	0.156	0.161
End-member composition**													
Almandine	64.81	72.75	77.51			77.91	83.10	86.97			61.97	63.09	64.36
Pyrope	7.33	10.76	13.39			5.95	10.46	12.99			14.70	15.00	15.19
Grossular	4.59	6.87	10.25			4.64	6.08	7.94			5.02	5.11	5.27
Spessartine	5.41	9.56	17.55			0.00	0.32	5.97			15.54	16.69	17.64

*Average values for rims and core were calculated from single spots from different garnets within each sample

** End-member compositions were calculated as follows

%Alm Fe/(Mg+Fe+Mn+Ca)
 %Prp Mg/(Mg+Fe+Mn+Ca)
 %Grs Ca/(Mg+Fe+Mn+Ca)
 %Sps Mn/(Mg+Fe+Mn+Ca)

Table I4b: Major element EMPA of garnet cores and rims

	core ^a	mean ^b	rim ^c	core	mean	rim	core	mean	rim
NCTK10-26B									
Wt %	Grt 1, n: 15			Grt 2, n: 10			Grt 3, n: 15		
SiO ₂	36.92	36.51	36.81	36.63	36.55	36.49	36.69	36.60	36.77
TiO ₂	0.08	0.05	0.04	0.09	0.05	0.02	0.02	0.06	0.03
Al ₂ O ₃	20.96	20.95	21.00	21.30	21.06	20.82	21.07	21.01	21.10
FeO _T	30.64	31.17	31.69	31.25	31.42	31.72	28.79	29.86	31.55
MnO	6.71	5.86	6.98	5.54	5.60	6.55	8.97	7.43	5.96
MgO	3.60	3.72	2.82	4.17	3.87	2.97	3.33	3.60	3.38
CaO	1.69	1.56	0.98	1.18	1.25	0.99	1.23	1.29	1.25
Cr ₂ O ₃	0.14	0.14	0.16	0.01	0.03	0.13	0.00	0.03	0.06
Total	100.73	99.96	100.48	100.15	99.83	99.69	100.11	99.87	100.09
Number of atoms in formulae (oxygen basis 12)									
Si	2.960	2.949	2.971	2.943	2.952	2.968	2.963	2.959	2.966
Ti	0.005	0.003	0.002	0.005	0.003	0.001	0.001	0.003	0.002
Al	1.980	1.994	1.998	2.017	2.005	1.995	2.005	2.001	2.006
Fe	2.054	2.106	2.139	2.100	2.122	2.157	1.944	2.018	2.128
Mn	0.455	0.400	0.477	0.377	0.383	0.451	0.613	0.509	0.407
Mg	0.430	0.448	0.340	0.499	0.466	0.360	0.401	0.434	0.406
Ca	0.146	0.135	0.084	0.101	0.108	0.086	0.106	0.111	0.108
Cr	0.010	0.010	0.012	0.000	0.002	0.009	0.000	0.002	0.004
Wt %	Grt 4, n: 20			Grt 5, n: 20			Grt 6, n: 19		
SiO ₂	36.65	36.59	37.06	36.57	36.58	37.09	36.81	36.58	36.56
TiO ₂	0.03	0.08	0.03	0.05	0.07	0.03	0.06	0.06	0.01
Al ₂ O ₃	20.12	20.66	21.02	20.46	20.74	20.78	20.76	20.69	20.96
FeO _T	25.49	28.89	31.68	29.05	29.65	32.30	29.30	29.60	31.72
MnO	11.11	8.60	5.99	8.72	7.76	6.40	8.99	7.98	6.63
MgO	2.48	3.20	3.16	2.89	3.28	3.05	3.22	3.28	2.87
CaO	2.97	1.57	1.21	1.81	1.75	1.06	1.30	1.49	1.06
Cr ₂ O ₃	0.69	0.31	0.10	0.26	0.26	0.47	0.36	0.39	0.23
Total	99.53	99.88	100.23	99.81	100.08	101.18	100.80	100.07	100.03
Number of atoms in formulae (oxygen basis 12)									
Si	2.983	2.964	2.985	2.972	2.958	2.973	2.961	2.959	2.964
Ti	0.002	0.005	0.002	0.003	0.004	0.002	0.004	0.004	0.001
Al	1.930	1.972	1.995	1.959	1.976	1.963	1.968	1.972	2.002
Fe	1.735	1.957	2.133	1.974	2.004	2.165	1.971	2.002	2.150
Mn	0.766	0.591	0.408	0.600	0.532	0.434	0.612	0.547	0.455
Mg	0.301	0.386	0.379	0.350	0.396	0.364	0.386	0.395	0.347
Ca	0.259	0.136	0.105	0.157	0.152	0.091	0.112	0.129	0.092
Cr	0.050	0.022	0.007	0.019	0.018	0.033	0.025	0.028	0.017
	min	mean	max						
End-member composition**									
Pyrope	9.8%	13.4%	16.8%						
Spessartine	10.6%	16.3%	25.3%						
Grossular	2.8%	4.2%	8.5%						
Almandine	56.7%	66.0%	73.1%						

Table I4b: Major element EMPA of garnet cores and rims

	core^a	mean^b	rim^c	core	mean	rim
NCTK10-16B						
Wt %	Grt 1, n: 15			Grt 2, n: 15		
SiO ₂	36.32	36.24	36.41	36.03	36.08	35.85
TiO ₂	0.01	0.05	0.07	0.06	0.05	0.04
Al ₂ O ₃	20.36	20.38	20.36	20.56	20.52	20.53
FeO _T	37.82	37.96	37.40	37.84	38.05	38.53
MnO	2.61	2.44	2.42	2.65	2.43	2.31
MgO	0.93	0.91	0.67	0.93	0.89	0.84
CaO	1.92	1.99	2.64	1.89	1.96	1.88
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.97	99.97	99.98	99.97	99.98	99.97
Number of atoms in formulae (oxygen basis 12)						
Si	2.987	2.479	2.449	2.431	2.431	2.414
Ti	0.001	0.003	0.004	0.003	0.003	0.002
Al	1.973	1.642	1.614	1.635	1.630	1.629
Fe	2.600	2.170	2.104	2.135	2.144	2.170
Mn	0.182	2.035	2.131	2.162	2.172	2.198
Mg	0.114	0.194	0.265	0.190	0.197	0.189
Ca	0.169	0.175	0.174	0.192	0.175	0.166
Cr	0.00	0.00	0.00	0.00	0.00	0.00
	min	mean	max			
End-member composition**						
Pyrope	3.7%	7.3%	9.9%			
Spessartine	4.7%	5.2%	5.8%			
Grossular	5.5%	6.6%	7.3%			
Almandine	78.5%	80.9%	82.0%			

Table I4b: Major element EMPA of garnet cores and rims

	core ^a	mean ^b	rim ^c	core	mean	rim	core	mean	rim
E591 479									
Wt %	Grt 1, n: 14			Grt 2, n: 25			Grt 4, n: 26		
SiO ₂	37.08	37.15	37.02	37.94	37.33	37.17	37.34	37.33	39.04
TiO ₂	0.01	0.02	0.00	0.02	0.02	-0.01	0.02	0.06	0.01
Al ₂ O ₃	21.33	21.61	21.37	20.97	21.38	21.64	21.22	v	19.86
FeO _T	29.35	30.12	32.25	30.69	31.09	32.12	30.20	30.34	32.76
MnO	4.41	3.18	3.04	2.14	2.11	2.40	3.56	2.86	3.23
MgO	4.82	5.12	4.07	5.75	5.77	5.01	5.00	5.07	4.61
CaO	3.11	2.82	2.08	2.22	2.34	2.00	2.93	3.06	1.95
Cr ₂ O ₃	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	100.12	100.00	99.82	99.73	100.06	100.38	99.82	99.82	99.82
Number of atoms in formulae (oxygen basis 12)									
Si	2.953	2.951	2.969	3.007	2.959	2.951	2.966	2.959	3.076
Ti	0.001	0.001	0.000	0.001	0.001	-0.001	0.001	0.004	0.000
Al	2.001	2.023	2.020	1.959	1.997	2.025	1.987	2.009	1.844
Fe	1.954	2.001	2.163	2.034	2.060	2.132	2.006	2.011	2.159
Mn	0.298	0.214	0.207	0.144	0.142	0.161	0.239	0.192	0.215
Mg	0.572	0.607	0.486	0.679	0.682	0.593	0.592	0.599	0.541
Ca	0.265	0.240	0.178	0.188	0.199	0.170	0.249	0.260	0.165
Cr	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wt %	Grt 5, n: 26								
SiO ₂	37.55	37.37	37.66						
TiO ₂	0.02	0.02	0.02						
Al ₂ O ₃	21.32	21.39	21.68						
FeO _T	30.08	30.19	32.12						
MnO	3.61	3.44	2.49						
MgO	5.29	5.25	5.00						
CaO	2.47	2.61	2.16						
Cr ₂ O ₃	NA	NA	NA						
Total	99.82	99.82	99.82						
Number of atoms in formulae (oxygen basis 12)									
Si	2.972	2.962	2.967						
Ti	0.001	0.001	0.001						
Al	1.988	1.998	2.012						
Fe	1.990	2.001	2.115						
Mn	0.242	0.231	0.166						
Mg	0.624	0.620	0.587						
Ca	0.209	0.222	0.182						
Cr	NA	NA	NA						
	min	mean	max						
End-member composition**									
Pyrope	13.8%	20.5%	23.0%						
Spessartine	4.4%	6.3%	11.3%						
Grossular	5.3%	7.4%	10.4%						
Almandine	60.8%	65.8%	73.0%						

Table I4b: Major element EMPA of garnet cores and rims

	core ^a	mean ^b	rim ^c	core	mean	rim	core	mean	rim
NCB11-24									
Wt %	Grt 1, n: 30			Grt 2, n: 27			Grt 3, n: 30		
SiO ₂	34.89	36.37	40.90	35.60	36.30	36.50	36.10	36.27	36.50
TiO ₂	0.01	0.06	0.13	0.00	0.05	0.12	0.02	0.07	0.14
Al ₂ O ₃	18.91	20.92	21.11	20.81	21.16	21.32	20.90	21.12	21.31
FeO _T	31.91	33.58	35.83	30.61	33.00	34.35	35.32	36.27	37.50
MnO	1.88	2.75	3.25	1.82	2.69	3.59	1.03	1.32	2.19
MgO	1.65	2.01	3.19	1.62	2.08	2.57	1.59	2.14	2.34
CaO	1.98	4.00	5.83	3.11	4.25	6.25	2.25	2.51	2.96
Cr ₂ O ₃	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	98.24	99.71	100.17	98.68	99.55	100.03	99.18	99.73	100.34
Number of atoms in formulae (oxygen basis 12)									
Si	2.883	2.958	3.256	2.936	2.950	2.960	2.942	2.954	2.965
Ti	0.001	0.004	0.008	0.000	0.003	0.007	0.001	0.004	0.008
Al	1.774	2.005	2.048	2.014	2.027	2.041	2.006	2.027	2.043
Fe	2.160	2.284	2.466	2.080	2.243	2.331	2.423	2.470	2.550
Mn	0.129	0.190	0.225	0.125	0.186	0.247	0.071	0.091	0.152
Mg	0.199	0.244	0.393	0.196	0.252	0.310	0.194	0.259	0.284
Ca	0.169	0.349	0.506	0.275	0.370	0.544	0.196	0.219	0.260
Cr	NA	NA	NA	NA	NA	NA	NA	NA	NA
	min	mean	max						
End member composition**									
Pyrope	6.4%	8.2%	12.5%						
Spessartine	2.3%	5.1%	8.1%						
Grossular	6.0%	10.2%	17.8%						
Almandine	68.3%	76.5%	83.9%						

Table I4b: Major element EMPA of garnet cores and rims

	core ^a	mean ^b	rim ^c
NCB11-28			
Wt %	Grt 1, n: 20		
SiO ₂	36.817	36.90	37.195
TiO ₂	0.117	0.07	0.023
Al ₂ O ₃	20.846	20.85	20.784
FeO _T	29.387	29.58	28.832
MnO	6.906	6.14	6.08
MgO	2.25	2.47	2.619
CaO	3.672	3.87	4.367
Cr ₂ O ₃	NA	NA	NA
Total	99.998	99.90	99.924
Number of atoms in formulae (oxygen basis 12)			
Si	2.97761	2.981	2.99471
Ti	0.00712	0.004	0.00139
Al	1.98688	1.985	1.9721
Fe	1.98737	1.998	1.9411
Mn	0.47303	0.420	0.41458
Mg	0.27129	0.297	0.31436
Ca	0.31816	0.334	0.37668
Cr	NA	NA	NA
	min	mean	max
End-member composition**			
Pyrope	8.9%	9.7%	10.7%
Spessartine	12.4%	13.8%	15.5%
Grossular	10.1%	11.0%	12.4%
Almandine	63.7%	65.5%	66.1%

^a Values from the single spot at the core of the garnet.^b Average of values from the core to the rim of the garnet.^c Values from the single spot at the rim of the garnet.

NA: no value measured

** End-member compositions were calculated as follows

%Alm Fe/(Mg+Fe+Mn+Ca)

%Prp Mg/(Mg+Fe+Mn+Ca)

%Grs Ca/(Mg+Fe+Mn+Ca)

%Sps Mn/(Mg+Fe+Mn+Ca)

Table 15: Major element EMPA of amphibole

	min	mean	max	min	mean	max	min	mean ^a	mean ^b	max
Wt%	NCB12-11A, n: 62			JAC1, n: 60			JAC15, n^a: 44, n^b: 11			
SiO ₂	42.420	45.807	50.149	41.379	45.274	49.077	41.959	44.593	51.307	53.338
Al ₂ O ₃	6.144	10.403	13.734	6.936	11.581	16.417	0.461	13.000	3.767	16.030
TiO ₂	0.233	0.435	0.814	0.163	0.286	0.416	0.011	0.331	0.073	0.678
V ₂ O ₃	0.000	0.042	0.090	0.010	0.098	0.262	0.000	0.124	0.038	0.216
Cr ₂ O ₃	0.000	0.162	0.585	0.000	0.092	0.331	0.000	0.057	0.022	0.282
ZrO ₂	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ZnO	0.000	0.020	0.084	0.000	0.010	0.062	0.000	0.019	0.032	0.075
NiO	0.002	0.022	0.040	0.000	0.012	0.037	0.000	0.006	0.007	0.027
FeO	11.983	13.870	15.616	13.797	15.225	17.795	14.040	16.999	22.865	25.877
MnO	0.293	0.375	0.428	0.159	0.243	0.492	0.177	0.265	0.647	0.787
MgO	9.728	11.946	14.845	8.739	10.907	14.089	7.069	9.088	13.926	15.881
CaO	11.287	11.589	11.885	7.193	11.367	11.723	0.561	10.869	3.508	11.822
Na ₂ O	0.787	1.165	1.538	0.570	1.059	1.589	0.014	0.798	0.197	1.042
BaO	0.000	0.004	0.026	0.000	0.004	0.078	0.000	0.007	0.006	0.030
K ₂ O	0.065	0.219	0.384	0.000	0.065	0.197	0.006	0.233	0.072	0.541
Cl	0.002	0.017	0.035	0.000	0.007	0.057	0.005	0.050	0.019	0.088
F	0.000	0.100	0.247	0.000	0.012	0.098	0.000	0.026	0.013	0.251

Amphibole species

Group Name	Calcium Magnesio- Hornblende			Calcium Magnesio- Hornblende			Calcium Magnesio- Hornblende			Mg-Fe-Mn cummingtonite
	JAC5, n: 51			NCB12-18, n: 23			NCB12-21, n: 32			
	min	mean	max	min	mean	max	min	mean	max	
SiO ₂	41.371	43.859	49.251	42.373	46.150	51.439	42.217	43.263	44.850	
Al ₂ O ₃	6.091	11.548	13.386	6.339	10.521	21.495	9.677	11.519	12.584	
TiO ₂	0.256	0.390	0.630	0.198	0.388	1.144	0.328	0.673	1.046	
V ₂ O ₃	0.000	0.069	0.201	NA	NA	NA	NA	NA	NA	
Cr ₂ O ₃	0.000	0.021	0.185	0.000	0.049	0.130	0.000	0.005	0.034	
ZrO ₂	NA	NA	NA	0.000	0.020	0.105	0.000	0.010	0.052	
ZnO	0.000	0.027	0.075	0.000	0.025	0.076	0.000	0.022	0.069	
NiO	0.000	0.017	0.042	NA	NA	NA	NA	NA	NA	
FeO	15.965	17.702	19.060	6.200	14.350	16.063	18.777	19.258	19.631	
MnO	0.372	0.484	0.556	0.222	0.383	1.456	0.229	0.279	0.342	
MgO	7.965	9.256	12.233	2.909	10.669	13.301	7.479	8.082	8.904	
CaO	10.548	11.318	11.722	9.165	11.965	12.416	11.289	11.454	11.622	
Na ₂ O	0.560	1.077	1.345	0.420	0.977	5.313	1.067	1.196	1.373	
BaO	0.000	0.003	0.026	NA	NA	NA	NA	NA	NA	
K ₂ O	0.066	0.172	0.244	0.089	0.171	0.318	0.276	0.377	0.475	
Cl	0.000	0.006	0.021	0.000	0.006	0.014	0.002	0.007	0.015	
F	0.000	0.051	0.125	0.000	0.013	0.088	0.000	0.006	0.060	

Amphibole species

Group Name	Calcium Magnesio- Hornblende			Calcium Magnesio- Hornblende			Calcium Ferro- Hornblende		
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a Mean calculated for hornblende species

b Mean calculated for cummingtonite species

NA No value measured

Appendix J

U-Th-total Pb methodology

We used the Cameca SX-100 electron microprobe at New Mexico Institute of Mining and Technology (NMT, Socorro, USA) to obtain in situ U-Th-total Pb ages for <100- μm anhedral resorbed to euhedral monazite grains that exhibit clear microstructural relationships with fabric elements (cf. Williams et al., 1999). The two-part EMPA portion of the investigation involved high-resolution compositional mapping to identify intracrystalline age domains and quantitative chemical analyses of Y, Th, U, and Pb. Monazite grains were identified through manual scanning of rock thin sections noting high Ce-peaks, in addition to using energy dispersion spectra (EDS). Images were collected using high sample current (>200 nA) and small step sizes ($\sim 0.5\ \mu\text{m}$), while rastering the electron beam with the stage fixed (50 ms per pixel resolution of 512 x 512 pixels). Elemental maps were analyzed for distinct chemical domains to identify compositional zones that are likely consequent of monazite re(?) -crystallization. This step is important to determine optimal spot placement and ensure analysis of resolvable age domains; analytical protocol was carried out following Williams and Jercinovic (2002). Matrix corrections were made using the PAP method of Pouchou and Pichoir (1984, 1985). Quantitative trace-element analysis was done using a beam current of 150-200 nA at 15 kV accelerating voltage with a counting time of 700-900 s. To determine the appropriate background levels for Th, Y, Pb, and U the data were processed in BKGII (BackgroundII), a program developed by M. Jercinovic that performs a regression analysis to determine background concentrations. Once concentrations of U, Th, and Pb were obtained, the age equation of Montel et al. (1996) was solved by iteration based on calculated Pb.

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Table J1 EMPA U-Th-total Pb data for monazite in metasedimentary rocks of the NCGB, NW Ontario

	Y	Th	U	Pb	Age	Std. Err.
NCTK10-19 <i>Ab schist</i> NAD27, zone 15: 692153E, 5821302N						
19-2-1*	12140	5120	2100	1200	1978	50
19-2-2*	7290	6520	1390	960	1780	50
19-2-3*	8580	6440	1600	1110	1921	50
19-2-4*	8260	7420	1700	1540	2324	50
19-3-5	3050	30320	860	3860	2427	50
19-3-6	3010	28150	960	3610	2399	50
19-3-7	3340	29230	960	3720	2392	50
19-3-8	3340	33760	1030	4330	2427	50
19-3-9	3420	25970	1010	3310	2350	50
19-4-10	4270	42710	1400	5920	2584	50
19-4-11	5110	47020	1590	6260	2484	50
19-4-12	2460	30690	760	3860	2429	50
19-4-13	4600	36960	1130	4650	2384	50
19-4-14	4480	33930	860	4240	2410	50
19-5-15	3510	39130	1020	5260	2570	50
19-5-16*	5420	40720	1290	5910	2703	50
19-5-17	4990	28420	1080	3840	2484	50
19-5-18	3130	29510	960	3820	2431	50
19-5-19	2690	15750	500	1920	2307	50
19-5-20	2680	13850	580	1690	2238	50
NCTK10-26A <i>Gt-bt schistose conglomerate</i> NAD27, zone 15: 694428E, 5823783N						
26A-1-1	11750	92160	2660	12380	2488	50
26A-1-2*	12560	98930	2690	13530	2600	50
26A-1-3	12090	112240	2820	15170	2591	50
26A-1-4	13300	52820	3750	8050	2509	50
26A-1-5	14380	44540	4660	7320	2457	50
26A-1-6	14470	62500	4500	9710	2545	50
26A-1-7	14510	49040	4890	7970	2462	50
26A-3-8	11060	29090	2490	4340	2369	50
26A-3-9	11340	35040	2520	5150	2425	50
26A-3-10	11730	44220	2910	6540	2479	50
26A-5-11	10290	22200	2420	3620	2415	50
26A-5-12	10660	37950	2630	5660	2474	50
26A-5-13	10770	23130	2620	3670	2335	50
26A-7-14	10560	15770	2930	2860	2245	50
26A-7-15	10510	16900	2900	3090	2324	50
26A-7-16	10750	15290	3110	2970	2302	50
26A-8-17	12100	35080	3530	5450	2363	50
26A-8-18	11440	17480	3720	3650	2403	50
26A-8-19	10140	22930	2480	3770	2437	50
26A-8-20	11010	5910	3460	1990	2202	50
26A-8-21	11140	15390	3830	3470	2407	50
26A-9-22	10230	29700	2870	4660	2407	50
26A-9-23	10800	16620	2940	3330	2483	50
26A-10-24	11800	39650	3230	5990	2421	50
26A-10-25*	6400	43600	80	3910	1915	50
26A-10-26	12100	47370	3160	7100	2502	50
26A-10-27	11680	33210	2660	5000	2423	50
26A-10-28	10680	28240	2350	4210	2382	50
26A-11-29	12860	45120	3370	6900	2492	50
26A-11-30	13890	43300	4170	7190	2530	50
26A-11-31	11270	59430	2510	8060	2460	50

Table J1 EMPA U-Th-total Pb data for monazite in metasedimentary rocks of the NCGB, NW Ontario

	Y	Th	U	Pb	Age	Std. Err.
NCTK10-38 Bt schist <i>NAD 83, Zone 15: 673555E, 5843971N</i>						
38-1-1	9600	28600	2110	4210	2416	50
38-1-2	9970	20700	2490	3750	2572	50
38-1-3	11140	18260	3560	3920	2539	50
38-1-4	10280	17670	3100	3690	2576	50
38-2-5	11420	18300	2530	3400	2524	50
38-2-6	11400	27850	2740	4740	2570	50
38-2-7	10390	44240	2540	6710	2596	50
38-3-8	9760	44640	1270	5520	2363	50
38-3-9	9820	40190	2230	5560	2407	50
38-3-10	9730	32740	2140	4710	2423	50
38-3-11	10660	32750	2800	5380	2576	50
38-1-12	9720	39340	2750	5770	2434	50
38-2-13	11320	17490	2480	3150	2440	50
38-?-14	10440	29910	2680	4790	2494	50
NCTK10-44A And-st schist <i>NAD 83, zone 15: 670289E, 5850342N</i>						
44A-1-1	10700	30120	3550	5450	2584	50
44A-1-2	10740	40460	3380	6050	2386	50
44A-1-3	12080	41650	3590	6300	2394	50
44A-1-4	11730	33610	3420	5950	2636	50
44A-2-5	12590	72340	3800	9840	2391	50
44A-2-6	10710	34660	2920	5660	2572	50
44A-2-7	11890	56560	3120	7660	2363	50
44A-3-8	11890	45650	3280	7220	2586	50
44A-3-9	11460	44190	3240	7110	2614	50
44A-3-10*	10760	41930	2990	6970	2703	50
44A-3-11	11380	51910	3060	7160	2376	50
44A-3-12	12850	71390	3550	9010	2254	50
44A-3-13	12040	70850	3250	9080	2312	50
44A-4-14	10760	68170	3120	8630	2287	50
44A-4-15	12110	65620	3580	8780	2342	50
44A-5-16	12320	116680	3570	14090	2296	50
44A-5-17	12370	51210	3070	7960	2633	50
44A-6-18	11390	106870	3390	12970	2298	50
44A-6-19	11720	73630	2770	8770	2218	50
44A-6-20	11490	90030	2910	10650	2241	50
44A-1-21	11290	40490	3420	6530	2543	50
44A-1-22	11240	33560	3210	5660	2568	50
44A-1-23	11340	36860	3090	5870	2519	50
44A-1-24	11020	29980	3000	4960	2498	50
44A-3-25	11670	56920	3100	8500	2583	50
44A-3-26	12030	55660	3350	8460	2580	50
44A-4-27	10850	56940	2950	8370	2568	50
44A-5-28	11520	108800	3240	14960	2591	50
44A-5-29	12590	60540	2880	8750	2562	50
44A-5-30	12070	84860	3090	12140	2628	50

Table J1 EMPA U-Th-total Pb data for monazite in metasedimentary rocks of the NCGB, NW Ontario

	Y	Th	U	Pb	Age	Std. Err.
NCTK10-51A <i>Bt schist</i> NAD83, zone 16: 312525E, 5819101N						
51-1-1	11190	24620	5250	5900	2685	50
51-1-2	9560	15960	2510	3170	2563	50
51-2-3	9280	15290	2000	2820	2550	50
51-2-4*	6750	28520	2450	4010	2246	50
51-2-5	10380	46210	4670	7670	2499	50
51-2-6	9770	42430	4180	7160	2551	50
51-3-7	11540	15490	2310	2990	2546	50
51-3-8	9000	29830	4170	5670	2564	50
51-4-9	8450	26720	3700	5160	2605	50
NCTK10-76 <i>Two-mica schist</i> NAD27, zone 15: 702814E, 5821125N						
76-1-1*	9230	43540	730	6740	3016	50
76-1-2	9500	40660	840	5490	2628	50
76-1-3	9770	44380	690	5230	2360	50
76-1-4	12210	57650	5010	8960	2447	50
76-1-5*	11970	71020	110	9710	2851	50
76-1-6	10960	75330	230	9910	2735	50
76-1-7	18130	73960	2530	9570	2399	50
76-2-8	12930	86230	960	11070	2595	50
76-2-9	9270	63170	880	7810	2481	50
76-2-10	10070	54340	1330	7560	2569	50
76-2-11*	19360	72020	3230	11830	2891	50
76-2-12	10920	86390	1870	12300	2748	50
76-3-13	8030	35830	750	4530	2472	50
76-3-14	10470	53550	190	6940	2692	50
76-3-15	12420	77560	2690	10770	2573	50
76-3-16	10430	132560	990	14940	2329	50
76-4-17	11440	57490	1800	8420	2728	50
76-4-18	10610	52680	1610	7820	2768	50
76-4-19	9370	7610	2590	2280	2638	50
76-5-20	12620	59560	6010	11020	2741	50
NCB11-34 <i>Meta-granule conglomerate</i> NAD 27, zone 15: 649138E, 5867125N						
B34-1-1	5500	26910	950	3420	2370	50
B34-2-2	4250	9770	670	1390	2377	50
B34-2-3	3650	6590	790	970	2154	50
B34-2-4*	3590	9340	390	1280	2486	50
B34-2-5	4130	5370	700	820	2170	50
B34-3-6	3340	14090	790	1900	2348	50
B34-3-7	3710	6270	620	900	2215	50
B34-3-8	3180	14190	570	1790	2318	50
B34-6-9	3560	12280	600	1590	2312	50
B34-6-10	19110	8080	0	830	2193	50
B34-6-11	3620	10210	630	1390	2330	50
B34-6-12	4570	3860	810	740	2250	50

Spot name follows the convention x-y-z;

where x = sample number, y = grain number, and z = spot number.

^a Elemental data in ppm; age and error in Ma.

* Denotes samples that were not used for determination of age populations.

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