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# Deciphering the Age and Significance of the Cora Lake Shear Zone: Athabasca Granulite Terrane, Northern Saskatchewan

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# DECIPHERING AGE AND SIGNIFICANCE OF THE CORA LAKE SHEAR ZONE: ATHABASCA GRANULITE TERRANE, NORTHERN SASKATCHEWAN

A Thesis Presented

By

SEAN P. REGAN

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**DEDICATION**

To my father, Paul J. Regan III

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**ABSTRACT**

**DECIPHERING THE AGE AND SIGNIFICANCE OF THE CORA LAKE SHEAR ZONE: ATHABASCA GRANULITE TERRANE, NORTHERN SASKATCHEWAN**

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Interpreting the tectonic significance of high strain zones requires detailed knowledge of the P-T-t-D history of rocks on either side and of tectonized rocks within the shear zone. In-situ monazite geochronology is particularly useful because it generates a time-integrated framework of metamorphism and fabric development. This can be achieved by correlating monazite compositional domains with the growth and consumption of major phases. Furthermore, monazite can be a fabric forming mineral, and can be directly linked to structural fabrics and kinematics. The Cora Lake shear zone (CLsz) represents a major lithotectonic discontinuity within the deep crustal Athabasca Granulite terrain, and preserves intense mylonitic to ultramylonitic fabrics. The 3-5 km wide CLsz strikes ~231°, and dips ~62° to the Northwest, has a moderately plunging stretching lineation (SW trend) with abundant sinistral kinematic indicators. These data indicate oblique extension with NW hanging wall down and to the SW relative to the SE footwall. The NW hangingwall is dominated by the ca. 2.6 Ga charnockitic Mary batholith. The southeastern footwall is primarily underlain by the heterogeneous ca. 3.3-3.0 Ga Chipman tonaite straight gneiss. Although both share common Archean (ca. 2.55 Ga) and Paleoproterozoic (ca. 1.9 Ga) deformation events, the style and P-T conditions of deformation are different. The earliest phase of deformation within the NW hangingwall consists of a penetrative subhorizontal flow fabric at 0.9 GPa and ~725°C (2.56 Ga), but folding in the SE footwall associated with the development of a strong upright axially planar fabric at 1.35 GPa and 850°C. Deformation at ca 1.9 Ga was characterized by upright folding, similar in orientation, in both hangingwall (0.9 GPa; 725°C) and footwall (1.17 GPa; 825°C). Deformation related to the CLsz occurred at 1880 Ma (0.9-1.06 GPa; ~775°C), and is responsible for juxtaposing two levels of lower crust. The Cora Lake shear zone is interpreted to be the culmination of a trend of increased strength, localization, strain partitioning, and vertical coupling. Furthermore, the CLsz overprints fabrics from each wall, marks the development of a major lateral lithotectonic discontinuity, and an introduction of major structural and compositional heterogeneity within the lower continental crust.

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# CHAPTER 1

# INTRODUCTION

Lower crustal properties are fundamental to the topographic, structural, and magmatic evolution of continental lithosphere during orogenisis (Rutter and Brodie, 1992; Beaumont et al., 2006). Therefore structural, compositional, and even age variations can have an effect on the behavior of continental lithosphere. Lower continental crust has been proposed to serve several important functions. It has been suggested to weaken and flow under high lithostatic stress serving to decouple the lowermost crust and lithospheric mantle from the middle and upper crust (Rey et al., 2010; Dewei, 2008). Furthermore, the lower crust likely serves as a zone of heat and mass transfer between crust and underlying lithospheric mantle (Chapman and Furlong, 1992; Kay et al., 1992; Kay and Kay, 1991; Sawyer et al., 2011). The strength and bulk density of lower continental crust exercises control on the isostatic and rheologic response of lithosphere during crustal thickening. Furthermore, lower crustal stiffness plays a critical role in the relationship of surface topography and mantle lithosphere force balance (Flesch and Bendick, 2012). Lastly, parts of the lower crust can melt to form plutonic and batholithic bodies, which coalesce at shallower crustal levels (Whitney, 1998; Sawyer et al., 2011; Brown et al., 2011). Therefore, an increased understanding of lower crustal properties is a requirement to validate the increased spatial and temporal resolution of lithospheric-scale tectonic models.

Estimations of lower crustal properties are still widely debated, and remain somewhat enigmatic: strong vs. weak, mafic vs. felsic, fertile vs. restitic, hot vs. cold, (Jackson, 2002; Holbrook et al., 1992; Percival, 1992; Mezger 1992; Rudnick and Fountain, 1995). However, one characteristic appears to be emerging from all modes of observation: heterogeneity. Compositional and structural heterogeneity has been observed at all scales within lower crustal exposures (Williams and Hanmer, 2005; Mezger, 1992), seismic studies (Holbrook, 1992), and lower crustal xenoliths (Rudnick, 1992). Therefore, to truly understand the physical-chemical properties of lower continental crust, we must characterize heterogeneity. Is the heterogeneity largely lithologic and due to lateral compositional and rheologic variations? Or is the heterogeneity structural in nature and due to variations in strain, and localization of deformation? Although evidence for heterogeneity comes from all modes of observation, high resolution characterization requires isobaric exposures of lower crustal rocks that have not been completely overprinted during exhumation. Furthermore, it is critical to place timing constraints on structures that generate lateral heterogeneity in order to evaluate when, in their respective tectonic history, the heterogeneity was introduced.

The Athabasca Granulite terrain in the western Churchill Province, Canada, exposes ~20,000 $Km^2$ of high pressure granulite, making it one of the largest exposure of exhumed lower continental crust in North America (Fig. 1; Mahan and Williams, 2005; Williams and Hanmer, 2006; Mahan et al., 2006a,b). The Cora Lake shear zone (CLsz) is one of the major structural elements within the terrain. It represents a major lithotectonic discontinuity that was active while the rocks were in the deep crust. It has been proposed to represent a fundamental boundary between a flowing (decoupled) domain and non-flowing (coupled) deep crust. Analysis of the CLsz provides a chance to observe lateral heterogeneity within lower continental crust, to propose and evaluate critical hypotheses regarding horizontal and vertical coupling, and provide insight regarding the role of heterogeneity in the growth and maturation of lower continental crust. Furthermore, block-style architecture is characteristic for Athabasca Granulite terrain, and many granulite terrains around the world, and as a major lithotectonic boundary, the CLsz will help identify the origin and significance of these structures.

## 1.2 Background

The Snowbird Tectonic Zone is a 2700 km geophysically defined lineament within the Western Canadian Shield, and divides the Western Churchill Province into the northern Rae and southern Hearne domain (Hoffman, 1988). Three crustal scale high P lozenges are exposed along the Central Snowbird Tectonic Zone, initially referred to as the striding Athabasca Mylonite zone (Hanmer et al., 1995), from southwest to northeast: 1) East Athabasca Mylonite Triangle, 2) Selwyn Lozenge, and 3) Three Esker Lozenge (Hanmer et al., 1995; 1997). When right lateral, Paleoproterozoic, strike slip motion is accounted for; the three lozenges compose a large-scale deep crustal terrain: The Athabasca Granulite Terrane (Mahan and Williams, 2005). The East Athabasca mylonite triangle is located in northern Saskatchewan, and is the southern portion of the Athabasca Granulite Terrane (e.g. Williams et al., 2009; Mahan and Williams, 2005; Hanmer et al., 1995a, b). It has been hypothesized that the region was resident in the deep crust for the ca. 650 million years (i.e. 2560-1900 Ma; Mahan and Williams, 2005; Dumond et al., 2010; Williams et al., 2009). This attribute makes the East Athabasca Mylonite Triangle a premier location to study lower crustal processes, stabilization, and reactivation.

The East Athabasca mylonite triangle consists of three structural and tectonic domains: the Northwestern domain, the Chipman domain, and the Upper Deck (Figure 1; Hanmer, 1994). The Legs Lake shear zone defines the southeastern boundary of the Chipman domain, and was a critical structure that exhumed the Athabasca Granulite Terrain at ca. 1850 Ma (Mahan et al., 2003; Mahan et al., 2006a). The Northwest domain and Chipman domain are separated by the Cora Lake shear zone (CLsz). The Grease River shear zone is the northern boundary of the Northwestern domain, and accommodated ca. 110 km of right-lateral strike slip motion at ca.

1800 Ma. An earlier (ca. 1900 Ma) shearing event on the Grease River shear zone has been suggested by Dumond et al. (2008). Discussion herein will focus on the CLsz, and its wall rock.

The Northwestern Domain is the hangingwall of the CLsz, and is composed of felsic to mafic plutonic rocks, the largest of, which is the ca. 2.63 – 2.6 Ga Mary batholith (Hanmer, 1994). The multiphase Mary batholith is dominantly charnockitic to mangeritic, and is interlayered on its northeastern boundary with the mafic granulite and anorthositic rocks of the ~2.6 Ga Bohica mafic complex (Dumond et al., 2010). Screens of felsic granulites occur throughout the Northwestern domain (Mahan et al., 2006; Dumond et al., 2010). Dumond et al. (2010) showed that the charnockitic gneisses have a sub horizontal $S_1$ layering, with top to the SE kinematics, interpreted as an exposed field example of lower crustal flow. The shallow fabric is cut by discrete meter-scale sub vertical shear zones ($S_2$), with kinematics consistent with Grease River shearing at ca. 1900 Ma (Dumond et al., 2008; 2010).

The Chipman domain is the footwall of the CLsz, and is dominantly composed of the Chipman tonalite straight gneiss (~3.2 Ga; Macdonald, 1980; Martel et al., 2008), with subordinate screens of garnet rich mafic and felsic granulite (2.6 Ga; Flowers et al., 2008; Mahan et al., 2006a; 2006b; 2008), and the 2.6 Ga Fehr granite, which is exposed only in the southeastern portion of the Chipman domain (Mahan et al., 2003; Koteas et al., 2010). Also present in this domain is the ca. 1900 Ma Chipman mafic dike swarm, which extends along strike for perhaps as much as 2000 km (Flowers et al., 2006a; Mahan and Williams, 2005). The dikes range from hornblende-plagioclase, fairly undeformed dikes, to garnet granulite, to melted and highly migmatitic members (Flowers et al., 2006a). Zircon grains separated from leaucosome within the melted Chipman dikes provide a minimum age of intrusion at 1896.2 +/- 0.3 Ma (Flowers et al., 2006a).

Mahan et al. (2008) performed detailed petrographic analysis of 2.6 Ga mafic granulites within the chipman domain, and found that within the 1.1 GPa assemblage (med-P) are necklaces of metamorphic products from an earlier, dismembered metamorphic reaction. The assemblage of Cpx + grt yielded quantitative thermo barometric results of greater than 1.3 GPa and 850°C, and based on zircon analysis from Flowers et al. (2008), Mahan et al. (2008) concluded that this earlier assemblage was a result of tectonometamorphism and subsequent folding at ca. 2.56 Ga (abbreviations after Whitney and Evans, 1983).

The CLsz has been has been previously mentioned in Mahan et al. (2008; 2011) and Dumond et al. (2010). Mahan et al. (2008) suggested that Chipman dikes are highly strained within the CLsz region, and to a lesser extent further east, suggesting that the CLsz was active post dike swarm. Dumond et al. (2010) briefly suggested a component of dextral shear along it at 1.9 Ga, during $D_2$. With crustal flow in the northwestern hangingwall observed by Dumond et al. (2010), it has been speculated that the CLsz may also be an older heterogeneity during flow, where rocks to the southeast were too strong to flow.

## 1.3 Methods

Detailed mapping of the CLsz, and adjacent subdomains, was carried out during a total of 14 weeks of field work during the summers 2010, 2011, and 2012. Characterization of the hangingwall to the northwest and footwall to the southeast involved integrated structural and metamorphic analysis. Although the two domains share common Archean (ca. 2.55 Ga) and Paleoproterozoic (ca. 1.9 Ga) deformation events, the structures and grades of metamorphism preserved are different, and thus are noted with a subscript N or C for Northwestern or Chipman domain (Southeastern) respectively. Structural analysis included fabric orientation, magnitude of internal deformation, and kinematic analysis. Kinematic analysis was performed on thin sections cut perpendicular to foliation, parallel to lineation.

Petrologic analysis was done with standard microscopy to determine equilibrium mineral assemblages and petrologic gradients within, and outward of the CLsz. Another main objective of this study was careful microstructural analysis of lithology's that contains suitable minerals for thermo barometry, and linking these textures and structures to rocks that contain monazite for geochronology. Samples for analytical work were chosen based on structural setting, fresh minerals for microanalysis, and proximity to samples that may contain monazite. Micro textural relationships, such as sub grain structure, recrystallization, and grain boundary sliding (i.e. angular misorientation; Passchier and Trouw, 2004) were identified with certain fabrics to establish a paired deformation-metamorphism relationship (Williams and Jercinovic, in press). These relationships help develop a better idea of stable assemblages during deformation, and establish a direct link of fabric to metamorphism.

#### 1.3.1 Compositional mapping and analysis

Wavelength dispersive spectroscopy (WDS) compositional maps and mineral analysis were acquired using a Cameca SX-50 electron microprobe at the University of Massachusetts, Amherst. Analytical procedures follow that of Williams et al. (2006) and Dumond et al. (2010). Highly polished thin sections were coated with 14.7 nm of carbon prior to analysis. Compositional maps of full thin sections were done using a 300 nA current at 15 KeV, a 25 ms dwell time, and a beam close to the step of 35µm. Five elements were mapped including Mg, K, Ca, Zr, and Ce to locate monazite and zircon in addition to providing a compositional base map of the thin section.

High Resolution maps of individual phases (i.e. Garnet, plagioclase, and pyroxene)were done using a 100 nA current, and 100 ms dwell time, and a step size of 2 to 10 µm. Electron microprobe compositional maps (*see below*) were utilized to characterize compositional zoning, and to choose domains for thermo barometric calculations. Monazite single grain compositional maps for geochronology are crucial for complete understanding of compositional zonating, and its potential petrogenic relationship to the growth and consumption of major and accessory phases (Williams et al., 2007). Monazite grains were mapped by rastering a beam with the stage fixed, with spectrometers set for Y, Si, Th, U, and Ca. These maps were done with a focused 200 nA current at 15 KeV at a step size of less than 0.5 µm to ensure sub-micron resolution. All maps were processed in Adobe Photoshop, and the same levels were applied to every grain within a thin section so that compositional domains could be compared with all grains (i.e. simultaneous processing). Monazite compositional maps were then superimposed on full thin section compositional maps to better evaluate the textural setting and history of each monazite crystal.

Quantitative mineral analyses were performed using a 20 nA current. Feldspar analyses were performed using a slightly defocused beam (2 µm) at 15 KeV to prevent Na diffusion. A focused beam was utilized for garnet and pyroxene. Calibration was performed using standards similar to phases analyzed. Matrix corrections were calculated using a PAP model (Pouchou and Pichoir, 1984).

Pressure and temperature estimates of major structural fabrics were calculated with TWQ 3.2 (Berman, 1994, updated in 2007; Plunder et al., 2012). Deformation microstructures were correlated with metamorphic assemblages to asses' mineral stability during fabric generation. Electron microprobe compositional maps were utilized to identify any potential compositional zoning to evaluate P-T history and select equilibrium domains. P-T conditions calculated by TWQ are estimated to have an absolute error of 50° C and 0.1 GPa (Berman, 1991; Plunder et al., 2012). Petrologic forward modeling (i.e.pseudo section) were made using Theriak-Domino, and bulk compositions presented in Williams et al. (2000;Capitani and Petrakakis, 2007; 2008). Both TWQ calculations and pseudo section modeling were done using Berman's 1994 thermodynamic database (updated in 2007) to remain internally consistent. Feldspar solution model used in both program versions is from Fuhrman and Lindsley (1988). Amphibole data was calculated with TWQ version 1.02 with data from Mader et al. (1994). Solution models for garnet and pyroxene are from Berman and Aranovich (1996).

### 1.3.2 Monazite analysis and geochronology

Monazite geochronology was performed in-situ using the Cameca SX-100 "ultrachron" at the University of Massachusetts, Amherst following the procedures outlined by Williams and Jerconovic (2002; Williams et al., 2006). Five spectrometers were used for measuring all the REE elements, U, Th, Pb, S, Ca, K, Sr, Si, Y and P. Lead was measured using two very large PET crystals (VLPET) simultaneously and counts were aggregated in order to increase count resolution. Background measurements were performed on the first measurement in a set of analyses within an individual compositional domains. Four to eight analyses per domain were taken per age, with standard error of the mean reported at the 95% confidence level (2σ).

Calibration for monazite analysis was performed on synthetic phosphates. $PbPO_4$ (Pyromorphite) was used for Pb, $ThPO_4$ (Barbanite) was used for Th, and $UO_2$ was used for U. Calibration was performed prior to every analytical session, and for long sessions, performed in the middle as well. Peak verification was routinely done for P, Ce, La, and Nd using synthetic phosphates prior to analytical session. An in house consistency standard (Moacyr), was analyzed prior to, and throughout, analytical sessions (506 +/- 1 Ma; *see discussion in* Williams et al., 2006; Dumond et al., 2008).

# CHAPTER 2

# ROCK TYPES

## 2.1 Introduction

The CLsz occurs along the boundary between the Northwestern and Chipman domain of the Athabasca Granulite Terrain. It reworks rock types of both domains, and thus has been divided into hanging wall (northwestern domain) and footwall (Chipman domain) affinity rocks. CLsz related deformation outside of the shear zone has not yet been observed. Published quantitative thermo barometry from both the northwestern domain, and footwall domain suggests a minimum of 0.2 GPa difference across the CLsz (Williams et al., 1995; Williams et al., 2000; Mahan et al., 2003; 2008; 2011; Mahan and Williams, 2005; Flowers et al., 2006a,b; Dumond et al., 2010)

## 2.2 Hangingwall

The northwestern hangingwall, within the field area, is dominated by the ~2.6 Ga, composite Mary batholith (Fig. 3a; Hanmer et al., 1994; Hanmer, 1997). The Mary batholith ranges from granitic to granodioritic in composition, and usually contains primary opx, along with plagioclase feldspar, Potassium Feldspar, Quartz, +/- biotite (Williams et al., 2000; Dumond et al., 2010). Commonly, this primary assemblage is heavily to completely overprinted by a metamorphic assemblage consisting of Plag+cpx+grt+/-qtz+/-kspar assemblage. The reaction:

$$2.2\ \text{Opx} + 8.0\ \text{Pl}_1 = 1.25\ \text{Grt} + 6.7\ \text{Pl}_2 + 1.2\ \text{Qtz}$$

has been discussed in detail by Williams et al. (2000), Dumond et al. (2010), and Holland (2012). Plagioclase$_1$ is relatively Ca rich compared to Plagioclase$_2$ is Na rich.

The ca. 2.6 Ga Bohica mafic complex dominates the northeastern part of the hangingwall (Fig. 3b; Hanmer et al., 1994). This suite is lithologically heterogeneous, ranging in composition from amphibolite to cpx+grt+plag anhydrous compositions to more intermediate, opx-bearing variants. The petrologic complexity of this suite is currently under investigation. There are local thin (~10 m thick) layers of a megacrystic, lilac grt bearing, granite (Beed Granite) interlayered with the Bohica complex and are likely textural variants of the Mary batholith.

Felsic granulite (diatexite) is typically exposed in thin, tens of meter wide screens (Hanmer, 1994). They have an assemblage of plag+kspar+qtz+grt+sill+/-opx+/-biot+/-musc+/-kyn. Garnet ranges in size from a few microns to 10's of centimeters in width, commonly displaying fractures perpendicular to penetrative foliation, and locally replaced by biotite+/-cordierite (Mahan et al., 2006a,b). Garnet commonly contains small, round quartz inclusions. This rock type typically contains abundant monazite, making it suitable for placing timing constraints throughout the region. Felsic granulites have been interpreted as remnants of biotite dehydration melting (Baldwin et al., 2004; Dumond et al., 2010).

### 2.3 Footwall

The heterogeneous, ca. 3.2 Ga, Chipman tonalite straight gneiss is the dominant lithology in the southeastern footwall (Chipman domain; Fig. 3c; Macdonald, 1980; Hanmer, 1994). This lithology is dominated by tonalite with local layers and schlierened amphibolite and grt granulite. Quartz is variable in abundance, and local exposures of anorthosite do occur within the field area. Tonalite layers range from garnet absent to garnet-rich (>15% modal grt), with varying crystal sizes.

The ca. 1.9 Ga Chipman dike swarm occurs throughout the footwall domain, and dikes range in width from <0.5 meters, to greater than 10 meters (Fig. 3d; Flowers et al., 2006a). Their composition ranges from a nearly pristine primary assemblage of hornblende and plagioclase, to granulite grade clinopyroxene and garnet, and migmatitic members (Flowers et al., 2006a; 2008). The dikes are commonly oblique to host fabric, and are almost exclusively

intrude Chipman tonalite, and Fehr granite further to the southeast (Koteas et al., 2010). Obliquity varies from clockwise to counterclockwise, and is generally no greater than a few degrees.

Circa 2.6 Ga mafic granulites occur within the footwall and contain hbl+cpx+grt+plg+/-opx+/-rt (Mahan et al., 2008; Flowers et al., 2008). They are generally exposed in meter to decimeter wide lozenges within the tonalite, and locally are associated with mag+grt layers. The mafic granulite layers are differentiated from chipman dikes by a coarser grain size, the presence of orthopyroxene, and characteristic boudins of coarse garnet + clinopyroxene + hornblende, which Mahan et al. (2008) interpreted to represent the first of two granulite grade metamorphic events to effect the area. The surrounding hbl+plg+opx+/-grt matrix anastomoses around these relict lenses.

**2.4 Lithology's within the CLsz**

The CLsz contains a wide variety of rock types and assemblages. Tectonized megacrystic granites, ultramylonitic granitoids, felsic granulites, mafic granulites , and well banded intermediate orthogneiss (+/- grt +/- opx) ultramylonites make up the CLsz within the study area (Fig. 4). Pseudotachylite and minor greenschist facies cataclasis zones occur within mafic and intermediate ultramylonites. They are parallel to the CLsz, and continuous for at least several kilometers. Hydrous assemblages are common throughout the CLsz and range from synkinematic rims of biot around grt to randomly oriented chlorite grains as pseudo morphs after garnet.  Garnet, within felsic granulites is commonly fractured, locally brecciated with biotite filling cracks.

# CHAPTER 3

# STRUCTURAL GEOLOGY

## 3.1 Northwestern wall rocks

The northwestern wall rocks contain two pervasive fabrics. The earliest ($S_{1N}$) is defined by gneissic layering, and is best exposed in low strain domains and fold hinge regions ($F_{2N}$). Folds are large amplitude and upright, with a calculated axis of ~12° to 240°. $S_{1N}$ gneissic layering is defined by compositional layering, which is generally associated with modal amounts of opx, cpx, and grt. Kinematic analysis within this field area of $L_{1N}$ suggests top to the East-South-East relative motion. Plagioclase porphyroclasts display core-mantle structures, both σ and δ- clast asymmetry, and s-c-c' geometries consistent with top to the east-south-east relative motion (Passchier and Trouw, 2004). Plagioclase recrystallization contains consistent microstructural evidence for dislocation creep, grain boundary migration, and rotation (Passchier and Trouw, 2004). Subgrain structure occurs along the edges of intact plagioclase porphyroclasts, and are surrounded by fine grained plagioclase grains with undulose extinction with an increasing angular misorientation away from the core (Williams et al., 2000). With a shallow enveloping surface and consistent kinematics, this fabric is correlative to $S_1$ of Dumond et al. (2010) further to the west where it was interpreted to represent lateral flow of the crust.

Axial planar to these large folds is a second planar fabric ($S_{2N}$), which ranges in intensity from a subtle mineral alignment to mylonitic with grain sizes approaching the sub mm scale. $S_{2N}$ strikes an average of 240°, is sub vertical, and contains a stretching lineation that plunges shallowly to the SW (12° to 242°).This fabric is strongest within limb domains, and far less developed to completely absent within hinge regions, although it is present throughout the northwestern hangingwall. S-C-C' geometries, σ-clast asymmetry suggest dextral sense of shear along $L_{2N}$. Porphyroclasts also display abundant microstructural evidence for dislocation creep, grain boundary migration, and sliding (Williams et al., 2000; Passchier and Trouw, 2004).

**3.2 Southeastern wall rocks**

The oldest observed fabric within the footwall is heterogeneously preserved. Crenulated domains of Chipman tonalite occur in thin exposures and may represent relict hinge domains. These crenulations have a sub horizontal enveloping surface similar to the northwestern hangingwall. This early fabric ($S_{1C}$), is best preserved within mafic granulites, and consists of layered $M_{1C}$ assemblage (Fig. 5d; Cpx+grt; after Mahan et al., 2008). Although, this original layering is usually highly transposed, and boudined, where present. This was interpreted by Mahan et al. (2008) to reflect early sub horizontal gneissic layering.

$S_{2C}$ is the dominant fabric within the field area. It is upright, and axially planar to open, upright meter-scaled folds. $F_{2C}$ are heterogeneously preserved Meter-scale upright folds of migmatites and mafic granulites (Fig. 5e), and on a km-scale with crenulated domains defining the hinge regions. Axes plunge shallowly to the SW, parallel to the $L_{2C}$. Kinematics varies, and may be inherited from $S_{1C}$ that was subsequently folded. $S_{2C}$ is extraordinarily straight, especially in the chipman tonalite. The banded nature of the Chipman tonalite suggests that large-scale transposition occurred throughout the region, and that larger scale folds are not intact.

### 3.3 Cora Lake shear zone ($S_3$, $M_3$, $D_3$)

The Cora Lake shear zone divides the rocks of the northwestern hangingwall from the rocks of the southeastern footwall, and is locally contains intense ultramylonite. The CLsz contains rocks that appear to have the same protoliths as wall rock, and are of either hangingwall, or footwall affinity. The shear zone strikes to the SW (~231°) and is steeply to moderately dipping to the northwest. The foliation is defined by alternating mafic and felsic layers and by leaucosome vs. restite layering. There is a strong mineral lineation, which plunges obliquely to the southwest, approximately 19° to 238°. This lineation well developed throughout the shear zone, locally with clinopyroxene forming long rods.

Abundant asymmetric porphyroclasts and S-C-C' geometries (Passchier and Trouw, 2004) within the CLsz all suggest oblique-normal, sinistral sense of motion, i.e. northwestern hangingwall moved down and west relative to the southeastern footwall. Therefore, the CLsz is a third deformation fabric, which effected all earlier fabrics within both hanging and footwall. However, since both wall rocks have multiple penetrative fabrics, deciphering a magnitude of inherited fabric compared to CLsz strain is difficult, and is thus interpreted to be a composite fabric. Pseudotachyalite and localized greenschist facies cataclasis zones occur within the CLsz, and appear to be relatively continuous along strike.

An east-west transect is presented below (Fig. 6). Divisions are based on structural and petrologic gradients across the shear zone, and associated fabric intensity, compositional variation, and mineral stability.

Zone 1: The southeastern margin of the CLsz (Cora Lake region) is primarily underlain by Chipman tonalite straight gneiss. There are also exposures of mafic and felsic granulite.

Gneisses are S>L tectonites, with minor preservation of an older folded fabric ($F_{2C}$). These folds do not contain an inherited Lineation (i.e. $L_{2C}$), but rather contain a strong $L_3$. Some folds contain only half of the hinge, with the rest of it being realigned into $S_3$. Kinematics is consistently sinistral. Garnet within felsic granulites are highly fractured perpendicular to $S_3$, and have texturally static biotite along fractures.

Zone 2: Zone 2 is a 100 m thick domain on the western shore of Cora Lake characterized by intense straight layered ultramylonite. On the northwestern shore of Cora Lake there is a spectacular cliff-forming ultramylonite. S=L tectonites, with grain sizes approaching the micron scale define this zone, and locally rocks look glassy. There are a variety of rock types, but layered anorthosite dominates. However, both cpx bearing anorthosite to tonalite, and biotite bearing anorthosite occur. Lineations are pronounced, with feldspar ribbons containing axial width ratios of greater than 1:60. Kinematic indicators are rare due to fine grain sizes. Plagioclase and cpx are unnanealed (Pennacchioni, 2004). Crosscutting and undeformed carbonate veins occur throughout this zone. Zone 2 grades into lower strained zone 3 rocks to the northwest.

Zone 3: This zone contains a strong $D_3$ fabric, but there are abundant strain gradients, and gradational rock type changes. Garnetiferous chipman tonalite grades into intermediate granulite +/- opx +/- grt to the northwest. Mafic granulites are present, but only occur as ~5 meter wide lozenges 10's to 100's of meters long. All rocks within this zone are mylonitic with sinistral σ-clasts defined by matrix recrystallization around coarse grt (Fig. 7b). Fine grained intrafolial fold hinges with axes parallel to the stretching lineation occur throughout this zone. Anastomosing ultramylonites, similar to those in zone 2, occur locally throughout this zone (Fig. 7c). Brittle faults and less abundant greenschist facies zones roughly 10 m wide are sub parallelto local fabric, but the continuity across them suggest that the brittle structures did not contribute significantly to the exposed structural complexity.  Pseudotachylite is also common within this zone, particularly in ultramylonitic mafic granulites.  Pseudotachylite networks range from $S_3$ parallel to slightly oblique, and similarly to ductile fabrics, contain sinistrial strike-slip separation.  Xenoliths of local wall rocks are fractured and bent within generation planes, and locally in smaller networks.  Quartz is unannealed in more felsic ultramylonites.  Grt is fractured and dismembered along foliation planes, with biotite filling in their cracks, and occasionally form synkinematic rims.

Zone 4: Zone 4 marks the transition from footwall affinity to hangingwall affinity rock types. Intermediate granulite is grades into semi-continuous sheets of felsic granulite interlayered on a decimeter scale with L>S felsic orthogneiss.  The orthogneiss ultramylonites increase in abundance northwestward.  Felsic granulites commonly contain alternating feldspar and quartz domains.  Both feldspar and quartz contain well developed sub-grain structure, but do not contain coarse, polygonal grain boundaries.  Although feldspar and quartz crystals are still somewhat unannealed, evidence of minor recovery suggests a higher degree recovery than in zone 2 and 3.  Kinematic indicators are rare within orthogneiss ultramylonites due to the high degree of strain.  Coarse garnet in felsic granulites are fractured, dismembered, and contain coarse-round quartz inclusions.  Biotite is also present in felsic granulite matrix.

Zone 5: Megacrystic granitoids (+/- biot) are intercalated with opx bearing migmatites at varying scales (Fig. 7d).  Along strike in the northeast portion of the study area, these lithology's are associated with intermediate to mafic lozenges, local garnetites, and felsic granulites.  The megacrystic granitoids ultimately pinch out completely to the northeast.  Folds are variably preserved on a meter to submeter scale, but contain a strong $L_3$.  Folds are defined by compositional layering, which varies from migmatitic layering with alternating leaucosome and melanosome layers to non-migmatitic gneissic layering. Tectonic slivers of intermediate granulite +/- chipman dikes occur locally.

Zone 6: Within this zone, the CLsz fabric is significantly less intense, with crystal sizes ranging from protomylonitic to subordinate mylonites. Charnockitic gneisses are interlayered on a 100 meter-scale with felsic granulites. Sparse σ-clasts and S-C-C' geometries suggest sinistral motion consistent with $D_3$ (Passchier and Trouw, 2004). Both quartz and feldspar crystals are well annealed. Charnockites contain anthophyllite after opx, but also hbl defining assymetric tails on opx, suggesting both dynamic and static hydration. Grt is generally intact, with small fractures perpendicular to host rock foliation. The fractures locally contain containing small amounts of biot.

The CLsz is extremely heterogeneous, but contains a structural and compositional gradient across it. We use this subdivision to target representative samples. Furthermore, it is apparent that localization has played a critical role in the evolution of the CLsz given the abundant strain gradients.

## CHAPTER 4

## METAMORPHIC PETROLOGY

### 4.1 Introduction

Five planar fabric generations have been identified within the field area. Systematic petrography of every fabric revealed metamorphic assemblages indicative of mineral stability during fabric generation or reorientation. By correlating microstructures to compositional zonation and/or the growth of phases at the expense of another, we can link a structural component in a rock to a metamorphic assemblage, and eventually use quantitative thermo barometry to calculate metamorphic conditions.

### 4.2 Northwestern Hangingwall

The earliest structural fabric within the northwestern hangingwall was a sub horizontal gneissic fabric($S_{1N}$). Along this fabric, plagioclase porphyroclasts are dynamically recrystallized and contain blood red garnet along the edges of recrystallized tails. Primary orthopyroxene +/- ilmenite crystals and mineral aggregates are fractured in a book shelved fashion, and contain kinematically significant tails and corona of garnet +/- clinopyroxene. The occasional absence of clinopyroxene in some assemblages is likely a result of bulk composition. Modal amounts of garnet vary from <5 % to >10 %.

Plagioclase porphyroclasts are zoned. In sample 11R-081 (Fig. 8), plagioclase compositions vary from $An_{37}$ in the core to $An_{27}$ in the dynamically recrystallized tails. The zoning is gradual, and correlates well with the development of recrystallized plagioclase and ultimately, the presence of garnet. Garnet grains do not show much zonation, and are consistently Grossular- rich Almandine ($X_{Alm}$ = 0.70 , $X_{Gr}$= 0.20, $X_{py}$= 0.09). Clinopyroxene also displays little zonation, has Mg/Mg+Fe ranging from 0.451 to 0.464. Sharp increases in this ratio along the rims suggest diffusional exchange with garnet during cooling. $X_{Di}$ is consistently 0.236 and $X_{Hd}$ is 0.29.

The second metamorphic event ($M_{2N}$) corresponds to the second fabric generation ($S_{2N}$). The mineral assemblage is similar to $M_{1N}$, which is not all that surprising considering an identical protolith. Plagioclase porphyroclasts contain blood red garnet crystals in the dynamically recrystallized tails interpreted to have occurred along $S_{2N}$. A significantly less amount of orthopyroxene was observed along this fabric, and where present is often pseudo morphed by anthophyllite. These orthopyroxene are interpreted to be primary, and contain tails of hornblende +/- garnet. These observations suggest both a dynamic, and a late stage static hydration with respect to $M_{2N}$. Clinopyroxene occurs in ribboned hornblende, and is interpreted to reflect anhydrous conditions at a local scale during orthopyroxene consumption. The presence of abundant hornblende was observed by Williams et al. (2000).

Plagioclase porphyroclasts interpreted to have recrystallized during $M_{2N}$ (along $S_{2N}$; Fig. 8) are also zoned similarly to $S_{1N}$ porphyroclasts. Plagioclase cores have a composition of $An_{47}$, which gradually decreases with distance into the dynamically recrystallized plagioclase ribbon to approximately $An_{33}$. Garnet is unzoned, and has a Grossular-Pyrope rich - Almandine composition ($X_{Al}$=0.64, $X_{Py}$= 0.16, and $X_{Gr}$= 0.19). Although significantly less common within this fabric, cpx does occur as small grains along foliation planes. Clinopyroxene is compositionally unzoned, and has a Mg/Mg+Fe ratio of 0.642, with a large increase at the very rim of the crystal consistent with diffusional reequilibration during cooling. They have a composition of $X_{Di}$ of 0.343 and $X_{Hd}$ of 0.191.

**4.3 Southeastern footwall**

2.6 Ga mafic granulites contain evidence for three phases of metamorphism (*for discussion see Mahan et al., 2008*). The texturally oldest assemblage, observed within this study, are boudined, folded, to completely dismembered pods of Garnet + Clinopyroxene + ilmenite. These texturally oldest garnets have orthopyroxene and plagioclase inclusions interpreted to be igneous. Hornblende is aligned with axial planes of folded layering with the above assemblage +/- quartz where early layering is preserved. These assemblages are overprinted by a peak orthopyroxene + plagioclase +/- garnet +/- hornblende. Garnet and hornblende crystals are texturally early, and were interpreted to have grown during the initial thermal reactivation ($M_{3a}$ after Mahan et al., 2008; $M_{2C}$ this study).

Petrographic analysis of a chipman dike forms the basis for metamorphic petrography, and accurately constrains the development of the main structural element within the region (10W-094a; $S_{2C}$' Fig. 9). The mafic dike contains evidence for two stages of metamorphism. The primary mineralogy of 10W-094a is fine grained hbl and plag. This assemblage contains corona and recrystallized rims of Cpx and grt, interpreted to represent the peak metamorphic assemblage. The texturally latest assemblage consists of hbl and plag, and occurs locally along cpx and grt grain boundaries. This is interpreted to be the result of minor amounts of retrogression in the footwall.

Plagioclase contains garnet overgrowths. Plagioclase composition is uniformly $An_{25}$. However, a slight increase in An content occurs immediately adjacent to the grt overgrowth suggesting late plagioclase growth. Garnet is also compositionally unzoned,except for adjacent to the analyzed plagioclase, $X_{Gr}$ decreases consistent with late diffusional reequilibration. Garnet has a composition of Pyrope-Grossular rich – Almandine ($X_{Al}$ = 0.637, $X_{Py}$ = 0.158, $X_{Gr}$ =

0.182). Clinopyroxene composition does not vary, has a Mg/Mg+Fe ratio of 0.554, and has a composition of approximately $X_{Di}$ of 0.282 and $X_{Hd}$ of 0.227.

**4.4 Cora Lake shear zone**

The CLsz contains a wide variety of lithology's, with an even broader number of mineral assemblages. Both dynamic and static hydration is widespread throughout the shear zone. The shear zone can be divided into rocks hangingwall affinity and rocks with footwall affinity (*see Fig. 5*). An opx-bearing, porphyroclastic felsic granulite, also containing plagioclase feldspar, quartz, potassium feldspar, garnet, hornblende, and biotite, from zone 5 (10W-112; Fig. 10) contains suitable mineralogy for thermo barometry, so was targeted for metamorphic analysis. A coarse plagioclase feldspar porphyroclast displays core mantle structures with dynamically recrystallized tails. Garnet crystals are fractured along discrete breaks, and show evidence for small amounts of displacement along the fractures suggesting fracturing during shearing. Orthopyroxene is boudinaged, fractured, and dispersed about the matrix along with hornblende. The fracturing of orthopyroxene with no evidence of reacting to something else suggests that this phase was in textural equilibrium.

There is no compositional variation throughout both the core and dynamically recrystallized tail of the well preserved core and mantle plagioclase feldspar. The plagioclase porphyroclasts have a uniform composition of $An_{34}$. Garnet is zoned with Grossular rich inner rims, which are continuous around the entire crystal. The core and outer rim of the garnet is uniform. $X_{Gr}$ ranges from 0.03 within the core to 0.065 in the inner rims. Overall, the garnet is a Pyrope-rich Almandine. Orthopyroxene is unzoned, but varies in composition very slightly from point to point. Mg/Mg+Fe ratios range from 0.62 to 0.65.

Mafic granulites from the footwall portion (zone 3) of the shear zone contain dynamically recrystallized clinopyroxene, fine grained red garnet, and extremely fine grained dynamically recrystallized plagioclase ribbons. Although very highly strained, one sample (10W-100a; Fig. 11) from within a lower strain portion of the outcrop was useful for metamorphic analysis. Minor hbl occurs along grain boundaries between cpx and grt. Clinopyroxene is generally located between grt and plagioclase domains. Garnet is subhedral, with clinopyroxene and plagioclase ribbons deflected around the crystals. Given the mineral assemblage, this rock likely shares a protolith with mafic granulites from the footwall. Deformation facilitated significant phase reequilibration, and has an assemblage that mimics the earliest assemblage ($M_1$ after Mahan et al., 2008). This is interpreted to represent cooling, and crossing back into the High P granulite field after Green and Ringwood (1967). Hornblende is interpreted to be synkinematic and present along grain boundaries due to thin section scale variability in fluid availability.

Anorthite content ranges from $An_{42}$ to $An_{49}$ with higher An contents along the rims of dynamically recrystallized plagioclase. Garnet contains slight zonation with $X_{Gr}$ ranging from 0.33 in the core down to 0.29 within the inner rims, with a slight increase back to core values along the outer rim. Mg/Mg+Fe ratio of garnet ranges from 0.12 to 0.139. The garnet grains analyzed are all Grossular-rich Almandine with an average composition $X_{Al}$ of 0.58, $X_{Py}$ of 0.09, with a slight increase in $X_{Al}$ rimward. Clinopyroxene is compositionally unzoned as well. Although there is more variation from analysis to analysis. The most representative composition for the cpx has a Mg/Mg+Fe value of 0.518, $X_{Di}$ of 0.264, $X_{Hd}$ of 0.246.

## CHAPTER 5

## QUANTITATIVE THERMOBAROMETRY

### 5.1 Introduction

Thermo barometric calculations were performed using the TWQ program, version 2.32 of Berman (1991; 2006; updated in 2007). TWQ calculations were used for the following equilibriums (*see methods for solution model and database citations)*. The following equilibriums were used:

| | |
|---|---|
| (1) | 6En + 3An = Gr + 2Py + 3βQz |
| (2) | 3En + Alm = 3Fsl + Py |
| (3) | 3An + 3Di = 3βQz + Py + 2Gr |
| (4) | Alm + 3Di = Py + 3Hd |
| (5) | 3Tsc + 12αQtz + 2Py + 4Gr = 12An + 3Tr |
| (6) | 3Tr + 5Alm = 5Py + 3FeTr |

Equilibriums (1) and (2) are calculated using Opx + Grt + Plag + Qtz, while (3) and (4) are calculated with Cpx instead of Opx. Wherever Cpx was found, equilibriums (3) and (4) were used to reduce error when comparing results. Equilibriums (5) and (6) were calculated using TWQ version 1.02 with Amph + Grt + Plag + Qtz. A compilation of results are summarized in Figure 8.

### 5.2 P-T Calculations

The northwestern hangingwall contains two penetrative fabrics. Both of these fabrics contain evidence for garnet +/- clinopyroxene, +/- hornblende to form at the expense of calcic plagioclase and orthopyroxene (the Mary Reaction; Figure 8). Points chosen for calculations are given in table xx, and were picked from the plateaus in rim compositions to ensure compositional equilibrium with surrounding garnet was attained. Using equilibriums (3) and (4), assemblages that formed on both $S_{1N}$ and $S_{2N}$ yield indistinguishable P-T conditions of 0.9 GPa and 725°C (11R-081 and 96W-062g, respectively). These data are in agreement with previously published results for P-T conditions within the region (Williams et al., 2000; Dumond et al., 2010).

The earliest assemblage ($S_{1C}$) was the focus of a thermo barometric analysis presented in Mahan et al. (2008). They concluded conditions of 1.35 GPa and ~825°C. A chipman dike from the footwall (*this study;* 10W-094a), using equilibriums (3) and (4), the dike yielded peak P-T of 1.17 GPa and 800°C. Using TWQ version 1.02, P-T calculation was made using the retrogressed assemblage within the mafic dike. It is important to note that there is significantly larger error when applying amphibole solution models, because certain thermodynamic data are not as well constrained. The chipman dike (10W-094a) yielded a P-T of 1.06 GPa and 725°C for hbl in the retrogressed assemblage using equilibriums (5) and (6).

Hangingwall affinity rocks within the CLsz yield P-T conditions of 0.87 GPa and 775°C using equilibriums (1) and (2), from an OPx bearing felsic granulite (10W-112). A mafic granulite from within the footwall portion of the CLsz yielded an equilibrium P-T of 1.08 GPa and 725°C using equilibriums (3) and (4) (10W-100a), indistinguishable from the retrogressed mafic dike. A higher strained mafic granulite ultramylonite from an outcrop adjacent to 10W-100a yielded 0.80 GPa and 725°C with the same equilibriums (10W-099).

# CHAPTER 6

# MONAZITE GEOCHRONOLOGY

## 6.1 Introduction

In-situ geochronological constraints are critical for accurately determining ages of important stages in the metamorphic and deformational history (Dumond et al., 2008; Williams et al., 2009; Mahan et al., 2006a; Williams and Jercinovic, 2002; and references therein). Monazite provides the spatial resolution capable of providing a means to link metamorphic petrology and structures. Monazite grains were targeted based on high resolution compositional maps in the context of full section fabric and texture.

## 6.2 Age relationships in the hangingwall

Monazite is a powerful geochronometer for linking mineral assemblages, deformation fabrics, and kinematics to absolute time (Williams and Jercinovic, 2002). The Northwestern hangingwall is characterized by two main deformation fabrics, the earlier of, which is a sub horizontal gneissic layering with strong mineral lineation's and well preserved reaction textures. Sample 11R-057c, is a felsic granulite, which is within 3 meters of the Mary granodiorite that also contains dextral kinematics, including asymmetric porphyroclasts and shear bands. The sample, from north of Beeche Lake, contains a strong S-C-C' fabric consistent with $S_{2N}$ dextral shear during the second phase of deformation (Fig. 14). Monazite grains vary in size, but most are larger than 100 µm, and are aligned with the dominant shear fabric. There are 4 distinct compositional domains identified, although not all grains host all four. Two common Y domains are present throughout the suite of monazite, with a high Y core and a low Y rim. Th zonation is a bit more complex. Th distribution in this suite of monazite ranges, but the most predominant and consistent character are high Th domains along inner rims, within the inner portion of the low Y rim. The last domain are ca. 3-5 µm outer rims that are low Y and low Th.

Systematic analysis of the four compositional domains within 11R-057c yielded three populations. High Y inner cores yielded two well constrained ages clustered near 2600 Ma. Three analysis of a high Y inner core yielded a weighted mean of 2594.1 +/- 8.6 Ma (MSWD: 0.58). Low Y outer cores yield results clustering around 2561 +/- 9.2 Ma (MSWD: 1.1), with a few analyses slightly older, closer to 2600 Ma. The best analysis yielded an age of 2560 +/- 13 Ma. One robust age was retrieved from high Th inner rims: 2585 +/- 20 Ma. Although these are texturally younger domains, this age is interpreted to represent final crystallization of partial melt, or primary magma. Four dates were obtained from very thin, low Th and low Y outer rims, and are 1903 +/- 20 Ma, 1901 +/- 16, 1875 +/- 18, and 1891 +/- 25 Ma. A weighted mean of 1890 +/- 34 Ma (MSWD: 2.2).

Monazite is a sensitive geochronometer because it participates in chemical reactions, and is sensitive to other phases that are either growing, stable, or breaking down (Williams and Jercinovic, 2002). The 2600 Ma age that is primarily defined by high Y inner cores is likely an igneous age because the monazite grains were not competing against garnet for Y. The two high Y cores that fall within the ca. 2560 Ma age group were not in close proximity to garnet, so likely didn’t respond to local Y depletions associated with garnet. Most low Y outer cores, consistent with the presence and/or growth of garnet have an age of ca. 2560 Ma. These data suggest garnet growth occurred during this interval. The age distribution of high Th inner rims is somewhat enigmatic, and may reflect the final phases of melt crystallization at ca. 2580 Ma.

The texturally youngest monazite generation are small 3- 5 µm rims around most grains and have are compositionally both low Y and low Th. This likely represents a second period of garnet growth/stability. One grain, in particular, contains outer rims that extend into the matrix within a dextral shear band. Most grains contain this monazite compositional domain, and rarely does it form continuous that surround the entire grain, but generally occur perpendicular to shortening direction, suggesting a syn-kinematic origin. They yield an average age of 1891 Ma, 600 My after the first garnet growth event.

**6.3 Southeastern footwall**

A significant amount of geochronological data has been published from the footwall (i.e. Chipman domain; Hanmer et al., 1995; Mahan et al., 2006a,b; Flowers et al., 2006a,b; 2008) Both zircon and monazite geochronology is thought to reflect peak metamorphic ages because only these geochronometers have a suitable blocking temperature to not be completely reset prior to exhumation (Dutch, 2009). Flowers et al. (2006a) performed ID-TIMS analysis on zircon crystals from chipman mafic dike leaucosomes, interpreted to represent a minimum age of the dike swarm, which was interpreted to coincide with peak Paleoproterozoic metamorphic conditions. The results yielded a very precise age of 1896.2 +/- 0.3 Ma (Flowers et al. 2006a). Zircons separated from mafic granulites in close proximity to the CLsz, yielded complex U-Pb systematics interpreted as zircon recrystallization and partial resetting (Flowers et al., 2008). Zircon crystals yielded ages that span from 2.55 Ga to 1.9 Ga, and were interpreted to represent two phase mixing (Flowers et al., 2008) caused by two granulite grade events at these times.

Uranium-Th-total Pb monazite has revolutionized the degree to, which we can decipher metamorphic, deformation, and fluid events (Mahan et al., 2006a; Williams et al., 2011). This approach was the focus of Mahan et al. (2006a,b). The authors presented data suggesting that deformation and metamorphism occurred during the Archean (i.e. 2.56 Ga) and

Paleoproterozoic (i.e. 1.90 Ga), followed by a period of isobaric cooling and subsequent uplift and hangingwall hydration along the Legs Lake shear zone at ca. 1850 Ma.

We present preliminary data from sample 10W-094g (Fig. 15). The sample is a felsic granulite that contains an $S_{2C}$ mineral alignment oblique to compositional layering ($S_{1C}$) within a set of meter-scale folds. This sample is from the same outcrop that peak $M_{2C}$ conditions were calculated in a mafic dike (10W-094a, *see above for discussion*). Monazite grains are mostly aligned with compositional layering, but contain rims that are oriented perpendicular to $S_{2C}$ mineral alignment, suggesting monazite crystal growth was parallel to the $L_{2C}$ mineral lineation. Most grains contain high Th inner rims, and low Th outer rims. Core compositions vary from grain to grain, and compositional textures suggest that dissolution-reprecipitation reactions may have affected some of the grains (Williams et al., 2011; Harlov and Heatherington, 2007).

Preliminary results from 10W-094G-2 suggest a dominantly Archean population, but a scatter in apparently altered domains, including ages as young as 2264 +/- 26 Ma. No analyses of high Th inner rims have been attained. However, low Th outer rims that are kinematically consistent with growing along the $S_{2C}$, yield 1892 +/- 25 Ma (M2) and 1908 +/- 24 Ma (M4). The core of M4 yielded an unusual age of 2984 +/- 43 Ma.

The rim ages are consistent with a ca. 1900 Ma tectonometamorphic event. Furthermore, the textural relationship of outer rims with a growth direction parallel to an axial planar fabric suggests a 1900 Ma age for folding in the footwall. Although no ages have been obtained for high Th inner rims, given their textural position, they must be predate ca. 1900 Ma outer rims. Furthermore, partial melting is defined by the compositional layering, suggesting melting occurred prior to folding. Therefore, melting occurred prior to ca. 1900 Ma, and pre-folding.

**6.4 Geochronology of the CLsz**

Zone 4 of the CLsz contains one dominant, very intense (*see Fig. 5)*. Sample 11R-028b, from Jeanotte Lake, is a felsic granulite that outcrops in a strain shadow of a decimeter-scaled mafic granulite boudin. It contains large monazite grains ranging in size from 50 to 100 µm's. Two domain types were identified from 9 mapped monazite grains. Core domains are defined by weak oscillatory Th zonation, which ranges both in width and intensity. The rims are unzoned, and range from 10 µm overgrowths, to tails elongated within the fabric for greater than 50 µm's.

Results from 11R-028b yield two well constrained populations (Fig. 16). The cores have a weighted mean of 1906.2 +/- 7.0 Ma (MSWD: 1.3). Rims have a weighted mean age of 1875 +/- 6.4 Ma (MSWD: 0.6). Although within error, systematic analysis of rims outward yielded an orderly decrease in age. These ages are interpreted to reflect $D_{2N}$ partial melting followed by subsequent deformation associated with $D_3$. Oscillatory zonation within cores suggests growth from a magma. No Archean monazite generations have been identified, and due to the predominance of this age population in most rock types, we suspect that this rock was not present during that phase of metamorphism.

The northern most portion of the CLsz along the southeastern portion of Scharfe Lake is underlain by coarse, megacrystic, Beed granite. Monazite grains from this rock (sample 10W-110), are large, ranging in size from 75 to 200 µm's. Preliminary analyses show that the majority of grains, and their complex zonation is Archean. There are several small tips on monazite crystals, which yield Paleoproterozoic ages. M9 contains two symmetric high Th rims on either side of the crystal, each yielding a 1903 +/- 3 and 1904 +/-24 Ma age. A texturally significant monazite crystal (M2), is located within a sinistral shear band, and has δ-type asymmetry on one side (Passchier and Trouw, 2004), but the majority of the grain is Archean in age. However, a very thin (~3 μm) rim yielded an age of 1885 +/- 11 Ma.

Sample 10W-110 contains spectacular protomylonitic fabrics, and is largely due to Archean tectonometamorphism. The three analysis that yielded Paleoproterozoic ages yielded results that are consistent with those above. A ca. 1900 Ma peak likely is the result of $D_{2N}$ tectonism, and the one ca. 1885 Ma age may represent the initiation of $D_3$. The coarseness of the rock suggests that it likely behaved stronger than surrounding rock types, and perhaps the majority of fabric has been inherited, thus is a composite of several fabric generations.

Monazite geochronological results from the CLsz suggest that deformation and metamorphism associated with it occurred after peak granulite facies metamorphism in both hanging and footwall. The range of ages further suggests that it may have initiated fairly quickly, if not immediately after large amplitude folding and associated axially planar fabrics and transposition in wall rocks. Furthermore, protomylonitic rocks have not yielded results suggesting post 1875 Ma shear (Sample 10W-110), suggesting that shear may have been localizing into zones of weakness facilitated by grain size reduction.

# CHAPTER 7

# DISCUSSION

## 7.1 Summary of tectonism within the study area

Three periods of tectonism have been identified within the Cora Lake area. Synthesizing data regarding polydeformed granulite terrains requires the use of Pressure-Temperature-time-Deformation (P-T-t-D) paths because they involve an integration of fabric development and orientation, kinematics, and metamorphism through time. Within the field area, three fabrics have been identified, the third of which, is the CLsz, and divides structurally and compositionally contrasting granulite domains. The two older fabrics within the wall rocks are penetrative and pervasive and regionally developed. The CLsz, however, is extremely localized.

The earliest phase of tectonism within the northwestern hangingwall is a sub horizontal gneissic layering. This fabric is best exposed within hinge domains of large amplitude folds. The mary reaction occurs along this fabric, with the transition from an orthopyroxene and megacrystic plagioclase bearing protolith deforming into a stable metamorphic assemblage of garnet, clinopyroxene, and a more sodic plagioclase (Williams et al., 2000; Dumond et al., 2010). This metamorphic assemblage yields thermo barometric estimates of 0.9 GPa and 750°C. This fabric contains evidence for layer parallel flow with kinematic indicators and S-C-C' geometries suggesting a relative motion of top the east south east. This fabric ($S_{1N}$) appears to be regionally extensive, and is identical to that described further west along the Fond du Lac (Dumond et al., 2010). Furthermore, reconnaissance work suggests that this early sub horizontal layering and kinematics are present in the BOHICA intermediate to mafic complex further to the northeast (unpublished data). These observations suggest that the whole northwestern hanging wall contains a laterally extensive fossilized exposure of flowing crust.

The earliest fabric observed within the footwall is the focus of Mahan et al. (2008). The authors suggested that a penetrative sub horizontal layering existed in mafic granulites. This early fabric overprinted an orthopyroxene and plagioclase dominated protolith (Mahan et al., 2008; 2011). This early gneissic layering was defined by a stable metamorphic assemblage of clinopyroxene, garnet, and ilmenite. Quantitative thermo barometry from this assemblage yielded peak conditions of 1.35 GPa and 850°C (Mahan et al., 2008, 2011). Preservation of this initial gneissic layering ranges from completely overprinted, to boudins of this earlier assemblage, and relict (isolated) fold hinges. The host tonalitic gneiss contains evidence for a similar, sub horizontal layering. Mahan et al. (2008) argued for folding almost immediately following this early layering, and concurrent hydration along a weakly defined axially planar fabric permitting the growth of hornblende at the expense of clinopyroxene and garnet. Therefore, the $S_{2C}$ was subsequently reactivated during the second granulite event ($M_{2C}$; Mahan et al., 2008; 2008). Both tonalite and mafic granulites show no evidence, or kinematics consistent with sub horizontal flow during this deformation event.

The nature of the second phase of tectonism is drastically different than the first in the northwestern hangingwall. This period involved open-upright folding, and the development of a partitioned axially planar fabric ($S_{2N}$). This fabric is strongest within limb domains, and ranges in intensity to mineral alignment to mylonitic. Strong mineral lineation's plunge shallow to the southwest on the sub vertical $S_{2N}$. The mary reaction is also present on this fabric, containing a metamorphic assemblage of hornblende, clinopyroxene, garnet, and sodic plagioclase. This reaction is interpreted to be present along this fabric because it is observed within crystals interpreted to be recrystallizing. However, hornblende is a major component of the metamorphic assemblage along this fabric suggesting that $S_{2N}$ acted as a conduit for fluid flow, favoring hornblende stability (Williams et al., 2000). Quantitative thermo barometry yields identical results to $M_{1N}$ of 0.9 GPa and 750 °C. Both σ and δ-type kinematic indicators, and S-C-C' geometries suggest dextral slip during $D_{2N}$.

The second phase of deformation observed within the footwall of the CLsz is defined by steeply dipping to sub vertical, and defines the axial plane of meter-scaled fold sets present within mafic and felsic granulites in low strain domains, and host tonalite. Furthermore, the presence of crenulated tonalite domains suggests relict hinge domains may still be present, with a significantly higher degree of transposition. A major component of $D_{2C}$ is the pervasive Chipman dike swarm. The dikes contain a strong $S_{2C}$ within the Cora Lake region, and display both clockwise and counterclockwise obliquity with respect to the host tonalite fabric, which is no more than 5°. A dike (10W-094a) contains a metamorphic assemblage of garnet and clinopyroxene. Mineral composition data yielded quantitative thermo barometric estimates of 1.17 GPa and 800°C. Mafic granulites have an orthopyroxene, plagioclase, hornblende, and garnet assemblage, which defines an anastomosing $S_{2C}$ fabric that wraps around the relict clinopyroxene and garnet assemblage. Kinematics vary, but are mostly sinistral from the Cora Lake region.

The Cora Lake shear zone represents the last event to affect the study area, and also is the most localized. It is 3-5 km wide, ultramylonitic throughout most of its width, and contains a sinistral-normal sense of shear with a dominant strike-slip component. There are abundant compositional variations and strain gradients throughout its width. Metamorphic assemblages vary from garnet, clinopyroxene, and plagioclase feldspar to orthopyroxene, garnet, plagioclase, with abundant hydrous phases like hornblende and biotite within most lithology's. Anthophyllite and randomly oriented chlorite grains (pseudo morphs of garnet and orthophyroxene) are interpreted to be post tectonic. Pressure-Temperature calculations from the CLsz record a wide range of P-T conditions ranging from peak P-T (Hangingwall: 0.9 GPa and 750°C; Footwall: 1.17 GPa and 800°C) to 0.82 GPa and 700°C (10W-099) from Chipman domain affinity rocks, suggesting a piece meal uplift of Chipman domain adjacent to the Northwestern domain, and perhaps localization through time associated with cooling. Hangingwall affinity rocks record a P-T very close to peak hangingwall conditions. In footwall affinity rocks, P-T conditions appear to decrease with increased strain. Although the majority of these data are within error, the relative P-T differences are what we are interpreting as significant. Therefore, it appears that the shear zone was localizing leaving some rock units with a record of higher P-T conditions. As deformation localized, the regions hosting active deformation continued to reequilibrate.

Monazite geochronology has provided key temporal constraints on the evolution of both hanging and footwall, and the CLsz. $D_1$ and $M_1$ of both wall rocks occurred during the Neoarchean, at roughly 2.56 Ga. This is constrained by Y low monazite in the hangingwall suggesting garnet growth during flow. The earliest fabric preserved within the footwall is constrained in time primarily by ID-TIMS zircon geochronology presented in Flowers et al. (2008; Mahan et al., 2008; 2011), and is interpreted to be 2.55 Ga. Subsequent upright fabrics defining the axial plane of folds in both hanging and footwall are interpreted to be 1.9 Ga. The hangingwall contains monazite crystals aligned with the $S_{2N}$, and yield ages of ca. 1.9 Ga. Monazite from a folded felsic granulite that preserves $S_{1C}$ compositional obliquity to a strong $S_{2C}$ mineral alignment suggest that this later, axially planar fabric was established at ca. 1.9 Ga. This is consistent with Chipman dike anatexis, which contain zircon close to this age (ca. 1896.2 +/- 0.3 Ma; Flowers et al., 2006a).

The CLsz contains monazite that record all events above. Results are currently preliminary, but do successfully time sinistral shear along the CLsz. Sample 11R-028b contains evidence for initial monazite growth during $M_2$ with cores that display oscillatory Th zonation, and rims elongated within the CLsz fabric. The monazite grains contained two dominant age populations. Cores yielded an average age of 1906 +/- 6.4 Ma and are interpreted to represent $M_{2N}$. A weighted mean of rim analyses yield an age of 1875 +/- 6.5 Ma, and are interpreted to represent deformation associated with CLsz deformation. Therefore, if deformation within the hangingwall persisted for a few million years, CLsz shear likely was active during the waning phases of $D_2$, and likely continued for several My. Evidence for sinistral shear at 1885 Ma from Scharfe Lake (10W-110) further supports a nearly immediate initiation for CLsz deformation at the end of $D_2$.

With integrated structural, petrologic, and geochronological data, we present a high resolution P-T-t-D path for both hanging and footwall, and incorporate deformation within the CLsz. Both hanging and footwall share the temporal aspect of tectonism. That is to say, the earlier and later phases of tectonism appear to be synchronous at the resolution of existing data. However, the structural style and metamorphic grade differ. Lateral crustal flow is preserved within the hangingwall with peak P-T conditions of 0.9 GPa and 750°C. Deformation within the footwall during $D_{1C}$ is defined by early sub horizontal layering and potentially subsequent folding (Mahan et al., 2008; 2011). The ca. 1.9 Ga ($D_2$) event is similar in both domains with respect to fabric development and orientation. Both hanging and footwall developed upright, open folds, with a strong axially planar fabric. In the northwestern hangingwall, $S_{2C}$ is not developed everywhere, and is focused within limb domains of large amplitude folds ($F_{2C}$). In the southeastern footwall, however, $S_{2C}$ is strongly developed, and transposes the majority of older fabrics within the chipman tonalite. Syn-tectonic chipman dikes record peak metamorphic conditions of 1.17 GPa and 800°C. Almost immediately after this major tectonic event, the CLsz begins deforming with a sinistral-normal sense of shear. Localization progresses as the footwall is brought adjacent to the hangingwall where the CLsz juxtaposes 0.9 GPa rocks adjacent to 1.17 GPa rocks of the footwall at just above 0.82 GPa.

**7.2 Juxtaposition of lower crustal domains**

The Cora Lake shear zone divides 0.9 GPa rocks to the northwest adjacent to 1.17 GPa rocks to the southeast, which were juxtaposed at pressures exceeding 0.8 GPa. An important question remains: what was the initial geometry of the region? Both domains share temporal components to their respective tectonic events, and even style of deformation during the Paleoproterozoic (i.e. upright folding in similar orientations). The CLsz contains a large left lateral strike-slip component, the Chipman tonalite is continuous for at least several tens of kms to the northeast along strike (Mahan and Williams, 2005). The CLsz contains a moderately plunging stretching lineation, suggesting minor amounts of normal motion associated with deformation. Given the barometric discrepancy across the CLsz, and no evidence for earlier dip-slip events, several kilometers of dip-slip motion was accommodated by the CLsz during the waning phases of granulite deformation, which would require lateral motion to be on the order of 15 to 20 km.

The Cora Lake shear zone represents a major barometric discontinuity. Juxtaposition of these two domains appears to be late within the orogenic history of the region. Therefore, given the barometric discrepancy, prior to CLsz motion, the two domains were likely at separate crustal levels during both Archean (ca. 2.56 Ga) and Paleoproterozoic (ca. 1.9 Ga) events. The spatial relationship of hanging and footwall during these times is enigmatic, but two main possibilities exist: 1) They were laterally separate, then juxtaposed and 2) they were vertically stacked, and the dip slip component to CLsz shear juxtaposed them. Either end member suggests that they represent separate crustal layers, which experienced a similar orogenic history. Given the discrete nature of the CLsz, and the along strike continuity of the Chipman tonalite, it seems likely that northwestern rocks may have been stacked above Chipman (southeastern) rocks. Juxtaposition may have been driven by dynamic uplift accommodated by extension resulting from the Chipman dike swarm (Flowers et al., 2006b).

The CLsz marks a major compositional, rheological, and structural heterogeneity. The CLsz has a steep foliation, dipping to the Northwest, and is the fundamental boundary between the two domains suggesting that even if they were not directly stacked prior to CLsz motion, they were proximal to one another at their respective crustal depths. Therefore, it seems that the major rheologic heterogeneity within this exposure of lower crust during its evolution was vertical.

**7.3 A new tectonic model**

A great deal of work has focused on the spatial and temporal evolution of the western Canadian shield (Hoffman, 1988; Aspler and Chairenzelli, 1995; Hanmer et al., 1995; Cousens et al., 2001; Mahan and Williams, 2005; Berman et al., 2007; Martel et al., 2008; Mahan et al., 2008; Corrigan et al., 2009; and references therein). Recent literature has focused on the importance of the ca. 1900 Ma event within the region (Berman et al., 2007; Martel et al., 2008; Dumond et al., 2008). These authors suggest an ocean basin collapsed along the central snowbird tectonic zone at this time. According to Berman et al. (2007) and Martel et al. (2008), the Snowbird Ocean separated two isolated continents: The Rae and Hearne domains of the western Churchill Province. Collapse of the ocean basin at ca. 1.9 Ga lead to the observed deformation and discontinuities associated with the Snowbird Tectonic Zone.

However, our data suggests an additional, older, event at ca. 2560 Ma (Mahan et al., 2008, 2011; Williams et al., 2009; Dumond et al., 2010). From 2630-2600 Ma, large-scale mafic to felsic plutonism occurred within the northwestern domain (Hanmer et al., 1995). Mafic granulites within the chipman domain are interpreted to be this age based on Sm-Nd isotopic systematics and metamorphic zircon geochronology (Flowers et al., 2008; Mahan et al., 2008). We envisage that arc related plutonism in the region was followed by collision between Rae and Hearn domains, causing pervasive high P granulite facies metamorphism of the lower crust, and induced crustal flow in juvenile rocks.

The ca. 1900 Ma event represents a time of large-amplitude, upright folding throughout the region, at lower crustal depths. Large amplitude folding accommodated significant northwest-southeast shortening. Furthermore, this event involved significant heating by way of Chipman mafic dike swarm (Williams et al., 1995; Flowers et al., 2006a). Based on titanite date, elevated temperatures associated with this event are thought to have lasted until approximately 1880 Ma (Flowers et al., 2006b). Fabrics became increasingly partitioned, and during the waning phases of granulite grade deformation, the CLsz served to bring the Chipman footwall adjacent to northwestern domain rocks, juxtaposing lower crustal domains. The kinematic change from dextral to sinistral of the northwestern domain may have been triggered by the uplift associated with intraplating of large batches of magma during chipman dike intrusion.

We interpret this event to represent far field effects of arc construction along the southern flank of the Hearne domain (Maxeiner and Rayner, 2011). The Chipman dike swarm caused extension and a moderate amount of unroofing following this event (Flowers et al., 2006b), suggesting that this area may be a result of retro arc extension exploiting an inherited lithospheric weakness, similar to that described by Haldiri and Rainbird (2011). We see no evidence for the closure of an ocean at this time.

**7.4 Evolution of Rheologic Properties and Tectonic Character**

Lower crustal properties are fundamental to our understanding of plate tectonics in general, and most importantly how these parameters effect seismic interpretation, geodetic surveys, and even the spatial and temporal distribution of igneous suites (Sawyer et al., 2011). Temporal variations of lower crustal properties are extremely important. The rocks exposed to the northwest of the CLsz respond extremely different to tectonic stresses under similar Pressure-Temperature conditions. When they were a juvenile suite of igneous rocks, the rocks exposed in our study area deformed by flowing, serving to decouple crustal layers (Dumond et al., 2010). Paleoproterozoic deformation involved large amplitude folding and the development of a partitioned axially planar shear fabric. During the first deformation event, the rocks grew a significant amount of garnet and clinopyroxene, which likely strengthened them. After 650 my (ca. 1900 Ma) of tectonic stability, the rocks underwent metamorphic conditions similar to that of $D_1$, but were no longer juvenile rocks. This event is marked by large amplitude folding, and a partitioned axially planar fabric. The reason for this behavior change is likely related to the addition of strong phases (i.e. garnet and clinopyroxene), which serve to strengthen rocks, and perhaps create rheologic heterogeneities with sufficient contrast to cause localization. Folds are similar to those exposed in the Chipman domain. Deformation was accommodated by steeply sub vertical shear fabrics, and layer parallel flow is not present. Therefore, both the Chipman domain and Northwestern domain were behaving similarly, in contrast to Archean deformation. This change represents a transition from decoupled crustal behavior to a coupled lower crust where different levels of crust are behaving similarly. We interpret this to represent the transition from a weak, fertile, and juvenile lower continental crust to a strong, coupled, and evolved lower continental crust (Williams and Hanmer, 2007).

Flesch and Bendick (2012) proposed that viscosity contrasts with depth effects the degree to, which surface kinematics reflect lithospheric kinematics. That is to say how representative surface motion of plates correlates to whole lithosphere motion. Based on our results, the behavior of deep crust can vary and evolve. When weak, and juvenile, lower crustal rocks deform by flowing, serving to decouble lower continental crust. However, when strong, and long metamorphic history, rocks behave similarly, without the ability to decouple. For example, if the lower crust is made of juvenile lithology's, surface kinematics may not be all that representative of lithospheric kinematics because juvenile lithology's serve to decouple crustal layers. However, crust that contains older rocks, that have an orogenic history, may serve to couple lithospheric layers, allowing for higher confidence kinematic analysis from geodesy. Furthermore, juvenile lower crust has not had the opportunity to densify, and may have impact on isostatic compensation. Therefore, it may be possible to predict lower crustal behavior based on the history of a particular regions lithosphere.

# CHAPTER 8

# CONCLUSIONS

The Cora Lake shear zone is a major lithotectonic discontinuity and heterogeneity in the Athabasca Granulite Terrane. It also represents a period of major strain localization. It divides rocks that evolved during an Archean (ca. 2.56 Ga) and a Paleoproterozoic (ca. 1.9 Ga) deformation events under different metamorphic conditions. Localization culminated with the CLsz, which accommodated uplift of the southeastern footwall (Chipman domain), adjacent to lower pressure rocks of the northwestern domain. The CLsz records a trend of decreasing pressure with increasing strain within footwall affinity rocks, suggesting that strain was increasingly partitioned within the shear zone during uplift. Monazite data confirms that shear along the CLsz occurred just after peak metamorphic conditions, and continued until ca. 1870 Ma. The Northwestern hangingwall contains an early flow fabric, which transformed the juvenile suite of igneous rocks into a stronger rock type by the addition of garnet and clinopyroxene. Subsequent Paleoproterozoic deformation involved folding, and partitioned sub vertical axial planar fabric. Both events occurred under metamorphic conditions of 0.9 GPa and 750°C. The southeastern footwall contains an early high pressure fabric (1.35GPa and 850°C; Mahan et al., 2008; 2011), which was subsequently highly transposed during upright folding during the Paleoproterozoic, and associated dike swarm. Peak metamorphic conditions during this event in the footwall are 1.17 GPa and 800°C.

We interpret the CLsz to be responsible for juxtaposing separate lower crustal layers, which evolved over 600 my, punctuated by two granulite grade metamorphic events. Furthermore, the rocks exposed in the Northwestern hangingwall preserve the transformation from weak and juvenile to strong and evolved lower crustal rocks. This change is caused by the growth of strong metamorphic assemblages, namely the addition of abundant modal garnet. The two lower crustal levels were coupled after deformation had strengthened the juvenile rocks in the northwestern hangingwall. These results suggest

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