

AMPHIBOLITE TO GRANULITE FACIES METAMORPHISM AND
DEFORMATION IN THE JEROME ROCK LAKES AREA,
SPANISH PEAKS, MONTANA

by

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ABSTRACT

Structural analysis, bedrock mapping, and quantitative thermobarometry reveal a protracted metamorphic history for the multiple lithologies present in the Jerome Rock Lakes area of the Spanish Peaks, located in the northern Madison Range, southwest Montana. Volumetrically-dominant quartzofeldspathic gneisses are primarily of the tonalite-trondhjemite-granodiorite (TTG) suite and record multiple episodes of high-temperature deformation. Coarse-grained hornblende in association with K feldspar-bearing leucosome indicates locally vapor-present melting. Clinopyroxene-bearing metabasic enclaves in the quartzofeldspathic gneisses record the subsolidus hydration of clinopyroxene porphyroclasts to hornblende and subsequent dehydration melting of hornblende in the transitional granulite facies to produce garnet coronae and clinopyroxene neoblasts under vapor-absent conditions. Variably migmatized garnet-sillimanite schists record amphibolite facies metamorphism at ca. 5.5 kbar and 640 °C, with extensive melt production via melting of biotite. Inclusions of staurolite in kyanite-bearing metaquartzite are inferred to indicate the presence of modern thicknesses of continental crust and a geothermal gradient similar to Phanerozoic values. Infrequent layers containing tschermakitic amphibole layers may represent the residuum of vapor-present melting of biotite and indicate local variation in the activity of water. Migmatized garnet amphibolites record peak upper-amphibolite to transitional granulite facies metamorphism at ca. 10 kbar and 800 °C.

A clockwise P-T path of Alpine character is proposed for the lithologies of the Jerome Rock Lakes area, with peak pressures in the kyanite field attained before peak temperatures, followed by rapid, steeply adiabatic to isothermal decompression. Early isoclinal folds developed during prograde metamorphism and were rotated into the regional foliation. Progressive deformation resulted in the formation of later isoclinal folds coplanar with foliation. Peak temperatures were attained after cessation of deformation, indicated by undeformed leucosomes. A second episode of deformation produced outcrop-scale parallel folds trending north-south.

The Precambrian tectonic history of the northern Madison Range is inferred to have terminated in a continental collision with northwest-southeast directed shortening that produced steeply-dipping, NNE-trending regional foliation. This style is generally consistent with that observed elsewhere in the Spanish Peaks and in the Tobacco Root Range, generated by the ca. 1.7 Ga collision of western North America with the Medicine Hat craton.

INTRODUCTION

The metamorphic processes operating in the middle continental crust are of great interest, as they drive the ongoing evolution of continents through metamorphism and deformation. Since this region of Earth cannot be directly observed, identification of metamorphic processes relies on the interpretation of compositional and textural signatures in rocks that have resided extensively in the midcrust prior to exhumation.

In the mid-crust, pressure-temperature conditions are sufficiently high to initiate partial melting (anatexis). For the purposes of this study, the threshold between metamorphism and anatexis is an arbitrary one, where anatexis is used to refer to those metamorphic reactions that produce melt. These melt-producing reactions are controlled primarily by composition of the protolith, physical conditions, and the activities of volatile species (dominantly H_2O). The composition and volume of melt and, therefore, its physical properties are determined by the anatectic reaction operating on the source lithology. If a sufficient volume of melt is produced, it has the potential to escape the system and become a magma, leaving behind a depleted source. The compositional and textural features of midcrustal rocks can, therefore, be used to identify the metamorphic reactions operating in the midcrust. Thus, investigation of exhumed midcrustal rocks can furnish insight into how new, highly differentiated rock is produced at crustal levels and how continental crust is modified.

Research Objectives

This study aims to determine the midcrustal melt-producing reactions that

affected the Archæan lithologies of the Jerome Rock Lakes (JRL) area, Montana, resulting in extensive migmatization. Thin-section petrography was used to identify major metamorphic and anatectic reactions and deformation history. Quantitative thermobarometric techniques were used to determine pressure-temperature conditions during peak metamorphism and reequilibration during waning from peak metamorphism, as recorded by mineral compositions. The compositionally diverse lithologies of the JRL area permitted the application of a broad suite of geothermometers and geobarometers, constraining the conditions of metamorphism and partial melting.

This study also aims to identify the tectonic event most responsible for the extensively folded rocks and regional foliation measured in the JRL area. Bedrock mapping established the spatial relationships between individual rock units. Stereonet plots and descriptive statistics of foliation, lineation, and fold measurements were prepared to reveal the degree of conformity between structural elements. The overprinting relationships between these structural elements have provided a framework to interpret the relative timing of deformation events.

For the JRL area, a polyphase tectonic history is hypothesized, on the basis of geochronology (Weyand, 1989) and structural analysis (Salt, 1987; Spencer and Kozak, 1975). Peak conditions in the lower amphibolite-transitional granulite facies are hypothesized for the last episode of metamorphism. It is expected that vapor-absent melting reactions were responsible for the extensive migmatization, and that biotite-rich lithologies produced the largest volumes of melt, per the model of Clemens and Vielzeuf (1987). The character of the JRL area is hypothesized to be dominantly the product of the

Big Sky orogeny, which affected the Tobacco Root Range to the northwest (Harms et al., 2004).

Regional Setting

The JRL area, shown in Figure 1, is centered around a trio of alpine lakes in the northern Spanish Peaks of the northern Madison range, Montana. Major structural features define the boundaries of the greater JRL area including: the Big Brother shear zone to the northwest, the Spanish Peaks fault to the southwest, and the Mirror Lake



Figure 1: Detail of the Willow Swamp 1:24,000 USGS topo map. The extent of the bedrock map developed by this study is outlined in black. The approximate trace of the Big Brother shear zone is shaded in grey. Directions towards the nearby southeast-striking Spanish Peaks fault and the northwest-striking Mirror Lake shear zone are indicated by the double arrow. Trails no. 410 and High Lakes trail no. 413 are indicated.

shear zone to the southeast (Figure 1).

The complex geologic architecture of the northern Madison range was mapped by Kellogg and Williams (2000) at 1:250,000 scale. Figure 2 contains a detail of the map, centered on the northern Spanish Peaks. Exposures of Archæan units have a general northeast-southwest regional trend, truncated to the southwest by the Spanish Peaks fault, which continues into the Gardiner area, north of Yellowstone National Park (Schmidt and Garihan, 1986). The map pattern of units in the JRL area consists of a northeastward pinching-out wedge of “hornblende-plagioclase gneiss and amphibolite”, which is bifurcated by a band of “aluminous gneiss and schist”, and completely enveloped by

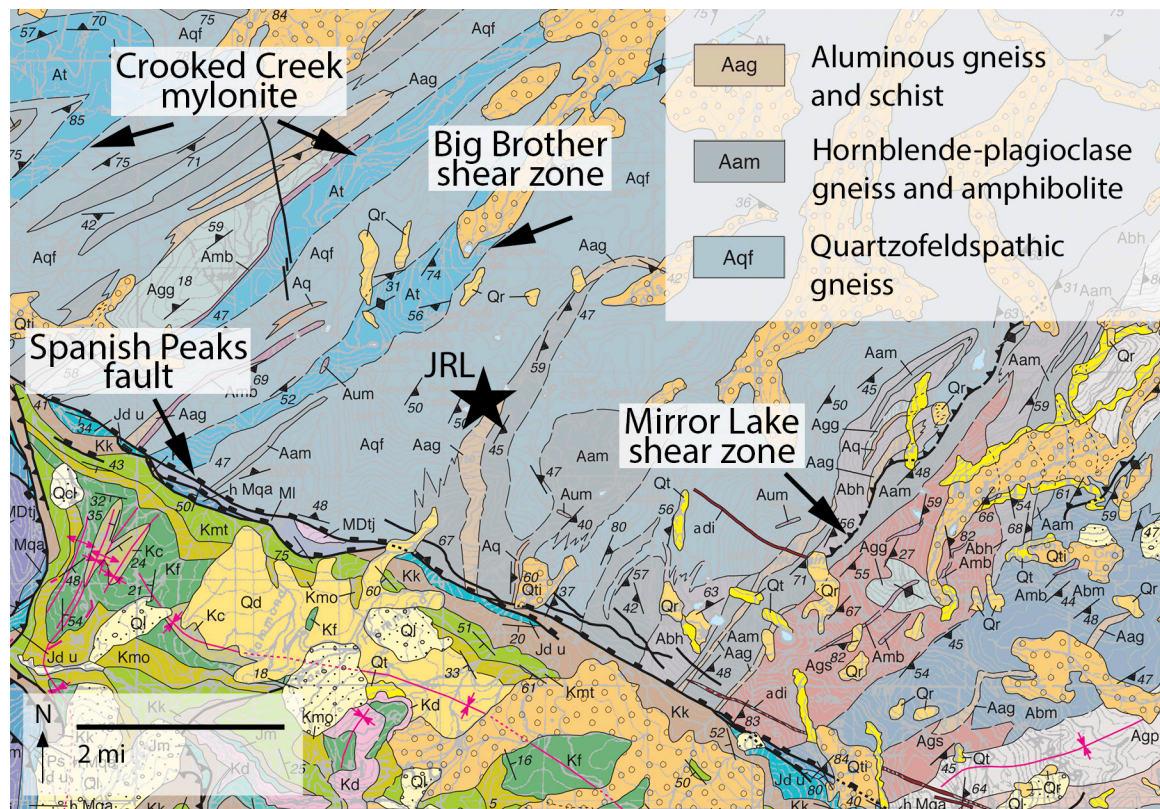


Figure 2: Detail of the northern Spanish Peaks region of the Ennis quadrangle 1:250,000 scale geologic map. Star indicates location of the Jerome Rock Lakes. Modified from Kellogg and Williams (2000).

“quartzofeldspathic gneisses” (Kellogg and Williams, 2000). Magmatic ages of the TTG rocks from the JRL area are 3.1-3.0 Ga (Weyand, 1989). In Figure 2, the Crooked Creek mylonite of Kellogg and Mogk (2009) and the Big Brother shear zone of Salt (1987) are mapped as mylonitized tonalitic gneisses and the Mirror Lake shear zone of Salt (1987) as a northwest-trending thrust fault.

The Madison range is one of six mountain ranges in southwestern Montana that contain significant exposures of Archæan cratonic and supracrustal lithologies (Figure 3). The volumetrically dominant quartzofeldspathic gneisses, so named “grey gneisses” for their mesocratic appearance, form the crystalline core of these ranges as well as the majority of continental crust worldwide (Winter, 2010). In southwestern Montana, these exposures supply the direct, extant record of the Wyoming Province, the Archæan cratonic component of western North America. Figure 3 shows the approximate extent of these exposures and the location of other structures of regional importance across southwestern Montana.

Early work by Giletti (1966) recognized that several suites of K-Ar and Rb-Sr dates were present in southwest Montana and were separable across a northeast-trending boundary through the Gravelly Range and Gallatin River canyon. Lithologies to the northwest yielded dates younger than 1.8 Ga and were interpreted to reflect a regional metamorphic event at 1.6 Ga not shared by the rocks to the southeast, of unknown true age (Giletti, 1966). This division of age became known as Giletti’s Line (Figure 3). Subsequent studies have revealed that Giletti’s Line roughly delineates a major intracratonic boundary (e.g. Mogk et al., 1992).

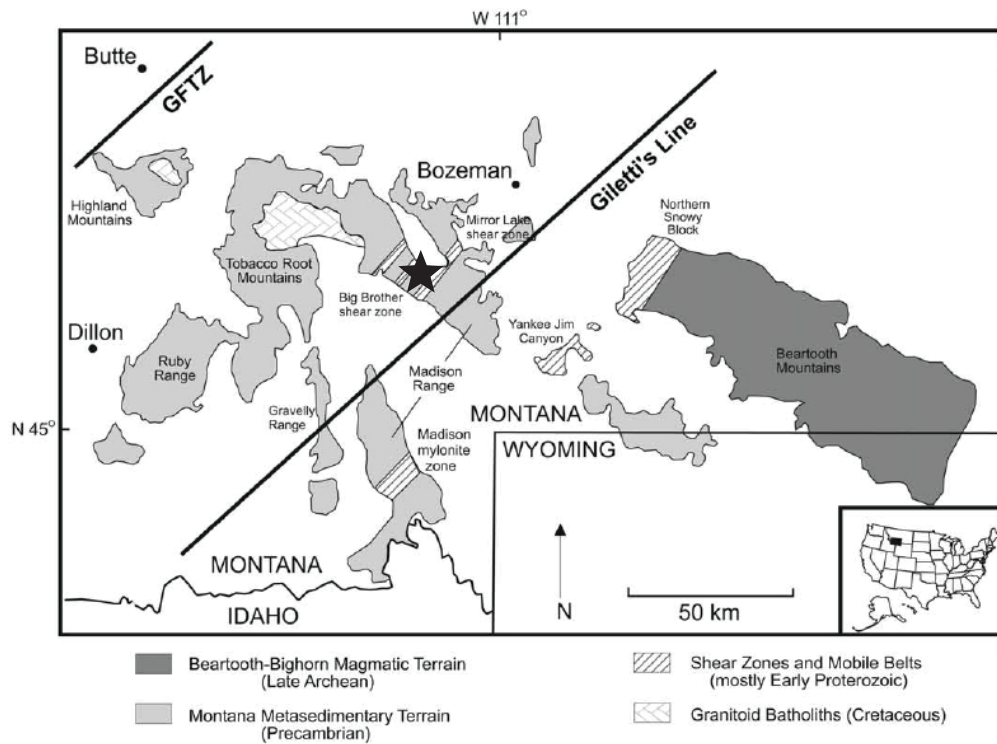


Figure 3: Schematic map of southwest Montana mountain ranges. Approximate subcratonic province boundaries are shown. Note the offset between Giletti's Line and the boundary between the Montana metasedimentary terrane (MMT) and the Beartooth-Bighorn magmatic terrane (BBMT). The northern margin of the Wyoming Province is given by the boundary with the Great Falls Tectonic Zone (GFTZ). Star indicates location of study area. Modified from Roberts et al. (2002).

The rocks to the northwest of Giletti's Line contain significant volume of metasupracrustal lithologies, including metapelitic schists, metaquartzites, marbles, and metabasites: the Montana metasedimentary terranes (MMT). The younger radiogenic dates identified by Giletti (1966) were the first evidence for a possible 1.8-1.7 Ga regional metamorphic event. In the Tobacco Root Mountains, this event has been dated to 1.780-1.720 Ga, using U-Pb ages of monazite inclusions in garnet (Cheney et al., 2004). Recent work by a number of authors shows that the Tobacco Root Mountains' current metamorphic character is primarily due to the Big Sky orogeny (see Burger, 2004 for

Archæan-Palæoproterozoic evolution of the Wyoming Province

• Early crust: Hadean-Palæoarchæan

MMT	Tobacco Root, Ruby ranges 3.96-3.4 Ga U-Pb dates of detrital zircons from metaquartzites (Mueller et al., 1998)
-----	--

BBMT	3.96-3.4 Ga U-Pb dates of detrital zircons from metaquartzites (Mueller et al., 1998) 3.5 Ga crystallization of TTG gneiss protolith (Mueller et al., 1996)
------	--

• Crustal formation: Palæoarchæan-Mesoarchæan

MMT	Tobacco Root, Ruby ranges 3.4-3.2 Ga U-Pb dates of detrital zircons from metaquartzites (Mueller et al., 1998) <u>Madison Range</u> 3.2-3.0 Ga crystallization of TTG gneiss protolith (Mueller et al., 2011; Mueller et al., 1998; Weyand, 1989)
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BBMT	3.4-3.2 Ga U-Pb dates of detrital zircons from metaquartzites: Mueller et al. (1998)
------	--

• Crustal modification: Mesoarchæan

MMT	<u>Madison Range</u> 2.8-2.6 Ga minor TTG magmatism (Johnson et al., 2014; Mueller et al., 1993; Weyand, 1989)
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BBMT	2.83-2.79 Ga voluminous TTG injections form cratonic keel (Mueller et al., 2010)
------	--

• Tectonism: Neoarchæan-Early Palæoproterozoic

MMT-BBMT conjoined 2.75-2.55 Ga (Kellogg and Mogk, 2009; Mogk et al., 1992)

MMT	<u>Madison Range</u> 2.45 Ga partial melting of TTG gneiss (Mueller et al., 2011) 2.58 Ga metamorphism (Eslev and Sutter, 1990) <u>Beaverhead Range</u> 2.45 Ga crystallization of gneiss protolith (Kellogg et al., 2003) <u>Tobacco Root Range</u> 2.45 Ga high grade metamorphism (Cheney et al., 2004)
-----	--

• Tectonism: Palæoproterozoic metamorphism

MMT	Tobacco Root range 1.78-1.72 Ga granulite facies metamorphism and deformation (Cheney et al., 2004; Harms et al., 2004; LeMieux et al., 2000) Tobacco Root, Highland, Ruby ranges 1.82-1.78 Ga metamorphism, 1.78-1.74 Ga biotite cooling dates (Roberts et al., 2002) <u>Madison range</u> 1.8-1.7 Ga metamorphism (Ault et al., 2012; Condit et al., 2013a and b) 1.8 Ga shear zone activation (Erslev and Sutter, 1990)
-----	--

Table 1: Partial geologic history of the northern Wyoming Province. Studies are grouped by location in the MMT and BBMT - individual mountain ranges listed correspond to those labeled in Figure 3. The scope of this partial literature review is limited to those studies that correlated metamorphism, magmatism, and deformation with geochronologic constraints.

a summary). Garnet growth during metamorphism has also been dated to 1.82-1.78 Ga in the Highland, Ruby, and Tobacco Root ranges (Roberts et al., 2002). LeMieux et al. (2000) postulated that the Big Sky orogeny resulted from the collision of the Wyoming Province with the Medicine Hat block to the north. The model of Harms et al. (2004) involves the collision of an arc terrane against the northwest edge of the Wyoming Province as part of the larger collision between the Wyoming Province and the Medicine Hat Block to the north, which resulted in the development of the Great Falls Tectonic Zone as a suture between the two cratonic blocks (Foster et al., 2006; Figure 4).

The rocks to the southeast of Giletti's Line are dominated by ca 2.8 Ga magmatism: the Bighorn-Beartooth magmatic terrane (BBMT). An extensive geochemical and geochronological study by Mueller et al. (2010) constrained the timing of injection of large volumes of TTG magma in the BBMT to 2.83-2.79 Ga. This magmatic addition thickened the craton and stabilized it. In the MMT, only isolated instances of magmatism in the MMT have been identified (Table 1), substantiating the conclusion of Mogk et al. (1992) that the two terranes had separate histories until conjunction in the Neoarchæan.

The Mesoarchæan-Hadean histories of the MMT and BBMT are less well defined. A major episode of crustal formation has been recognized from TTG magmatism and detrital zircons in metaquartzites. In the MMT, the major crust-forming event occurred at 3.2-3.0 Ga, while in the BBMT, it occurred ca. 200 Ma earlier (Table 1). Detrital zircons yield U-Pb dates of up to 3.96 Ga from quartzites in both terranes, suggesting that very old crust was once present across the northern Wyoming Province (Mueller et al.,

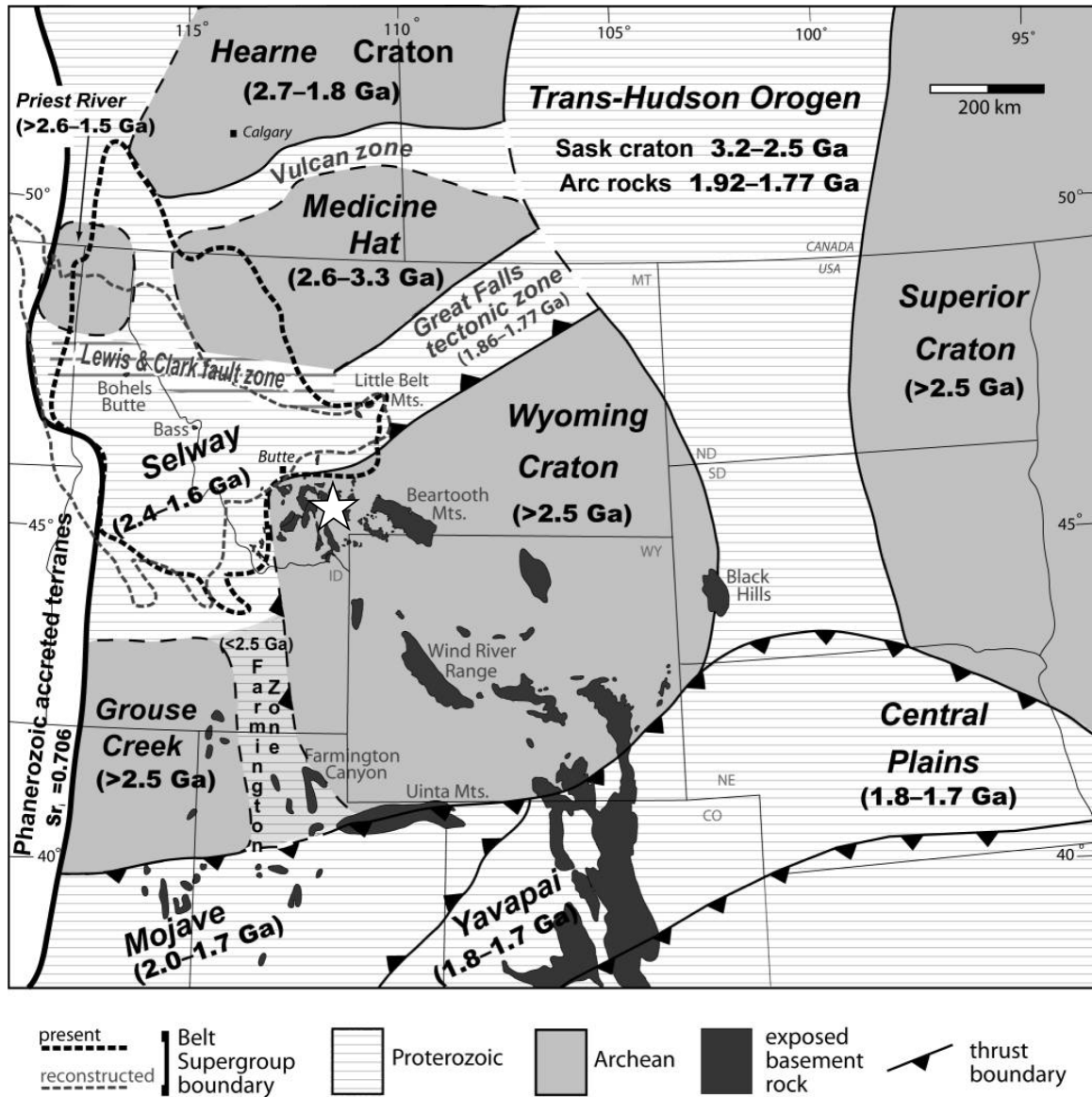


Figure 4: Schematic map of the modern North American craton. Note the location of crystalline basement in southwest Montana, exposing the northern Wyoming Craton, and proximity to the 1.86–1.77 Ga Great Falls Tectonic Zone. Star indicates approximate location of study site in the Madison Range. From Foster et al. (2006).

1998).

While the character of crystalline lithologies in the Madison Range was established during the Hadean/Archæan-Paleoproterozoic, subsequent tectonism was responsible for the final uplift and exhumation of these units. Rifting during the

Mesoproterozoic led to the development of the Belt basin at ca. 1.5 Ga. Normal faults are inferred to have developed along the modern western margin of the Madison Range (Schmidt and Garihan, 1986). U-Pb dating of the Moyie sills in Belt basin sediments has been used to constrain the age of deposition of lower members of the Belt Supergroup to 1.47 Ga (Sears et al., 1998). Phanerozoic tectonic activity within the Madison Range occurred as Late Cretaceous Laramide shortening along the Spanish Peaks fault uplifted and exposed the Precambrian metamorphic core of the range (Kellogg and Harlan, 2007). Uplift and exposure continued as Cenozoic Basin-and-Range extension downdropped the Madison valley to the west along the Madison fault system, exploiting zones of weakness previously developed during the Neoproterozoic rifting of the Belt basin and Laramide shortening. Tectonism continues today along the Madison fault, for which young fault scarps and recurring earthquakes provide evidence (Lageson et al., 1997).

Previous Work

An early structural study by Spencer and Kozak (1975) synthesized crosscutting and overprinting relationships between intrusions and structures with radiometric dates previously published by Gilletti (1966) and Gilletti (1971) to develop a coherent Precambrian history for the Spanish Peaks. Two orogenic events were proposed, based on the observation of two distinct folding styles in the Spanish Peaks. Northeast-trending isoclinal folding of previously developed foliation and compositional layering in the gneisses was assigned to the first orogeny, while northeast-trending open folds, which refold the isoclinal folds, was assigned to a second orogeny. Additionally, some open

northwest-trending folds are recognized, which refolded second-generation open folds and may have occurred during the second orogeny or during a later, unknown event. Spencer and Kozak (1975) suggest two possible correlations of orogenic events and previously published radiometric dates, predicated on the interpretation of 1.6 Ga Rb-Sr biotite cooling dates from nearby Gallatin Canyon in relation to 2.8-2.6 Ga Rb-Sr whole rock dates and 1.9 Ga K-Ar cooling hornblende dates from folded amphibolitized boudins. If the biotite cooling date reflected the absence of significantly elevated pressures and temperatures across the region after 1.6 Ga, then the amphibolitization of boudins would have occurred at 1.9 Ga and both orogenies would have occurred at 2.8-2.6 Ga. If the biotite cooling date was a manifestation of a third thermotectonic event occurring to the northwest, then the first orogeny, which produced northeast-trending isoclinal folds, occurred at 2.8-2.6 Ga and the second, which produced northeast-trending open folds, at 1.9 Ga.

Salt (1987) divided Spencer and Kozak (1975)'s "Precambrian gneiss" map unit in the northern Spanish Peaks into numerous discrete, sill-like igneous bodies, ranging in composition from hornblende monzodiorite to granite. Quartzofeldspathic gneisses of the southern Jerome Rock Lakes terrane (JRLT) near Mirror Lake were found to be granitic, while similar gneisses in the Gallatin Peak terrane (GPT) from Bear Basin to the Chilled Lakes were found to be tonalitic. The GPT was mapped as a broad, km-scale synform thrust over the northeast-striking, steeply dipping units of the JRLT by the previously unrecognized Mirror Lake shear zone. Peak metamorphic conditions for the JRLT were estimated in the transitional granulite facies at 745-782 °C and 6.0-8.3 kbars, and in the

amphibolite facies for the GPT at 665-726 °C and 6.8-8.3 kbars (Salt, 1987). Structural measurements in the GPT identified both isoclinal and open fold styles, similar to the two generations identified by Spencer and Kozak (1975). However, Salt (1987) postulates that both were produced by a single orogenic event, reflecting local variation in melt production and consequent deformation.

Weyand (1989)'s geochemical study of the Spanish Peaks utilized the same samples of Salt (1987). U-Pb geochronology of whole zircon and sphene grains from quartzofeldspathic gneisses in the JRLT and the GPT identified three different age suites that were compositionally distinct. Zircon ages are interpreted as the date of protolith crystallization. The oldest, ca. 3.25 Ga zircons are found only in mafic to intermediate units in the GPT. Trondhjemitic gneisses of both terranes were found to host 3.10-3.00 Ga zircons. The youngest zircons, 2.80-2.70 Ga, were found in granitic gneisses of both terranes. In the JRLT, the youngest samples were collected from granitic gneisses in the Big Brother shear zone. Although Salt (1987) proposed separate geologic histories for the GPT and JRLT on the basis of metamorphic conditions, Weyand (1989) found geochemical similarities between rocks of the same age suite in both terranes, suggesting that the terranes may not have been distinct from each other.

To the north of the JRL area, Kellogg and Mogk (2009) mapped the previously-unidentified Crooked Creek shear zone. Previously published U-Pb geochronology of zircon in a mylonitized granodiorite constrained deformation to after 2.78 Ga (Mueller et al., 1995) and before 2.56 Ga in a cross-cutting trondjemite (unpublished data in Kellogg and Mogk, 2009). Three separate deformation events were recognized in the

area, each with a distinct folding style. During the first deformation event D1, cm- to m-scale NE trending isoclinal intrafolial folds developed. Metamorphic conditions during D1 are estimated in the lower granulite facies, at 8.5 kbar and 700 °C (Kellogg and Mogk, 2009). D1 is thus characterized as a protracted episode of high-temperature ductile shearing in the midcrust during NW-SE transpression. The second episode of deformation (D2) is characterized by similarly oriented, larger-scale folds with steep axial planes. Overprinting of large-scale N to NW-plunging open folds on all other folds was inferred to represent a final episode of deformation. These three events concur with the three fold styles documented by Spencer and Kozak (1975).

The Spanish Creek mylonite, located east along strike from the Big Brother shear zone, was identified by Johnson et al. (2014). A crystallization age of ca 2.80 Ga for granitic protoliths of mylonites, protomylonites, and gneisses was obtained from U-Pb dating of zircons. Two older dates, 3.038 and 3.244 Ga, were obtained from an unmylonitized sample, and are considered representative of an older component in the quartzofeldspathic gneisses. Similarly old dates were not found in zircons from the mylonite. Two models for the timing of deformation are proposed: one in which deformation occurred synchronously with injection, before the protolith cooled; and another in which deformation occurred some indefinite time after injection and cooling (Johnson et al., 2014). The second model could be satisfied by a Proterozoic tectonic event such as the Big Sky orogeny.

Further evidence for ca 1.7 Ga thermotectonism is provided by recent petrologic and geochronological studies. Ault et al. (2012) documented P-T conditions from a

deformed mafic dike in Bear Trap Canyon, in the northernmost Spanish Peaks, of 12 kbar and 800 °C. These conditions were associated with a sub-20 μm population of 1.75 Ga matrix zircons, utilizing a novel U-Pb geochronologic technique. Work by Condit et al. (2013a) in Bear Basin, southern Spanish Peaks, correlated peak metamorphic conditions in metapelites and aluminous metaquartzites of 8.5 kbar and 700-750 °C with U-Pb monazite dates of 1.75 Ga. Similar investigation by Condit et al. (2013b) in biotite schists from the same area revealed conditions of 8.5 kbar and 700 °C, linked to 1.75 Ga U-Pb dates in monazite, while a nearby deformed mafic dike yielded conditions of 9.2 kbar and 725 °C, associated with 1.74 Ga matrix zircons.

From these studies, a picture of the Spanish Peaks emerges as a collage of Archæan midcrustal blocks, separated by at least five ductile shear zones. Thermotectonism began with formation of continental crust at 3.2-3.0 Ga, followed by minor magmatism, ductile deformation, and granulite facies metamorphism at ca. 2.8 Ga, and terminating in granulite facies metamorphism at ca. 1.7 Ga. This geologic history concurs with that of the greater MMT, suggesting that the effects of the Big Sky orogeny were widespread (Burger, 2004; Cheney et al., 2004; Harms et al., 2004; Roberts et al., 2002). The location of the JRL area offers the opportunity to determine the metamorphic and deformational character of the northern Spanish Peaks and, by doing so, establish its relationship with the surrounding subcratonic units of the Wyoming Province.

METHODS

Fieldwork

Fieldwork was undertaken primarily during the summer months of 2012.

Supplementary work was completed in summer 2013 and fall 2014. The field area was accessed via Falls Creek Trail No. 410 and High Lakes Trail No. 413 (Figure 1). The junction of these trails occurs immediately east of Lower Jerome Rock Lake. Generally, the area studied is bounded to the southeast by quartzofeldspathic gneisses outcropping near Upper Falls Creek Lake and to the northwest by the Big Brother shear zone.

Bedrock mapping utilized the Willow Swamp USGS 7.5-minute series quadrangle topographic map as a base map. The field area was mapped at approximately 1:7,000 scale over the larger-scale 1:24,000 base map. Intermittent exposure of lithologies required frequent inferring of contacts, based on overall trend. Lithologies were grouped into three distinct units: garnet amphibolite (GAM), metasedimentary – dominantly metapelitic – rocks (MSD), and quartzofeldspathic gneisses (QFG). For the digital map, color codes were assigned to each lithology and are used consistently throughout this study. A protanopic- and deuteranopic-compatible color scheme for qualitative data was selected, using the ColorBrewer digital cartography resource (Harrower and Brewer, 2011).

Structural measurements of foliations, lineations, and fold hinges were taken throughout the field area. GPS measurements, accurate to 9 m, recorded the location of structural measurements and major features. Equal area, lower hemisphere plots (Schmidt

nets) of structural data, mean vectors, and best-fit planes to data were generated in the computer program OSXStereonet (Cardozo and Allmendinger, 2013; Allmendinger et al., 2012).

Petrography

Photographs, photomicrographs, and panoramas were processed in Adobe Lightroom®, Photoshop®, and Illustrator® CS6. Scale bars for photomicrographs were automatically generated in Adobe Photoshop®, using a custom measurement scale.

Photomicrographs were taken in plane-polarized and cross-polarized light, under a petrographic microscope. Whole-slide images taken with cross-polarized light utilized a slide scanner and a custom slide holder fitted with orthogonally-oriented polarizing films.

Geochemistry and Thermobarometry

Samples for thermobarometry were previously collected by D.W. Mogk and K. Salt. Microprobe analyses were supplied by D.W. Mogk. Credit for the development and availability of individual mineral formulae calculation spreadsheets goes to D. Henry, Louisiana State University, for biotite, garnet, and feldspar; A. Tindle, The Open University, for amphiboles; and G. Droop, University of Manchester, for ilmenite. Garnet-biotite thermometry was performed using Microsoft Excel® spreadsheets developed by Wu et al. (2004). Ti-in-biotite thermometry was calculated within the biotite formulae Microsoft Excel® spreadsheet of D. Henry. Hornblende-plagioclase thermometry utilized the computer program HBL-PLAG, developed and made freely

available by T. Holland, University of Cambridge, and J. Blundy, University of Bristol. GASP barometry was calculated using a Microsoft Excel® spreadsheet authored by D. Waters, University of Oxford.

Computational Thermobarometry

Multi-equilibria calculations were performed using the software package TWQ v. 2.34 (Berman, 2007). Mineral oxide data was normalized in the winCMP module and equilibria calculated in the winTWQ module. The winTERSX module was used to compute intersections between equilibria curves and perform statistical weighting to yield an average P-T condition. winCLEAN and winDXF modules were used to plot output diagrams in the .dxf file format. Both thermodynamic databases bundled with TWQ v2.34 were utilized: Berman (1988) and Berman et al. (1996). In database v1.02, the following mineral solution models were used: amphiboles (Mader et al., 1994), biotite (McMullin, 1991), feldspar (Fuhrman and Lindsley, 1988), and garnet (Berman, 1990). In dataset v2.02, updated solution models for biotite (Berman et al., 2007) and garnet were used (Berman et al., 1996).

Classical Thermobarometry

The computer program Program GTB (Spear and Kohn, 2014) was used to calculate thermobarometric results using a suite of published ‘classical’ thermometers and barometers, listed in the thermobarometry chapter. Input datasets consisted of mineral cation abundances in atoms per formula unit, which were formatted in Microsoft Excel®

as comma-separated value files. Output data was exported as a graphic plot of K_{eq} lines and a datafile giving the intercepts of each K_{eq} line with the specified P-T limits of the graphic plot. Exact, numeric values for the intersections of selected thermometers and barometers were calculated algebraically from the contents of the datafile.

LITHOLOGY

The Jerome Rock Lakes area (JRL) is underlain by volumetrically dominant quartzofeldspathic gneisses containing garnet-clinopyroxene enclaves and migmatized, interleaved garnet amphibolites, garnet-sillimanite schists, and minor kyanite metaquartzite. The discontinuous character of exposures in the JRL has necessitated inference of contacts in order to extend the continuity of units. On this basis, an effort has been made to group the observed units into three meaningful lithologies: quartzofeldspathic gneisses, garnet amphibolites, and metasedimentary units. These main lithologies reflect an effort to see through widespread anatexis to original protolith and associations; therefore, there is textural and compositional overlap between these units. While this section is mainly descriptive, observations are interpreted in the anatectic framework of Sawyer (2006). Where possible, major metamorphic reactions are also proposed.

Geologic Map

The 1:7,000 scale map in Figure 5 shows bedrock exposures throughout the JRL area. Contacts are relatively continuous along strike and generally trend northeast-southwest. The nature of these contacts is obscured by subsequent tectonism. Minor occurrences of Cretaceous intrusive porphyry are documented, as they may reset radiogenic systems in the minerals of adjacent rock units and result in erroneous radiometric dates. The central JRL area is characterized by interleaved, alternating layers of metapelitic schist and garnet amphibolite. Quartzofeldspathic gneisses continue

Geologic Map of the Jerome Rock Lakes area

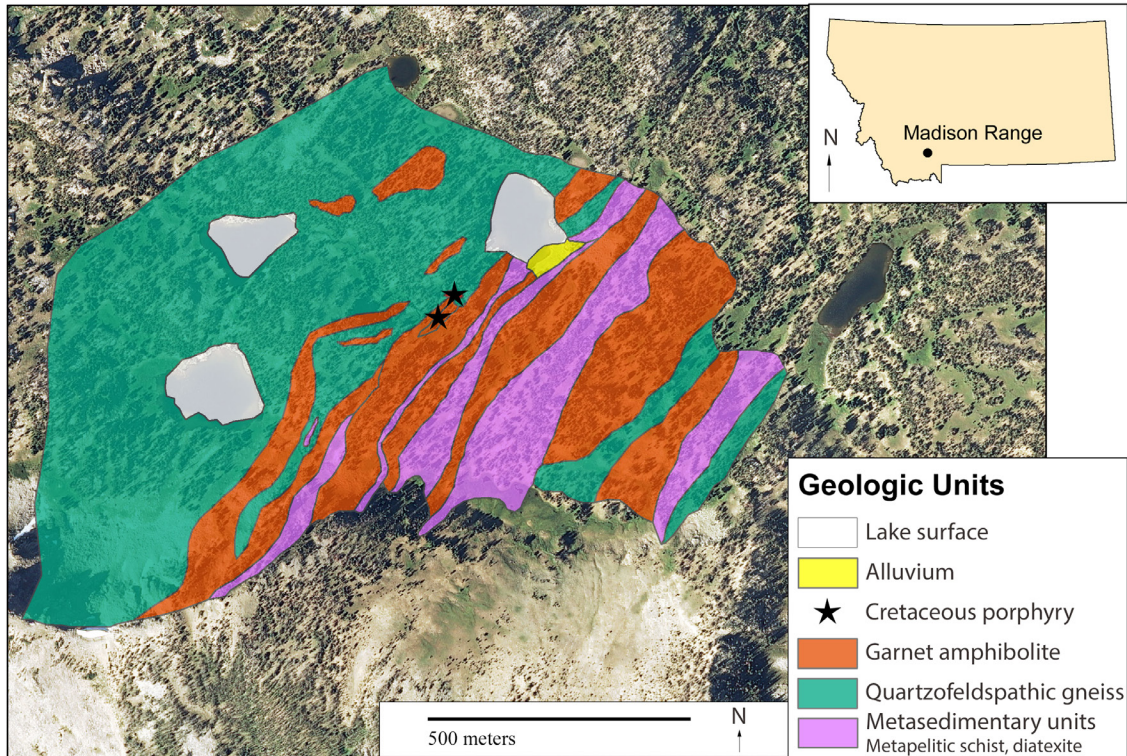


Figure 5: Bedrock map of the JRL area at 1:7,000 scale. Contacts between lithologies are roughly parallel and trend northeast-southwest. The headwall above the lakes is visible in the southern half of the image. The Willow Swamp quadrangle 7.5 minute topographic map was used as the base map. The satellite image used as a background here is taken from the NAIP 2009 orthophoto series.

beyond the map area to the southeast, towards the Mirror Lake shear zone and the Gallatin Peak terrane of Salt (1987), and to the northwest towards the Big Brother shear zone.

Gneiss and Associated Lithologies

Quartzofeldspathic Gneiss

Quartzofeldspathic gneisses are exposed to the northwest and southeast of the

JRL area as long ridges to 100 m in length that surround the central exposures of garnet amphibolite and metasedimentary units. Topographic high points around the lakes, including the 3000 m-high headwall and the northern and southern drainage divides, are entirely composed of this highly resistant unit. One outcrop within the central JRL has also been documented. Analysis of a sample from this outcrop and near the southern drainage divide by Weyand (1989) indicated they are high-Al trondhjemitic gneisses.

Generally, the quartzofeldspathic gneiss is a foliated plagioclase-K-feldspar-quartz-hornblende-biotite gneiss. Meso- to melanocratic hornblende-biotite layers alternate with leucocratic plagioclase-quartz or K-feldspar-quartz layers. Thickness of layering varies from 1 mm to several centimeters. Garnets are infrequently found in leucocratic layers as millimeter-size subhedral to anhedral crystals.

The quartzofeldspathic gneisses manifest a variety of mesoscopic textures, including: an L-tectonite near the Big Brother shear zone; locally unfolded, compositionally layered gneiss; and extensively folded, segregated gneiss. Folding is observed at centimeter to meter scales, typically tight to isoclinal recumbent, and involves both mesocratic and leucocratic layers in harmonic to polyharmonic structures. Structural elements of the JRL area are discussed in detail in the subsequent chapter.

Decussate embayed hornblende and disseminated subhedral biotite to 5 mm occur in varying proportions throughout mesocratic layers (photograph C, Figure 6). Hornblende grains are roughly anticlustered – rare contact between grains is characterized by straight boundaries – and embayed by plagioclase and quartz. Additionally, small inclusions of hornblende are found in plagioclase and quartz. Subhedral biotite is

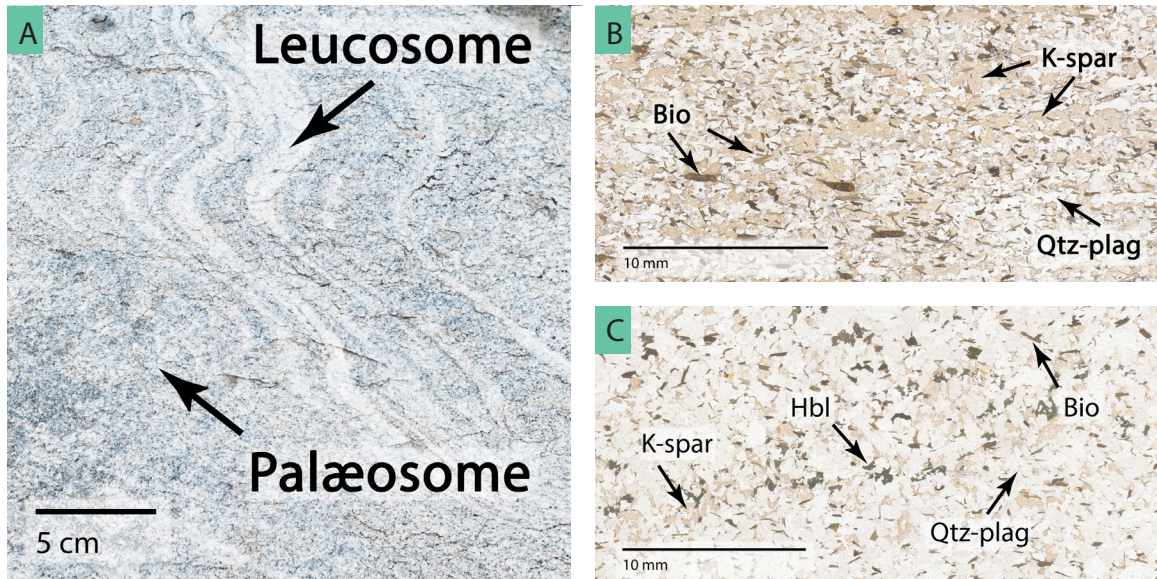


Figure 6: General textural and compositional spectrum of quartzofeldspathic gneisses in the JRL area. Photograph A - macroscopic compositional segregation into leucocratic and mesocratic layers. Photograph B - well-developed foliation of K-feldspar and lepidoblastic hornblende and biotite. View of sample SP-139 in K-stained thin section, under plane-polarized light. Photograph C - equigranular texture in dominantly quartz-plagioclase matrix with minor hornblende, biotite, and K-feldspar. View of sample SP-141 in K-stained thin section, under plane-polarized light.

similarly anticlustered but frequently is aligned to form a weak, discontinuous foliation.

Melanocratic layers are defined primarily by the increased mode of hornblende; biotite content increases slightly and remains a minor constituent.

Leucocratic layers are composed of interlocking interlobate plagioclase, K-feldspar, and quartz in varying proportions. The mode of K-feldspar varies from 10% to over 50%; however, it occurs generally as anhedral to embayed grains with inconsistently-developed tartan twinning. Quartz and plagioclase occur in subequal amounts in both leucocratic and mesocratic layers. Minor disseminated subhedral biotite and garnet are also observed.

K-feldspar additionally occurs as distinct anhedral megacrysts. Large elongate

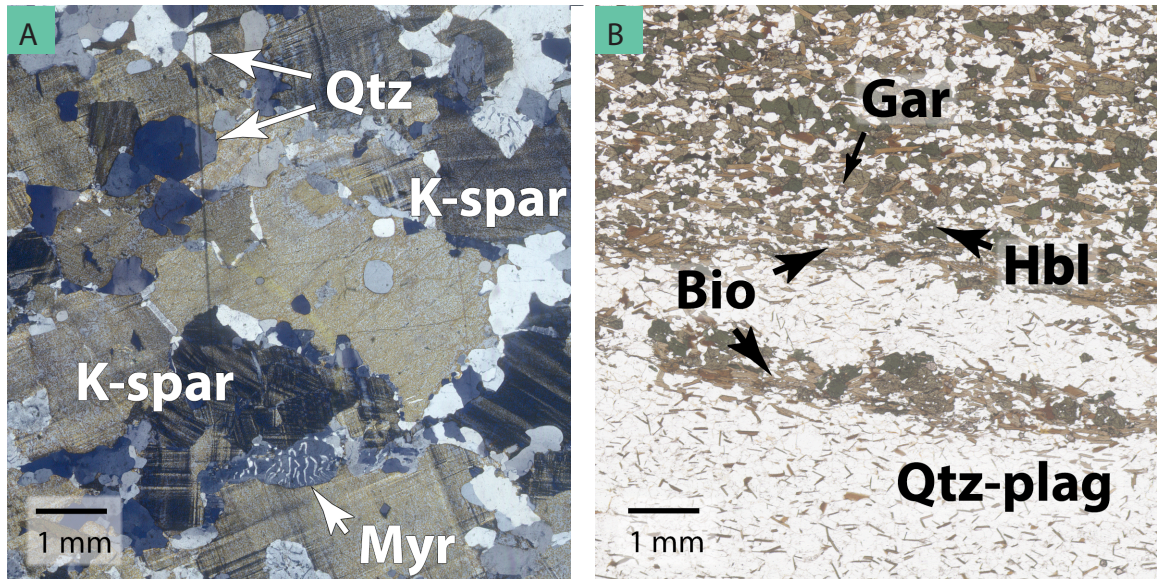


Figure 7: Textural variations in quartzofeldspathic gneisses, viewed in thin section under cross-polarized light. Photograph A - aggregate of interlocking K-feldspar megacrysts. Note myrmekite development embaying K-feldspar grains. View of sample SP-133 in K-stained thin section, under cross-polarized light. Photograph B - alternating melanocratic and leucocratic layers. Garnet is present as very small anhedral grains adjacent to hornblende in the melanocratic layers. View of sample JSC-005B in thin section, under cross-polarized light.

grains subparallel to biotite foliation are segregated into compositional layers alternating with quartz and plagioclase. Stout embayed porphyrocyts are found with minor quartz, plagioclase, and quartz-plagioclase myrmekite in thick, leucocratic layers. Photograph A of Figure 7 shows an occurrence of K-feldspar megacrysts with well-developed albite and pericline twinning.

Melanocratic layers are exceptionally hornblende-rich and contain small anhedral grains of clinopyroxene and garnet (photograph B, Figure 7). In the field, these appear as distinct layers 5 mm to 2 cm thick that alternate with quartz-plagioclase layers.

Finer-grained leucocratic layers, such as that seen in photograph B of Figure 7, may reflect a reduction in grain size as a result of dynamic recrystallization during

deformation. The interlocking grain boundaries of K-feldspar, plagioclase, and quartz indicate growth from a liquid.

The overall mesocratic nature of the quartzofeldspathic gneiss precludes definitive distinctions between leucosome, residuum, and palæosome. However, disequilibrium textures indicate the presence of at least two different leucosome compositions: granite *sensu stricto* and tonalite-trondhjemite. The trondhjemitic protolith identified for the

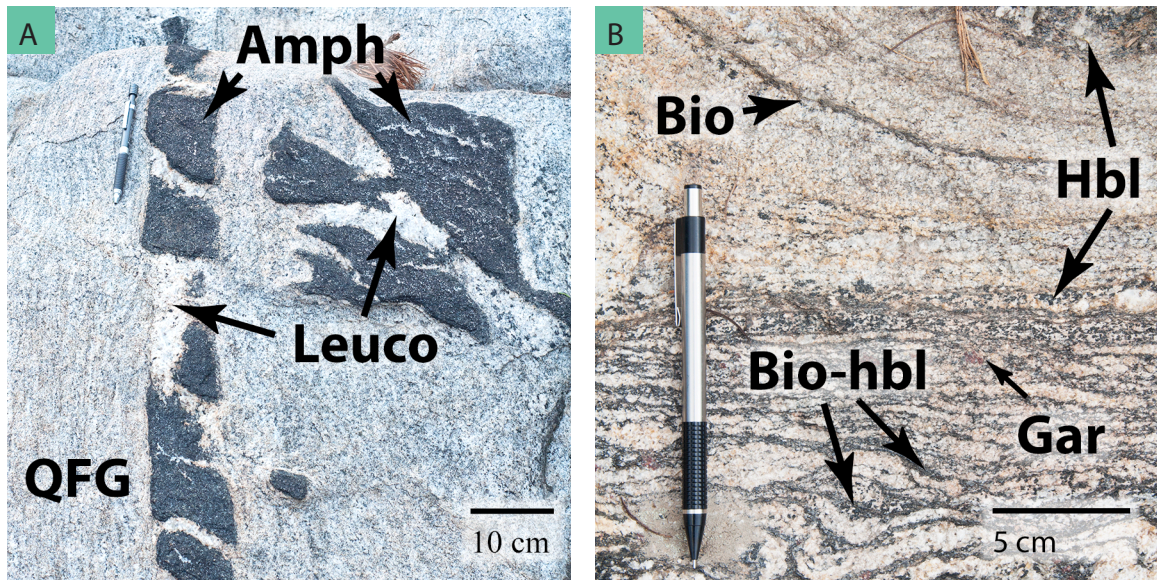


Figure 8: Additional mesoscopic textures in quartzofeldspathic gneisses. Photograph A - partially dismembered amphibolite dyke. The surrounding gneiss contains fine layering of quartz-plagioclase and hornblende-biotite-plagioclase (stromatic metatexite). Gaps between boudins are infilled by plagioclase-quartz. The dyke was likely injected before crystallization of the leucosome. Tensile stresses resulting from the competent behavior of the dyke collected melt from the surrounding host. This outcrop is located above the northwestern JRL. Photograph B - extensive anatexis under vapor-present conditions. The upper part of the image is dominated by two leucosome textures, the uppermost of which is fine-grained and the lower coarse-grained. Hornblende occurs as coarse grains and in thin melanocratic layers with biotite. The increased degree of deformation in the lower part of the image is attributed to the locally vapor-present melting of biotite, producing peritectic hornblende and garnet. This outcrop is immediately adjacent to the southeast edge of the garnet amphibolite-metasedimentary schist exposures.

JRL quartzofeldspathic gneisses (Weyand, 1989) lacks the necessary biotite to produce a granitic leucosome. The minor subhedral biotite observed likely grew during waning from peak metamorphic conditions.

The association of thin, biotite-dominated melanocratic layers with thick, coarse-grained leucosome and equant amphibole grains, such as seen in Figure 8, comprises a minor component of the JRL quartzofeldspathic gneisses. The presence of peritectic hornblende indicates partial melting of biotite in the presence of water, as a hydrous phase is stabilized during prograde metamorphism.

Plagioclase and quartz embaying anticlustered hornblende in hornblende-dominated melanocratic layers suggests that they grew at the expense of this phase, producing a tonalitic-trondhjemitic leucosome. This leucosomal composition would be in disequilibrium with a K-feldspar-rich leucosome, leading to the development of interstitial myrmekites. The thickness of melanocratic layers containing clinopyroxene and garnet, like those shown in Figure 6, indicates that they are the residuum complement to the tonalite-trondhjemite leucosome, resulting from partial melting of hornblende. In photograph A of Figure 8, the leucosome is clearly separated from the gneiss, due to the effect of the more competent amphibolite dyke. Clinopyroxene and garnet neoblasts in residuum layers subsequently grew during prograde dehydration of hornblende.

Transitional Granulite

Clinopyroxene- and garnet-bearing amphibolite units occur as meter-scale lineated lenses within the quartzofeldspathic gneisses. In some areas, they appear as dismembered boudins, with near-continuity to several meters of separation. Fabric

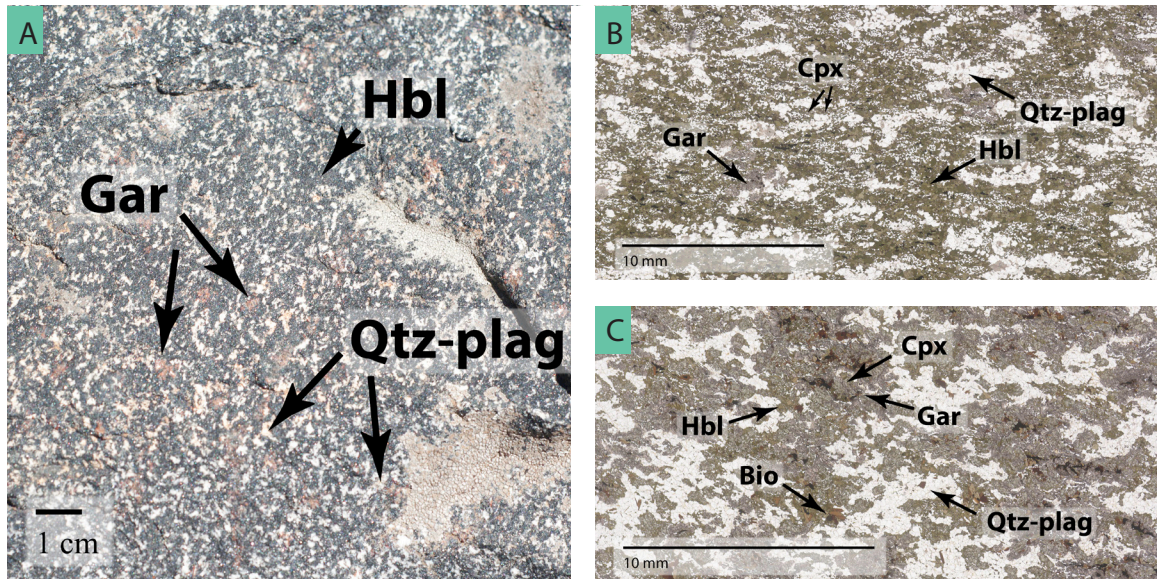


Figure 9: Representative texture of transitional granulite lenses in quartzofeldspathic gneiss. Photograph A - typical mesoscopic texture showing equant fabric with small garnets. Photograph B - well-defined lineation resulting from elongation of plagioclase-quartz and nematoblastic clinopyroxene aggregates. View of sample JSC-003 in thin section, under unpolarized light. Photograph C - minimal development of lineated fabric. Garnet is much more abundant, surrounding large clinopyroxene porphyroclasts. Hornblende is significantly less abundant than in sample JSC-003. View of sample JSC-006 in thin section, under unpolarized light.

development is variable among occurrences, ranging from generally decussate to strongly lineated. Where a lineated fabric is developed, it is subparallel to compositional layering in the enclosing quartzofeldspathic gneiss. At contacts between lenses and host gneisses, grain size reduction and mineral lineations have been observed. Photograph A of Figure 9 documents an example of moderate fabric development.

The lenses are composed of anhedral clinopyroxene porphyroclasts surrounded by partial garnet coronae and polygonal hornblende in a matrix of polygonal quartz and plagioclase with minor anhedral clinopyroxene neoblasts (Figure 9). The texture of plagioclase-quartz associations ranges from small, dissociated grains to elongate lenses.

Minor decussate biotite and globular opaque phases occur throughout. Clinopyroxene porphyroclasts contain fluid inclusions, acicular ilmenite grains, and apparent lamellae of hornblende. Photograph B of Figure 10 shows an anhedral clinopyroxene porphyroclast embayed by small euhedral hornblende grains and a partial corona of garnet with anhedral plagioclase and hornblende inclusions. The included core of the clinopyroxene porphyroclast contains rounded fluid inclusions, acicular ilmenite, and hornblende lamellae. Not all porphyroclasts are surrounded by garnet coronae, but all share the inclusion suite and density.

A typical occurrence of the second, minor mode of clinopyroxene is detailed in

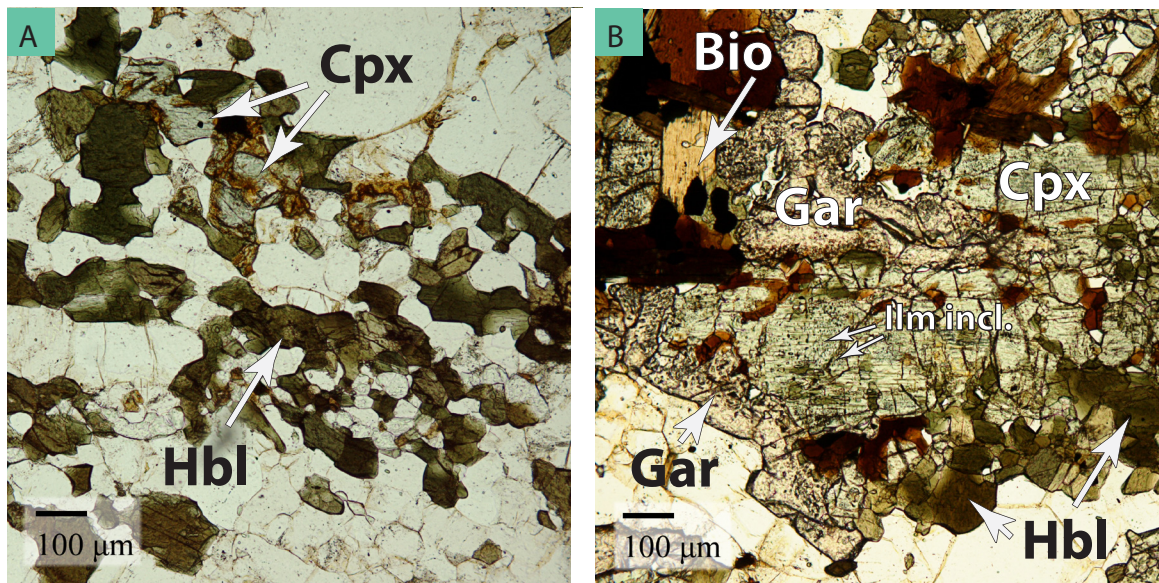


Figure 10: Details of significant microtextural elements in transitional granulite. Photograph A - very small anhedral clinopyroxene grains surrounded by polygonal hornblende and distributed in leucocratic matrix. View of sample JSC-003 in thin section, under plane-polarized light. Photograph B - clinopyroxene porphyroclasts surrounded by polygonal hornblende and partial garnet coronae. Garnet growth at the expense of clinopyroxene and hornblende is reflected in the numerous small inclusions. Note apparent lamellae of hornblende. View of sample JSC-006 in thin section, under plane-polarized light.

photograph A of Figure 10. The small anhedral neoblasts are associated with subhedral hornblende grains and opaque phases within the leucocratic matrix. The various types of inclusions observed in the porphyroclasts are not seen in the neoblasts. Additionally, garnet coronae are not found in association with neoblasts.

Moderately included garnet coronae partially surround clinopyroxene porphyroclasts that are in contact with plagioclase. Density of rounded plagioclase and hornblende inclusions increases towards the clinopyroxene grain boundary. No clinopyroxene inclusions have been observed within garnet coronae.

Partial coronae of polygonal hornblende surrounding clinopyroxene porphyroblasts likely result from the incomplete hydration of clinopyroxene to hornblende. Similar coronae are not observed around clinopyroxene neoblasts; the subsolidus hydration of the porphyroclasts occurred before growth of the neoblasts.

Partial coronae of garnet likely result from a reaction between matrix plagioclase and clinopyroxene porphyroclasts. Apparent lamellae of hornblende within clinopyroxene porphyroclasts are mostly likely the product of passive replacement along crystal planes within the clinopyroxene structure and not evidence for exsolution of orthopyroxene (Passchier and Trouw, 2005). Acicular ilmenite inclusions within clinopyroxene porphyroclasts suggests that the porphyroclasts grew at high temperature, as required by the high titanium content necessary for ilmenite growth.

The protolith of the clinopyroxene- and garnet-bearing amphibolite enclaves crystallized from a mafic liquid containing high-titanium clinopyroxene phenocrysts and plagioclase. Absence of orthopyroxene lamellae indicates relatively rapid cooling

following injection. Subsolidus hydration of clinopyroxene porphyroclasts followed, producing polygonal hornblende. Subsequent granulite-facies metamorphism is recorded by the growth of garnet from igneous clinopyroxene and plagioclase and the growth of a second generation of clinopyroxene. This sub-lithology is referred hereafter as a transitional granulite, since it contains plagioclase but lacks the diagnostic orthopyroxene.

(1) *clinopyroxene (I) + H₂O → hornblende*

(2) *hornblende + plagioclase → clinopyroxene (II) + garnet + melt*

Metasedimentary Lithologies

Metasedimentary units typically occur as decimeter to meter-scale foliated

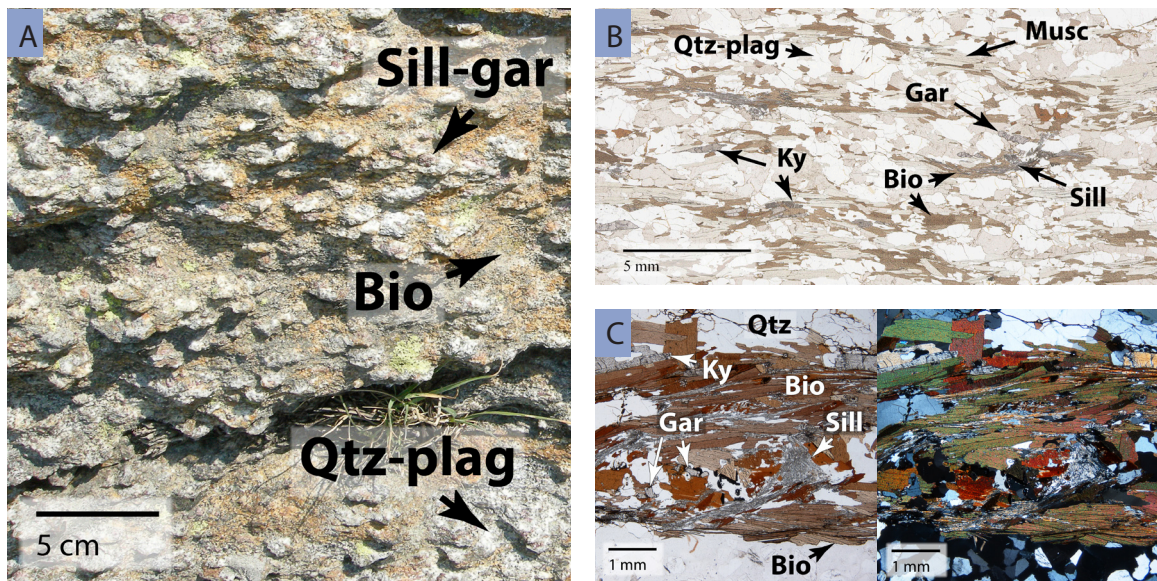


Figure 11: Garnet-sillimanite gneiss. Photograph A - typical macroscopic texture with fibrolite mats and well-defined schistosity. Photograph B - biotite-muscovite foliation and elongate plagioclase and quartz. View of sample JSC-022B in thin section, under unpolarized light. Photograph C - detail of fibrolitic sillimanite-biotite lozenge with amoeboid garnet at core. Note subhedral kyanite prism associated with biotite. View of sample JSC-022B in thin section, under plane- and cross-polarized light.

exposures in the central JRL area, continuous along strike 100 m -1 km. Individual layers are typically interleaved and folded with garnet amphibolite layers. Two distinct lithologies have been observed: garnet-sillimanite schist and kyanite metaquartzite.

Garnet Sillimanite Schist

1-3 m thick, laterally-extensive layers of garnet-sillimanite schist are exposed in the central JRL area. The units are continuous along strike up to 100 m and interleaved with folded and unfolded garnet amphibolite layers.

Anhedral garnet porphyroblasts to 1 cm are surrounded by lozenges of biotite and fibrolitic sillimanite to 3 cm in a plagioclase-quartz-mica matrix. Schistosity is defined by lepidoblastic biotite and muscovite and deflects around the lozenges. Minor compositional layering is defined by abundance of lozenge-rich and leucocratic layers.

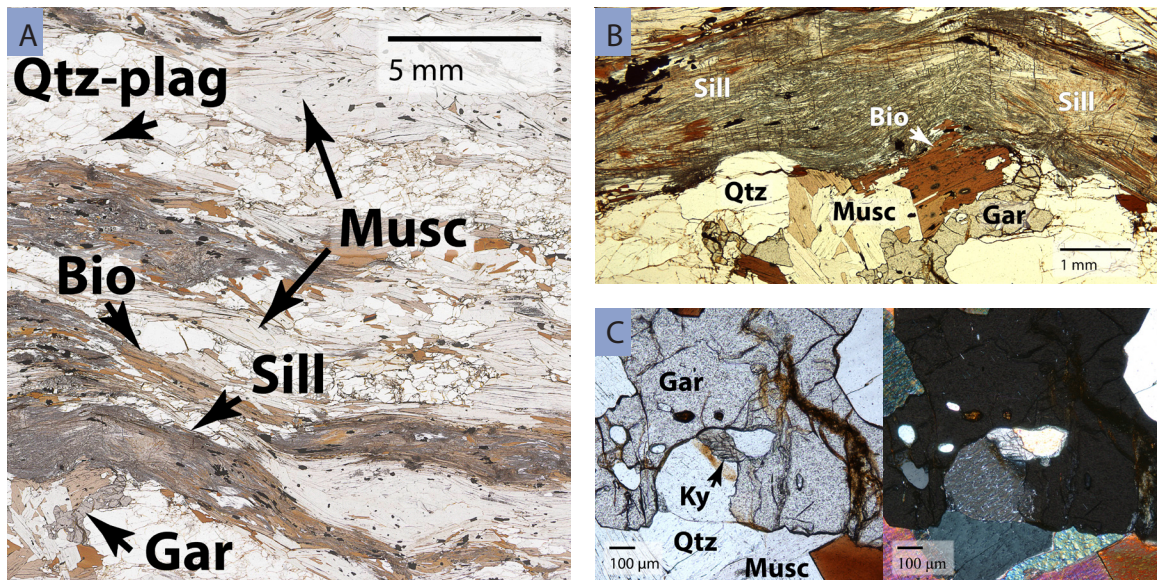


Figure 12: Sillimanite mats in thin section of sample JSC-002. Photograph A - fibrolite clots in matrix. View under unpolarized light. Photograph B - association with biotite and garnet. View under plane-polarized light. Photograph C - detail of garnet in photograph B, showing inclusion of kyanite and quartz. View under plane- and cross-polarized light.

Photographs B and C of Figure 11 details typical matrix and biotite-rich lozenge textures. Lenses and layers of leucocratic quartz-plagioclase show interlocking, interlobate grain boundaries. Grain boundaries between lepidoblastic biotite and muscovite are straight; however, biotite in contact with leucocratic material is embayed. Additionally, small inclusions of biotite are present in leucocratic material.

The biotite-rich sillimanite lozenge shown in photograph C of Figure 11 contains a typically small amoeboidal garnet porphyroblast. Acicular sillimanite is dominantly associated with large biotite grains and often contains small biotite inclusions. Kyanite occurs as subhedral prisms, inclusions in biotite and muscovite after biotite, and as small distributed grains in the matrix. Lepidoblastic muscovite is closely associated with biotite and often completes a subhedral grain outline.

Figure 12 documents a more sillimanite-rich and leucocratic occurrence of garnet-sillimanite schist. Lozenges are nearly monomineralic sillimanite aggregates, preserving minor biotite and opaque inclusions. Amoeboidal garnet is a minor constituent, as is biotite. Bands of subhedral muscovite with minor biotite and kyanite inclusions anastomose through interlocking plagioclase and quartz. Photograph C of Figure 12 also documents a small inclusion of kyanite in quartz, partially surrounded by garnet.

Interlocking plagioclase and quartz grain boundaries in augen and discrete layers indicate that these phases crystallized from a liquid. Inclusions of kyanite in biotite and sillimanite growing over biotite reflect prograde metamorphism from the kyanite into the sillimanite stability field. Embayed biotite and biotite inclusions in the leucocratic material are interpreted as the result of incipient melting.

Generally, the disequilibrium between biotite, sillimanite, garnet, and the plagioclase-quartz leucosome indicates the breakdown of biotite to yield garnet, sillimanite, and the leucosome. The deformation experienced by this lithology, which developed a strong schistosity, may also have aided in the migration of the leucosome. K-feldspar-containing leucocratic layers, discussed subsequently, may represent the extracted leucosome of the garnet-sillimanite biotite schist.

Kyanite Metaquartzite

A single 0.5 m-thick unit of translucent metaquartzite occurs between the northmost exposure of the garnet amphibolite and quartzofeldspathic gneiss. The metaquartzite displays an anastomosing centimeter-spaced weak foliation of muscovite

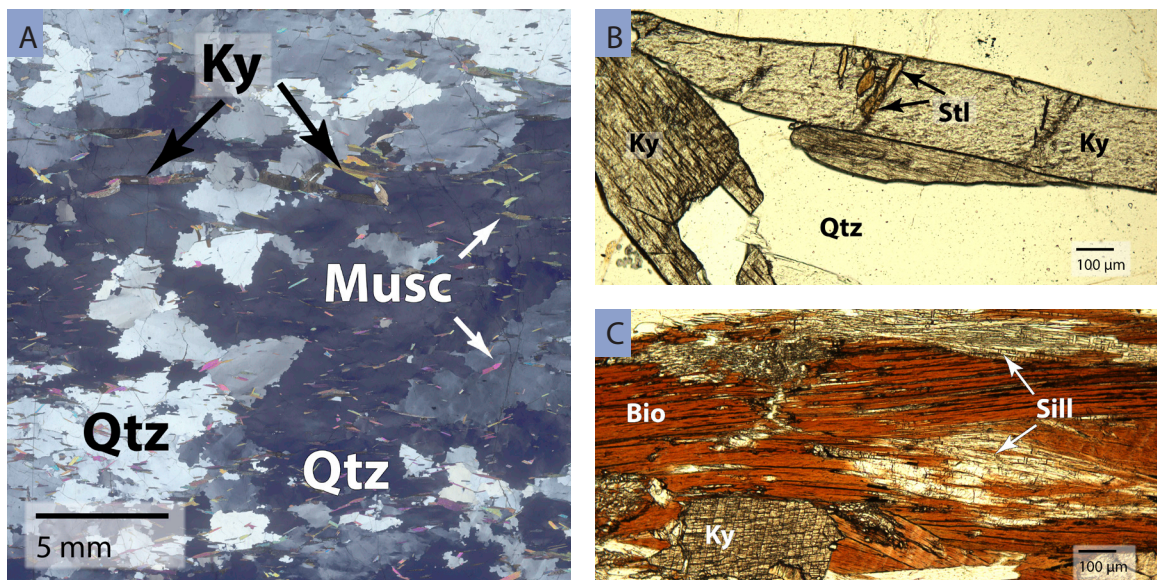


Figure 13: Kyanite metaquartzite of sample JSC-013. Photograph A - irregular grain boundaries of quartz and weak muscovite foliation. View of thin section under cross-polarized light. Photograph B - staurolite inclusions within kyanite prisms. View of thin section, under plane-polarized light. Photograph C - kyanite and biotite with sillimanite overgrowth. View of thin section under plane-polarized light.

and minor biotite, separated by nematoblastic kyanite porphyroblasts to 2 cm and large quartz microlithons with suture grain boundaries and undulose extinction. Acicular sillimanite occurs at the margins of biotite grains and within biotite aggregates.

Photograph B of Figure 13 shows a kyanite grain with small staurolite inclusions. Staurolite does not occur independently within the quartz matrix. Kyanite grains that occur within the quartz matrix are generally tabular subhedral with undulose extinction and are, in some cases, bent. Tabular kyanite grains are frequently rimmed with muscovite grains that complete a subhedral outline. Kyanite grains associated with biotite are subhedral to anhedral and wholly to partially enclosed by biotite. Acicular sillimanite occurs intergrown with biotite and shows some minor deflection. Sillimanite grains are not consistently associated with kyanite but are with undeformed muscovite.

The protolith of this unit was likely a quartz arenite. The light-green color of muscovite in hand sample suggests minor trivalent chromium substitution.

This sublitology records a prograde metamorphic path, followed by exhumation and cooling. Staurolite inclusions in kyanite indicate early prograde conditions, leading to the formation of sillimanite via biotite breakdown at peak conditions. Cooling resulted in the retrograde growth of muscovite on kyanite and biotite.

A generalized metamorphic progression for the metaquartzite unit follows:

- (1) *Early prograde: growth of staurolite, early garnet, biotite*
- (2) *Increasing prograde: breakdown of staurolite, growth of kyanite*
- (3) *Peak conditions: breakdown of biotite, growth of sillimanite and garnet*
- (4) *Cooling: growth of chlorite, replacement of kyanite and biotite by muscovite*

Mafic (Metabasic) Lithologies

Garnet Amphibolite

Garnet amphibolite units occur as 10-100 m exposures with well-developed compositional layering and hybrid mineral foliation. These units are continuous along strike for approximately 100 m -1 km and are intricately interleaved with metasedimentary schist layers of similar dimensions.

Compositional layering is defined by melanocratic matrix texture, as well as garnet porphyroblast size and abundance. A hybrid mineral foliation is produced by hornblende grains parallel to a planar trace but poorly aligned within the plane. Thin

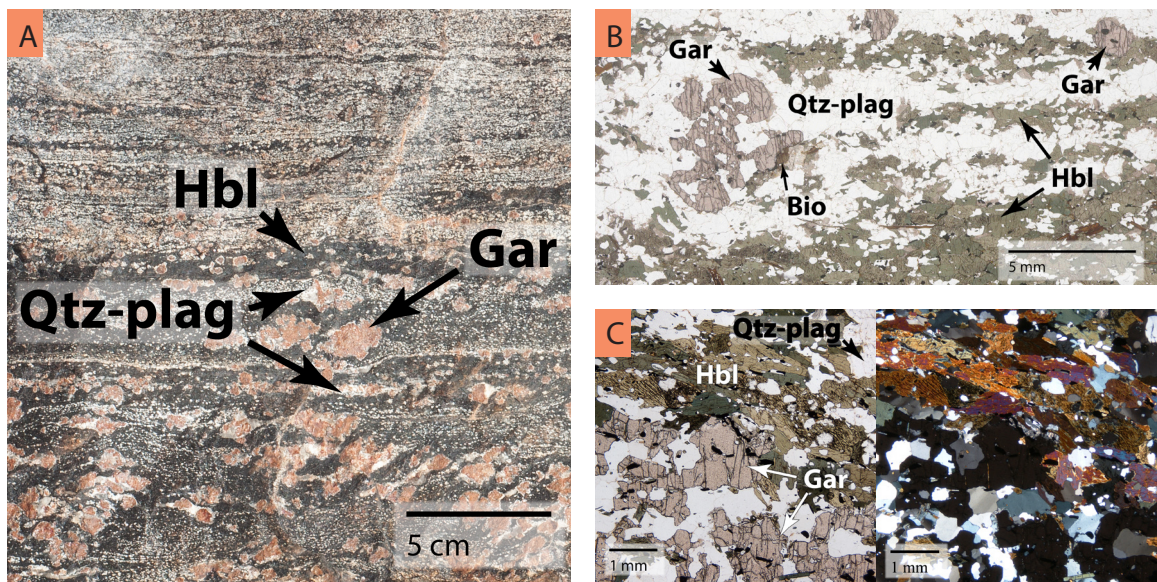


Figure 14: General textures of garnet amphibolites. Photograph A - macroscopic texture showing cm-size garnets and compositional layering of varying thickness. Photograph B - quartz-plagioclase augen with amoeboid garnet at core deflecting hornblende foliation. View of sample JSC-014 in thin section, under unpolarized light. Photograph C - detail of association between garnet, hornblende, and leucosome. View of sample JSC-009 in thin section, under plane- and cross-polarized light.

leucocratic layers lacking porphyroblasts have also been observed concordant to foliation.

This lithology is characterized by amoeboidal to skeletal garnet porphyroblasts to 2 cm in diameter, surrounded by typically elongate augen of interlocking plagioclase and quartz to 5 cm in a foliated hornblende-plagioclase-quartz melanocratic matrix (Figure 14). Garnet porphyroblasts have numerous rounded quartz and plagioclase inclusions and are extensively fractured subperpendicular to the hornblende foliation. Low temperature alteration products are rarely observed along these fractures or throughout the rock.

Matrix texture varies from a salt-and-pepper, nearly homogenous distribution of hornblende and plagioclase-quartz with small garnet porphyroblasts to monomineralic hornblende layers that alternate with augen-hosted garnet megablasts, approaching gneissic banding. Matrix foliation deflects around the augen and is defined by subhedral to anhedral grains of hornblende. Boundaries between individual hornblende grains are typically straight, while those with quartz and plagioclase are embayed. Small adjacent inclusions of hornblende within the augen and leucocratic layers have optical continuity. Hornblende is occasionally overgrown by thin biotite selvages at contacts with augen. Globular to tabular opaque inclusions are associated with hornblende and garnet grains.

Preferred orientation is observed as elongation of augen and matrix hornblende layering. Elongation can also be observed as stretching lineations of the augen that are visible on exposed foliation planes. Augen that are entirely filled by garnet porphyroblasts display little to no elongation, however.

Interlobate grain boundaries in the foliated melanocratic matrix between embayed hornblende grains and globular-anhedral plagioclase and quartz, as well as optical

continuity of hornblende inclusions in the augen, suggest derivation of the leucocratic material from incipient melting of the hornblende. Partial melting of the hornblende, therefore, produced a plagioclase-quartz leucosome. The absence of a foliation within the leucosome suggests that the foliation of the melanocratic protolith predates the formation of the leucosome. While the leucosomal composition is adequate to reflect derivation from hornblende melting, the significant volume of remaining protolith suggests that the augen are in-source leucosomes: melt that has migrated some small distance within its host rock. The migration may have been driven by synchronous deformation, leading to the extensive compositional layering of this lithology.

The absence of K-feldspar indicates that breakdown of a potassic mineral such as biotite is an unlikely source for the leucocratic material – melting of hornblende would produce the plagioclase-quartz leucosome observed, as well as supply the necessary ferromagnesian component for garnet growth. The hornblende-rich bulk composition reflects the mafic character of the igneous protolith, although it cannot be determined whether the hornblende is igneous or metamorphic in origin. The mafic protolith may have cooled either as an injected body or a subaerial flow. A generalized scheme for the evolution of garnet amphibolite follows:

- (1) *Crystallization from mafic magma*
- (2) *Hornblende $\rightarrow$ garnet + melt*
- (3) *Minor low temperature retrogression (chloritization)*

'Ordinary' Amphibolite

'Ordinary' amphibolites in the JRL are dominantly composed of lineated

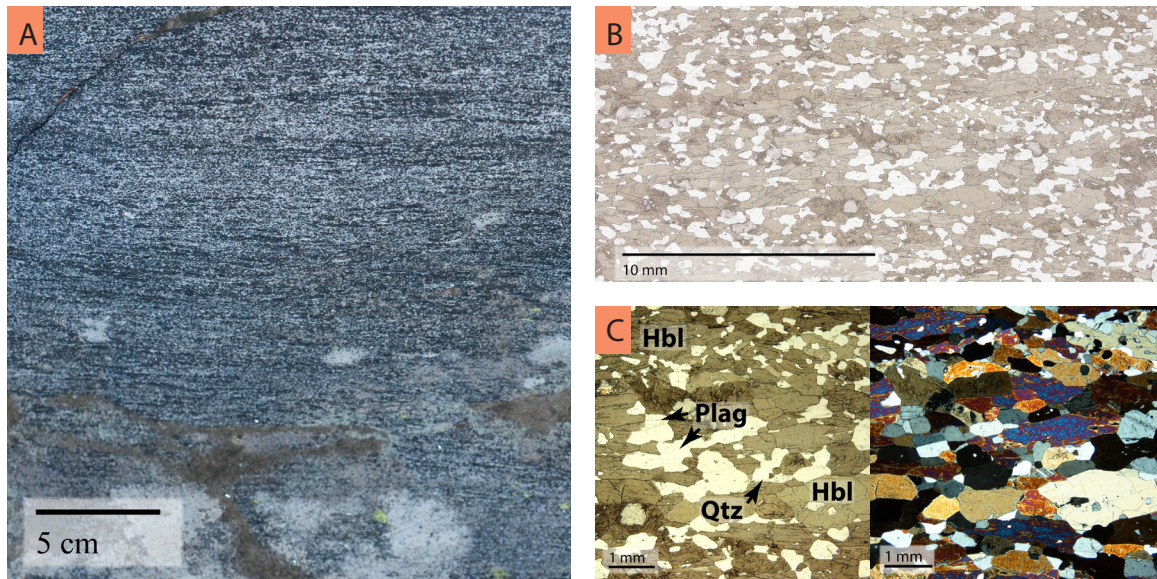


Figure 15: Ordinary amphibolite JSC-019 found in association with garnet amphibolites. Photograph A - macroscopic texture, showing strong lineation. Photograph B - strongly lineated hornblende fabric. Note that quartz and plagioclase do not manifest the same fabric. View in thin section, under unpolarized light. Photograph C - detail of embayed hornblende grain boundaries and lobate grain boundaries of plagioclase and quartz. The lighter pleochroism may indicate a lower Fe content than observed matrix hornblende of the garnet amphibolites. View of thin section under plane - and cross-polarized light.

amphiboles with disseminated quartz and plagioclase. The occurrence discussed here is as strongly lineated meter-scale enclaves in an intensely folded region of interleaved migmatized garnet amphibolites and metasedimentary schists. Lineation is defined by millimeter-size nematoblastic amphibole grains and weak foliation of compositional layering. This lithology is distinguished by its lack of porphyroblasts.

The main assemblage is composed of dominantly nematoblastic amphibole and anhedral interlocking plagioclase and quartz. Small anhedral inclusions of amphibole occur in quartz and plagioclase. Grain boundaries between individual amphibole grains are straight, while those in contact with quartz and plagioclase are embayed. Some deformation of amphiboles around quartz and plagioclase is observed. Low-temperature

alteration of the sample is limited to minor sericitization of plagioclase.

Sample JSC-019 is the only sample to contain a stable assemblage without evidence for disequilibrium at peak conditions. The light color of amphibole, seen in photograph C of Figure 15, may suggest a lower Fe content relative to hornblende compositions in the garnet amphibolites and transitional granulites. This amphibolite may have been injected into the metasupracrustal units late in the JRL area's tectonic history, since it lacks evidence for partial melting or extensive deformation.

Diatexites

Throughout the central JRL area, leucocratic layers containing porphyroblastic garnet are exposed. These units range in thickness from several centimeters to 2 meters, are laterally continuous to 100 m, and manifest variable fabric development. Thinner units tend to occur as isolated unfoliated layers. Thicker units often occur intercalated with garnet amphibolite, particularly at the headwall above the lakes, and have developed mineral foliations and compositional layering. Foliation, where present, ranges from an anastomosing foliation involving millimeter-thick melanocratic layers and elongated leucocratic augen to well-developed gneissic banding. Compositionally, these occurrences can be grouped by the presence or absence of K-feldspar as a major component of the leucocratic layers.

K-feldspar Leucosomes

K feldspar-containing leucocratic layers are composed of anhedral garnets distributed in an unfoliated, inequigranular leucocratic matrix of interlocking quartz,

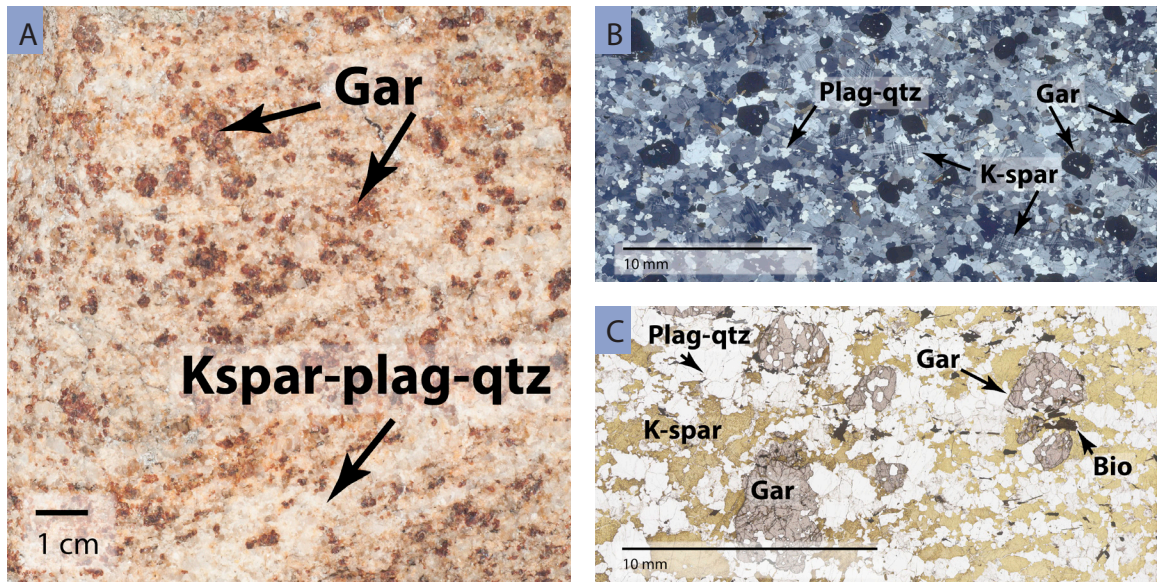


Figure 16: K feldspar-plagioclase-quartz leucocratic layer with garnets. Photograph A - macroscopic texture showing sub-cm garnets in leucocratic matrix. Photograph B - microscopic texture of leucocratic matrix, showing interlocking grain boundaries. View of sample JSC-001 in thin section, under cross-polarized light. Photograph C - Interstitial texture of K-feldspar. View of sample JSC-016B in K-stained thin section, under unpolarized light.

K-feldspar, and minor plagioclase. Minor anhedral opaque phases and decussate subhedral biotite with muscovite rims are distributed throughout the rock.

Garnet porphyroblasts are variably included by quartz and likely feldspar, up to a poikiloblastic texture, and vary in grain geometry from subhedral to amoeboid. Since twinning is not developed in the inclusions, distinction between quartz and feldspar is not possible.

Figure 16 details the overall texture of the K feldspar-containing leucocratic layers containing garnet. Photographs B and C document the undulose extinction and convex to interlobate grain boundaries of matrix quartz and the interlobate to amoeboid grain boundaries of K-feldspar. Characteristic tartan twinning is well developed in

K-feldspar.

The general interlocking texture of quartz, K-feldspar, and plagioclase indicates crystallization from a liquid. Convex K-feldspar grain boundaries suggest that this phase crystallized following quartz and plagioclase. The low abundance of garnets suggests a related low ferromagnesian content within the quartz-K feldspar leucosome. The absence of a melanosome suggests a high degree of anatexis and melt extraction: a diatexite.

Plagioclase Leucosomes

Leucocratic material lacking K-feldspar is most often observed intercalated with garnet amphibolite in several meter-thick layers. This unit is characterized by anastomosing, discontinuous millimeter-thick biotite foliation and quartz-plagioclase

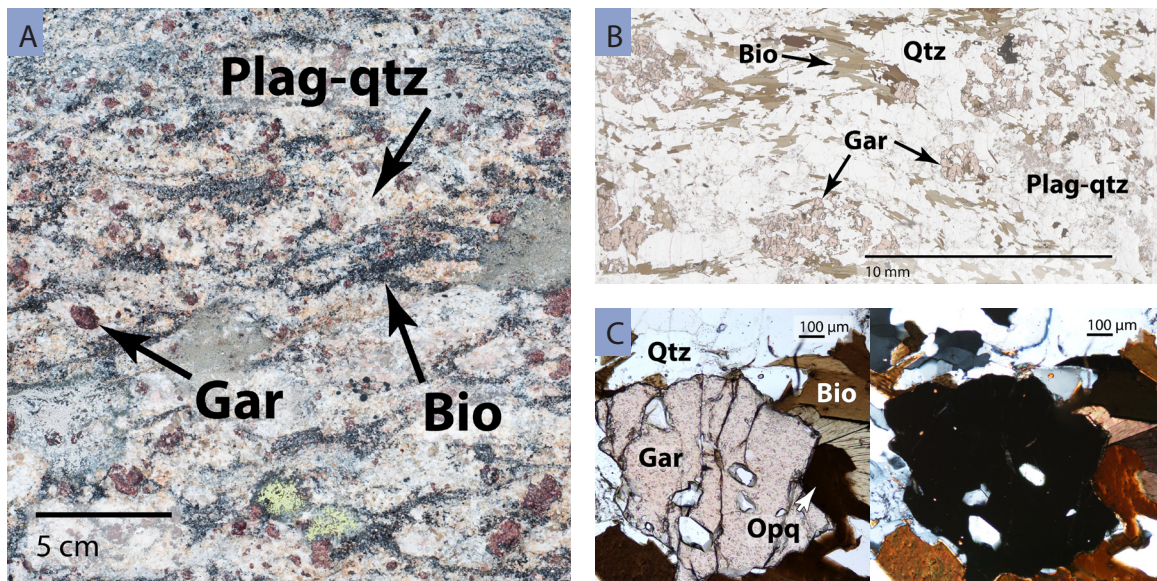


Figure 17: Garnet leucogneiss lacking K-feldspar. Photograph A - macroscopic texture showing sub-cm garnets and moderate foliation. Photograph B - weak biotite foliation deflecting around quartz-plagioclase layers. View of sample JSC-015 in K-stained thin section, under unpolarized light. Photograph C - detail of garnet showing association with biotite. Note that hornblende is not observed in this sub-lithology. View of sample JSC-015 in thin section, under plane- and cross-polarized light.

augen with porphyroblastic garnet cores (Figure 17). Some exposures contain minimal mineral foliation and segregation of leucocratic augen into larger lenses.

The general textures are documented in Figure 17. Amoeboid, inclusion-rich garnet porphyroblasts and interlocking quartz-plagioclase grain boundaries are similar to those seen in the K-feldspar leucosome. Lepidoblastic subhedral biotite forms thin foliations and is also distributed throughout the rock volume.

Quartz-plagioclase augen comprise the deformed but unfoliated leucosome that roughly parallels the biotite foliation. The absence of K-feldspar in the neosome suggests

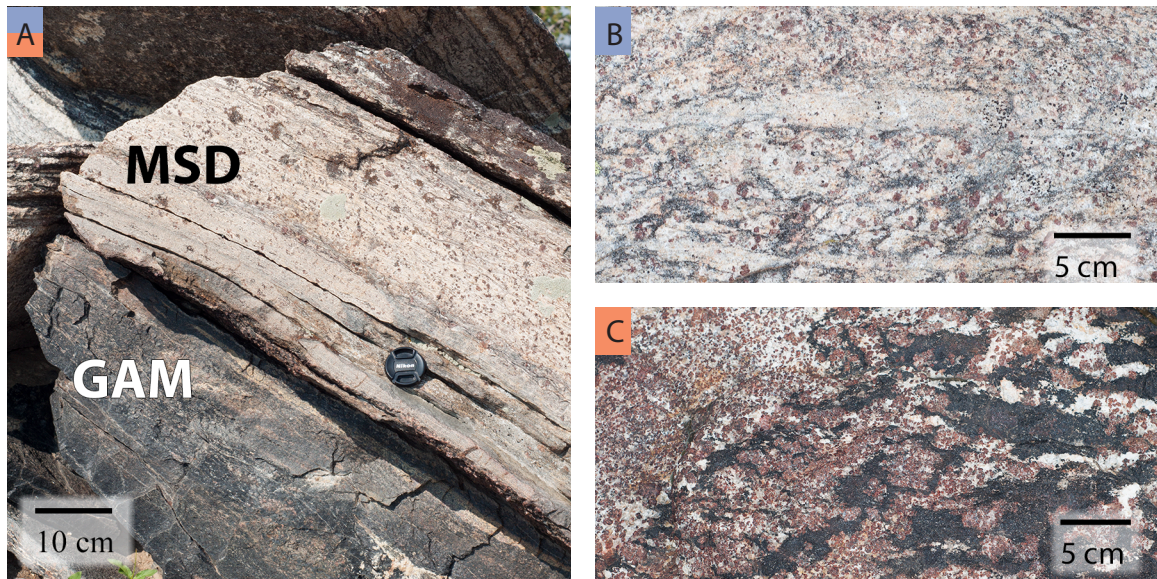


Figure 18: Diatexitic migmatites of the JRL, located at the headwall above the lower Jerome Rock Lake. Photograph A - Contact between nearly monomineralic garnet amphibolite, containing few garnets, and leucosome-dominated metapelite. Photograph B - Leucosome-dominated metapelite in outcrop, showing discontinuous biotite foliation (schlieren) and K-feldspar-plagioclase-quartz augen. Boundaries of garnet grains do not overgrow schlieren, indicated that garnet growth before complete crystallization of the leucosome. Photograph C - Extensive segregation of leucosome and melanosome in garnet amphibolite. The accumulation of plagioclase-quartz in the upper left of the image is only found in this location. The hornblende residuum is very depleted in plagioclase. Garnet megablasts are the largest observed in the JRL and likely grew before crystallization of the leucosome.

that a potassic mineral was not a component of the protolith, and that the biotite grew later, possibly during reversal of a melting reaction. This leucosome-rich, garnet-bearing plagioclase-quartz unit reflects extensive anatexis and is also considered a diatexite.

These diatexites are best observed at the headwall above the lower Jerome Rock Lake. A gradient in anatectic degree is observed in JRL outcrops, increasing from the trail junction and lower Jerome Rock Lake upslope to the headwall. Garnet amphibolites at the headwall contained the largest garnet megablasts, monomineralic hornblende layers, and the most segregated plagioclase-quartz leucosome. Metapelites became leucosome-dominated, with only small, dissociated biotite schlieren remaining. Several ca. 10 cm-thick veins of K feldspar-plagioclase-quartz, bearing millimeter-size garnets, were observed to intrude garnet amphibolite layers.

Figure 18 shows the intimate association of monomineralic garnet amphibolite with a diatexitic metapelite. The degree of anatexis is extensive in both units; however, the metapelitic is leucosome-dominated. Photographs B and C, as well as the two preceding figures, document the textural extremes of anatexis in the JRL.

STRUCTURE

The Jerome Rock Lakes area (JRL) has undergone extensive penetrative deformation that manifests as planar and linear features observable in all lithologies at a variety of scales. Foliation generally dips steeply to the southeast and is observed as compositional layering and schistosity. Lineations are subparallel to dip direction. Folds are observed at scales ranging from millimeter to outcrop. Most folds can be characterized as tight to isoclinal reclined. This section is intended to provide an overview of the main structural features of the JRL area and a model for its deformational history.

Foliation

Planar fabric elements within JRL lithologies are comprised of mineral foliations and compositional layering. Mineral foliations are produced by preferred orientation of biotite and muscovite in metasedimentary layers. Compositional layering produced by relative abundance of minerals, porphyroblast size, or a combination of the two is observed throughout the JRL area in all three lithologies. Original sedimentary structures within metasedimentary layers have not been observed and are most likely obliterated by subsequent high-temperature, high-pressure metamorphism, anatexis, and ductile deformation.

In garnet amphibolite and quartzofeldspathic gneiss lithologies, a hybrid foliation is produced by idiomorphic hornblende grains growing in the plane of compositional layering but poorly aligned within the plane. This texture is observed frequently as

melanocratic hornblende-rich layers 5 mm to several centimeters thick. Within the quartzofeldspathic gneiss, this hybrid foliation alternates with leucocratic quartz-plagioclase layers to produce characteristic gneissic banding.

Compositional layering produced by variation in porphyroblast size is well-developed in the garnet amphibolite. Individual garnet porphyroblasts range in size from 1 mm to 2 cm and are surrounded by leucocratic quartz-plagioclase augen. Other manifestations of layering are produced by relative abundance of garnet porphyroblasts, quartz-plagioclase augen, and idiomorphic hornblende. Thickness of individual layers varies from 5 mm to several centimeters.

Foliation within the metasedimentary units is produced by a combination of schistosity and compositional layering. Muscovite and biotite strongly define foliation in the garnet-sillimanite schist and K-feldspar diatexites, which is parallel to and often indistinguishable from compositional layering produced by intercalation with garnet-bearing amphibolite and from compositional layering produced by porphyroblast size and abundance. The kyanite metaquartzite displays a thin spaced muscovite foliation.

Lenses of transitional granulite in the quartzofeldspathic gneiss are unfoliated but have a well-defined mineral lineation, discussed later. Occurrences of 'ordinary' amphibolite within the garnet amphibolite are similarly unfoliated but lineated.

Figure 19 contains photographs of representative foliations and a Schmidt net containing measured planar fabric elements from the three main lithologies of the JRL. Poles to all foliation measurements within the metasedimentary units (purple), garnet amphibolite (orange), and quartzofeldspathic gneiss (green) are clustered tightly, as

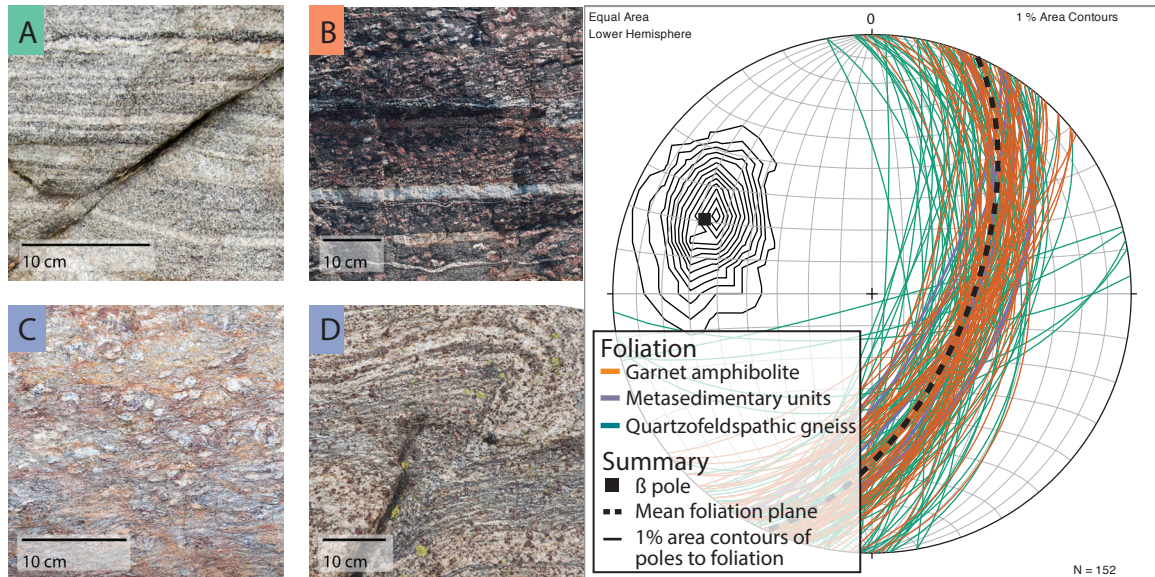


Figure 19: Representative foliations from JRL lithologies. Photograph A - typical gneissic banding in quartzofeldspathic gneiss. Photograph B - spectrum of compositional layering in garnet amphibolites, including porphyroblast size and abundance. Photograph C - mineral foliation in garnet-sillimanite schist. Photograph D - compositional layering in a K-feldspar-garnet leucogneiss. The Schmidt net contains all measured foliations in the JRL area, 1% area contours of poles to foliations, beta pole trending 294 and plunging 30° west, and trace of the mean foliation plane, striking 024 and dipping 60° east.

shown by 1% area contours, about a beta pole with a trend of 294 and plunge of 30°, which corresponds to an average foliation plane with a strike of 024, dipping 60° to the east.

Lineations

Most of the measured lineations from the JRL are stretching lineations. Strongly elongate quartz-plagioclase augen, surrounding garnet porphyroblasts, are exposed on foliation planes in the garnet amphibolite. The size of the augen varies from 1 to 6 cm in exposed length, surrounding garnet porphyroblasts up to 2 cm in diameter.

Mineral lineations are observed in compositionally-layered quartzofeldspathic

gneiss as preferred orientations of hornblende grains and plagioclase aggregations (Figure 20). Stretching lineations in the garnet amphibolite are clustered subparallel to the dip of the mean foliation plane, as shown in the stereonet of Figure 20.

Unfoliated lenses of transitional granulite in the quartzofeldspathic gneisses show moderately to well developed mineral lineations. This fabric is penetrative within the lenses and is best developed at margins with the enclosing gneiss, where grain-size reduction has also been observed. Internal development of a lineated fabric suggests that the lenses underwent ductile, locally constricted deformation after formation and that relative movement along their margins occurred. However, it is important to note that not all lenses of transitional granulite have developed a penetrative lineated fabric.

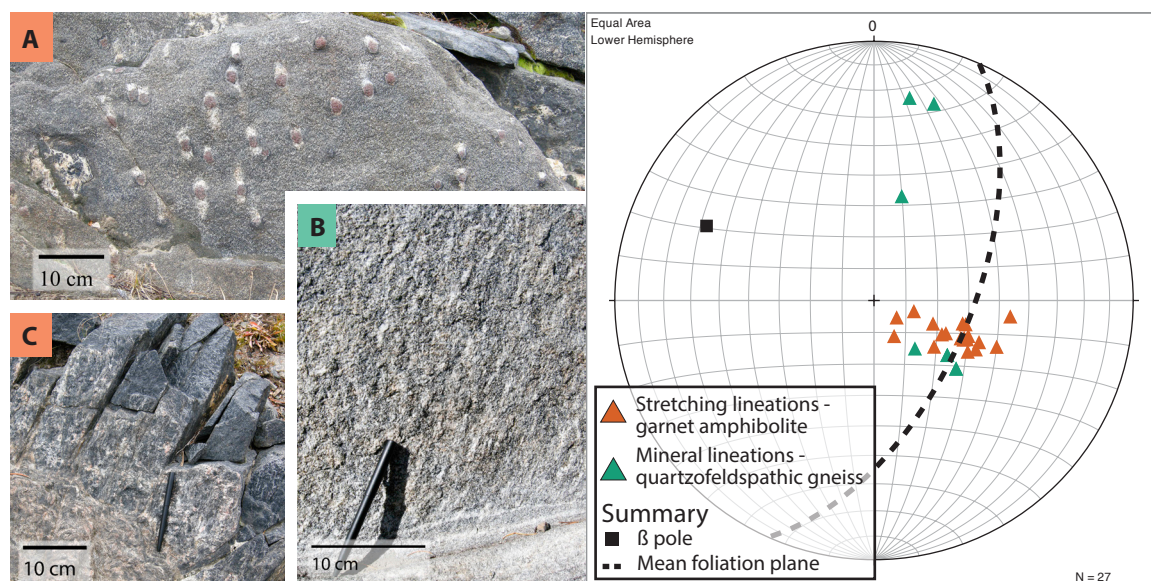


Figure 20: Stretching and mineral lineations in the JRL area. Photograph A - typical elongation of quartz-plagioclase augen in garnet amphibolite. Photograph B - preferred orientation of hornblende grains in quartzofeldspathic gneiss. Photograph C - lineated plagioclase-hornblende in garnet amphibolite. Note grain-size reduction at margin. The Schmidt net contains trend-and-plunge data for measured lineations in the garnet amphibolite and quartzofeldspathic gneiss, as well as the beta pole trending 294 and plunging 30° west, and trace of mean foliation plane striking 024 and dipping 60° east.

Folds

Folds are observed at outcrop to sub-centimeter scales. Generally tight to isoclinal and inclined to reclined, folds involve the three main lithologies but are concentrated in the metasedimentary layers and quartzofeldspathic gneiss. Extensive limb thinning and hinge zone thickening in these folds is frequently observed, corresponding to the class II of Ramsay and Huber (1987). Meter-scale folds occur throughout the JRL area, but centimeter-scale and smaller isoclinal folds tend not to occur in the garnet amphibolite layers.

Outcrop- to decimeter-scale folds dominantly involve the metasedimentary layers and garnet-bearing amphibolite. Folds of a similar scale have been observed in the quartzofeldspathic gneiss north of the JRL area, near the Big Brother shear zone, and deforms alternating melanocratic and leucocratic layers. Adjacent to the garnet amphibolite and metasedimentary units, the quartzofeldspathic gneiss has complex centimeter-decimeter scale fold patterns, discussed subsequently.

Folds in Garnet Amphibolites

Folds in the garnet amphibolite manifest at a variety of scales and styles. Meter- to decimeter-scale reclined isoclinal folds are frequently observed at most outcrops and involve a range of compositions and textures.

Figure 21 details a reclined, approximately cylindrical outcrop-scale similar fold and isoclinal decimeter-scale folds. The reclined isoclinal fold in photograph A is harmonic at the outcrop scale and is typical in garnet amphibolite outcrops in the JRL

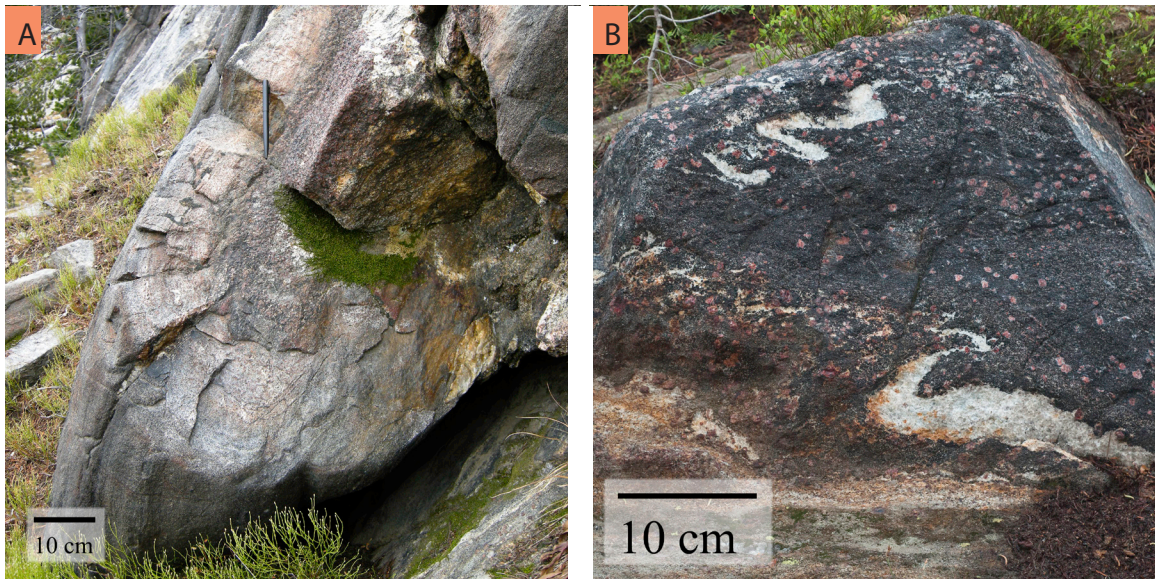


Figure 21: Representative folds in garnet amphibolite units. Photograph A - meter-scale reclined isoclinal fold near Upper Falls Creek Lake, involving multiple compositional layers. The outer arc of this fold is dominantly composed of a homogenous garnet-plagioclase-hornblende amphibolite with individual grain sizes less than 5 mm. The interior of the fold contains leucocratic plagioclase-quartz and melanocratic garnet-hornblende layers. Photograph B - reclined tight fold in contact with garnet-sillimanite schist, seen at the bottom of the outcrop. Parasitic S-Z folds of leucocratic vein indicates ductility contrast with amphibolitic host unit and progressive deformation of originally symmetric M-folds.

area. Smaller-scale folds, such as those documented in Photograph B, are polyharmonic at sub-meter scales where observed. Both large- and small-scale folds deform foliation, as seen in Figure 21; however, clear development of axial planar foliation has not been observed.

Outcrop-scale open folds have been infrequently observed. Like the reclined isoclinal folds, compositional layering is folded and axial planar foliation is absent. However, only one limb is typically exposed and dips correspondingly with mean foliation.

An exception to the above fold styles is the occurrence of unfolded, moderately

foliated, highly segregated garnet amphibolite at the headwall above the lakes. Large garnet porphyroblasts, 1-3 cm in diameter, are surrounded by strongly elongate quartz-plagioclase augen in a monomineralic matrix of idiomorphic hornblende. Meter- or smaller scale folds have not been observed in this occurrence. The exceptional compositional segregation, porphyroblast size, and augen development make this occurrence a textural endmember.

Disharmonic Folds

A rheological basis for the general difference in fold styles between garnet amphibolite and metasedimentary lithologies is proposed. Figure 22 illustrates an outcrop-scale cusped-lobate isoclinal recumbent fold involving an intercalated section of garnet amphibolite and biotite-sillimanite schist. Foliation is well-developed in



Figure 22: Contact between garnet amphibolite layer and garnet-sillimanite schist. Exposures that clearly demonstrate laterally-extensive concordance between these two lithologies are rarely observed. Schistosity deforms around the folded amphibolite and the original character of the contact is obscured.

both units: compositional layering of garnet porphyroblast size in the amphibolite and schistosity in the metasedimentary layer. The stiffness of the amphibolitic layer with respect to the markedly more ductile behavior of the schist manifests as sharp terminations of the schist against more-broadly arcing fold hinges of the amphibolite.

The original nature of the contacts between the garnet amphibolite and schist has been strongly affected by subsequent high-temperature deformation. Evidence for tectonization and transposition of original contacts includes: grain-size reduction, attenuation of foliation in the schist, and thin, centimeter-scale chemical reaction zones of biotite.

Folds in Metasedimentary Units

Folds within the garnet diatexite are observed at a variety of scales. The sole exposure of kyanite metaquartzite is well-foliated but unfolded. Garnet-sillimanite schist units rarely preserve folds, even where intercalated with garnet amphibolite. Thus, folds are typically seen only in outcrops of diatexites. Figure 23 documents typical fold styles. In both examples, compositional layering is deformed in similar folds. Photograph A shows a series of exposed decimeter-scale open fold hinges in garnet diatexite with moderately developed foliation. Intercalated and more rigid garnet amphibolite layers at this location share the same fold geometry and amplitude.

While the series of harmonic asymmetric folds in photograph B of Figure 23, appear initially similar to those in photograph A, the former occur throughout a large outcrop of diatexitic metapelite that is not intercalated with garnet amphibolite.

Exposed folds in metasedimentary units appear to be generally harmonic.

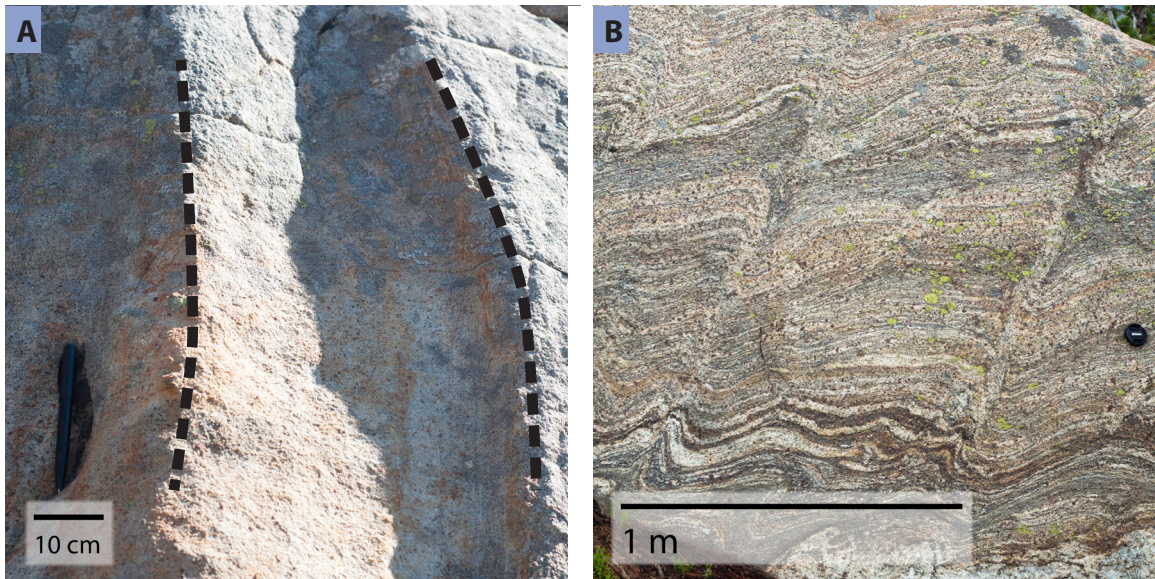


Figure 23: Representative folds in metasedimentary lithologies. Photograph A - exposed fold hinges (indicated by dashed lines) in garnet diatexite in the central JRL area. This location is characterized by interleaving with garnet amphibolite layers, which have similar fold geometries and amplitudes. Photograph B - series of asymmetric folds in garnet diatexite near Upper Falls Creek Lake.

However, folds are not generally observed in outcrops of biotite-sillimanite schist, dominantly found in the central JRL area. Meter-scale disharmonic folds in intercalated garnet-sillimanite schist and garnet amphibolite, discussed previously, suggest that the garnet-sillimanite schist deformed much more ductily and failed to preserve the same structures.

Folds in Quartzofeldspathic Gneisses

Folds in the quartzofeldspathic gneisses are characterized by decimeter- to meter-scale plunging, upright to reclined folds. Exposures of hinge zones are limited, as most folds are revealed in partial cross-sections. Most folds are at least locally harmonic, involving both melanocratic and leucocratic layers. Figure 24 shows two representative

examples of folded compositional layering within the gneiss.

Ptygmatic pegmatite veins are infrequently observed and indicate a high viscosity contrast between the gneiss and pegmatite vein, as well as a low volumetric contribution to the overall gneissic composition. Deflection of the host rock's compositional layers around the deformed vein, such as in photograph A of Figure 24, indicates that the ductility contrast between the host and vein had developed prior to the last tectonic event responsible for the deformation of the vein. Additionally, the compositional layering was necessarily developed prior to the injection and cooling of the vein, which produced the ductility contrast.

Outcrop-scale folds, such as those documented in garnet amphibolites, has not been observed in the quartzofeldspathic gneisses. The density of smaller-scale folds is

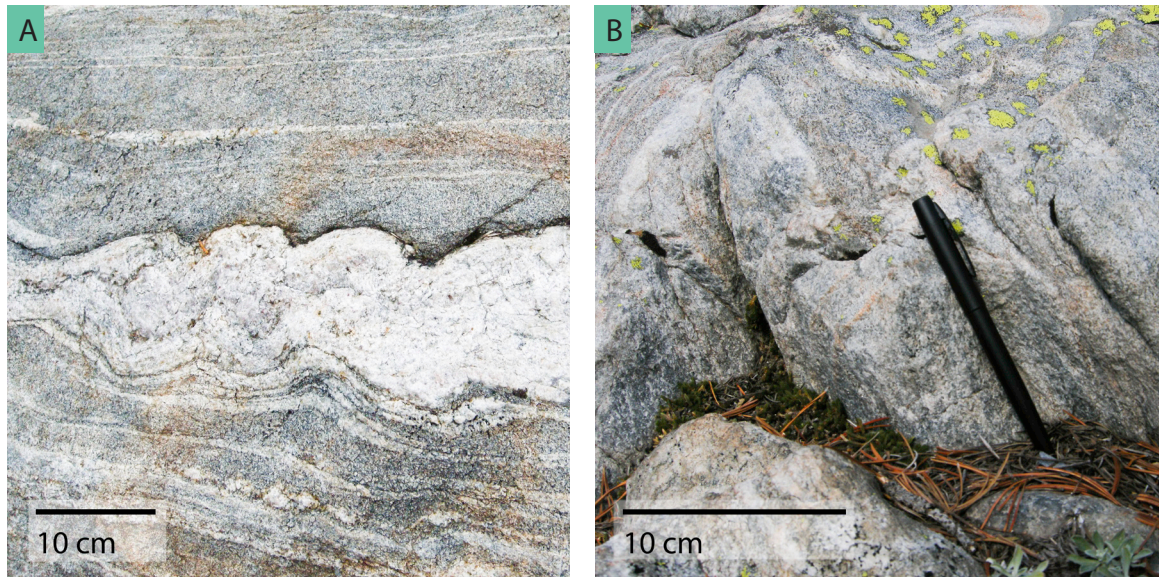


Figure 24: Representative folds in quartzofeldspathic gneisses of the JRL area. Photograph A - ptygmatic vein of coarse-grained K feldspar-plagioclase-quartz, demonstrating ductility contrast with surrounding gneiss. Photograph B - tight, nearly vertical polyharmonic folds in compositional layering. Exposures of measurable fold hinges in the quartzofeldspathic gneisses are rare.

similar to that observed in the metasedimentary schists and suggests a similar ductility during deformation.

Synthesis of Fold Styles Throughout Lithologies

Figure 25 details additional examples of folds within the main lithologies and a Schmidt net of measured hinge lines. Photograph A documents the substantially more rigid behavior of garnet amphibolite in a large, approximately parallel fold (Class IB of Ramsay and Huber, 1987) that plunges moderately to the south.

A cylindrical best-fit plane to fold hinges throughout the lithologies shows reasonably strong correspondence. Garnet amphibolite fold hinges group in two clusters, while fold hinges in the quartzofeldspathic gneisses are broadly distributed along the

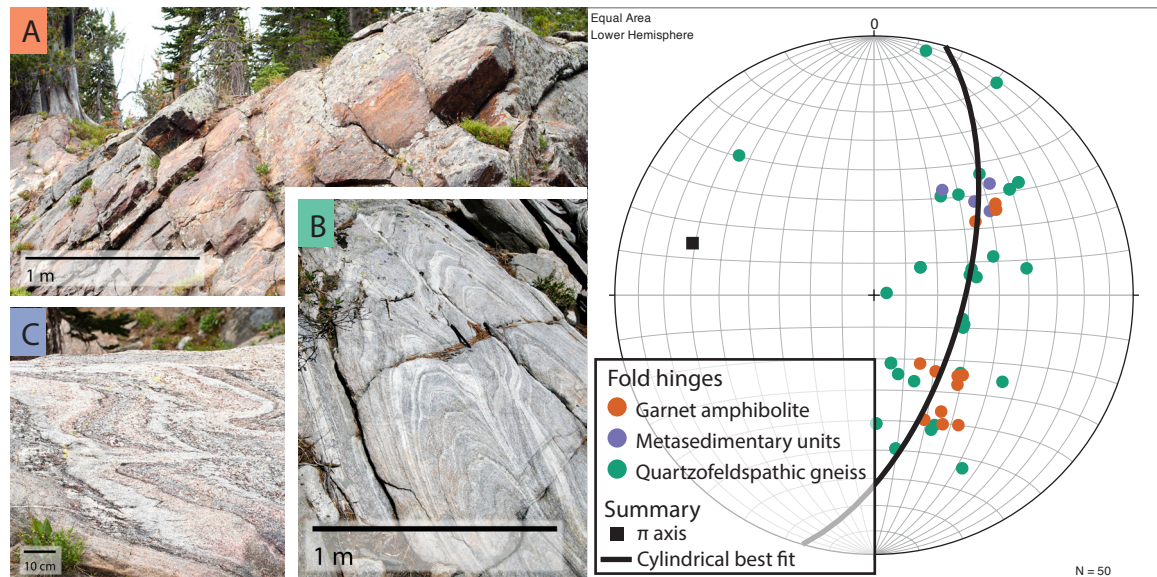


Figure 25: Additional examples of folds in the JRL area. Photograph A - large open fold involving entire outcrop of garnet amphibolite. The fold hinge line plunges moderately to the south. Photograph B - plunging tight folds in quartzofeldspathic gneisses. Photograph C - tight folds in garnet diatexite dragged into incipient cm-scale shear zone near Upper Falls Creek Lake. The Schmidt net contains all measurements of fold hinges in the JRL area, a calculated cylindrical best-fit plane striking 016 and dipping 62° east, and the pole to this plane (the π axis, trending 286 and plunging 28° west).

plane. The pole to this plane, the π axis, trends 286 and plunges 28° west. A single outlier in quartzofeldspathic gneiss may result from proximity to the Big Brother shear zone. Generally, the hinge lines dip moderately regardless of trend.

While field observations indicate folds are distributed throughout lithologies, the data gathered underrepresents the metasedimentary units. This bias reflects the poor exposure of hinge zones in garnet-sillimanite schist layers. A possible explanation is the relative lack of resistance to chemical weathering in the montane environment, a consequence of the mica-rich composition.

Synthesis of Structural Elements

All types of structural data from the JRL area are summarized in Figure 26. The average foliation plane, calculated from the mean of the poles to foliation, is plotted in lieu of individual foliation measurements. Fold hinge and lineation measurements together trace out a great circle. A cylindrical best fit to the fold axes has been calculated and plotted as well.

Comparison of mean foliation and fold best-fit planes reveals a striking similarity in orientation. Mean foliation strikes 026 and dips 60° east, while a calculated cylindrical best fit to fold axes strikes 016 and dips 62° east. Thus, the predominantly isoclinal folds, mineral lineations, and stretching lineations are approximately concordant with foliation throughout the JRL area.

The near-coplanarity of the cylindrical best fit to isoclinal fold axes and the mean foliation suggests that these folds (F1) were produced early during the main

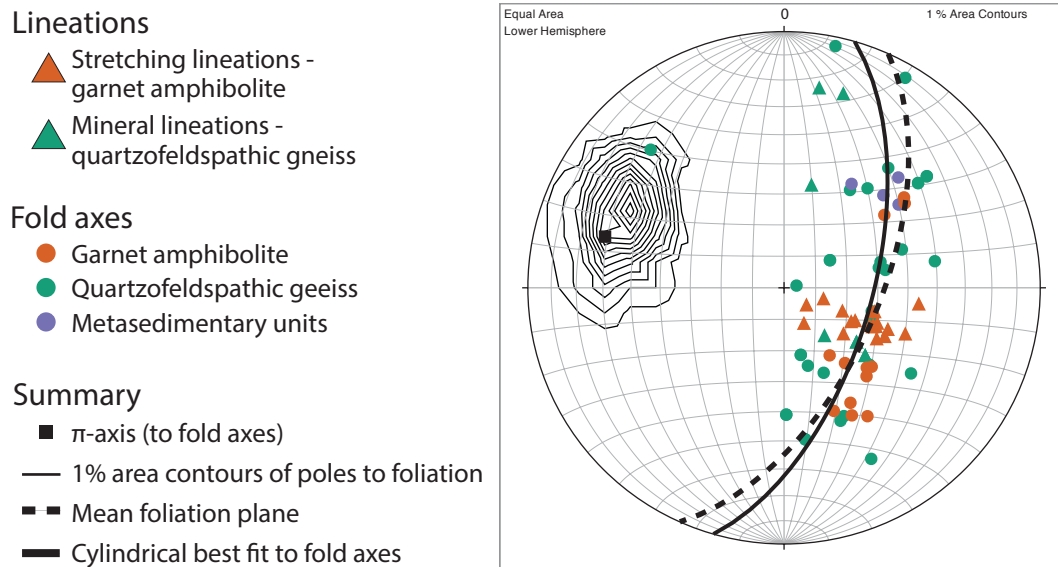


Figure 26: Summary Schmidt net of all structural data from the JRL area. Linear features are grouped by lithology and a best-fit plane calculated, striking 016 and dipping 62° east. Foliation measurements have been condensed into 1% area contours and a mean foliation plane striking 026 and dipping 60° east. The pole to the cylindrical best fit plane, striking 016 and dipping 62° east, is the π axis, trending 286 and plunging 28° east. The π axis plots near the center of the contours of poles to foliation.

deformation event (D1) and rotated into the developing regional foliation (S1) by progressive deformation. It is likely also that some of the F1 folds were produced during peak and final D1 deformation, resulting in the isoclinal folds observed in the diatexites. Lineations measured within the JRL area plot near the midpoint of the mean foliation plane, indicating that they were also produced during D1. The rare outcrop-scale open cross folds (F2) suggest a much later period of deformation (D2) with less ductile character.

THERMOBAROMETRY

Sample Descriptions

Unpublished data from eight previously-analyzed samples, collected from the Jerome Rock Lakes area (JRL), were utilized in classical and computational thermobarometry. Microprobe analyses were performed by D.W. Mogk. Complete oxide and compositional datasets are provided in appendix A and complete thermobarometric datasets are provided in appendix B. Color coding of lithologies in figures follows the scheme previously presented: purple indicates metapelite samples, orange indicates metabasite samples, and green indicates samples from quartzofeldspathic gneisses and associated lithologies. A complete discussion of lithologies and their occurrences is

Lithology	Sample	Phases analyzed
MSC	SP-12*	Feldspar Garnet Biotite <i>Sillimanite schist from JRL (Salt, 1987)</i>
	SP-143	Amphibole <i>Garnet leucogneiss with more mafic appearance</i>
	SP-148	Feldspar <i>Metapelite from south of main trail junction</i>
	SP-149	Feldspar Garnet Amphibole Spinel <i>Metapelite from south of main trail junction</i>
	SP-154	Feldspar Garnet Spinel <i>Garnet leucogneiss near Upper Falls Lake (SE JRL)</i>
GAM	SP-153	Feldspar Garnet Amphibole Biotite Spinel <i>Garnet amphibolite from near Margo Lake</i>
QFG	DL-33B*	Feldspar Garnet <i>'Metagabbro' near Mirror Lake shear zone (Salt, 1987)</i>
	SP-141	Feldspar <i>Quartzofeldspathic gneiss from central JRL</i>

Table 2: Inventory of microprobe samples. Italics indicates sample description taken from field notes. Samples SP-143, SP-148, SP-149, and SP-154 may be candidates for reassignment to other lithologies on the basis of composition. Asterisk indicates sample previously analyzed and reported by Salt (1987).

provided in the lithology chapter.

Feldspar (plagioclase and K-feldspar), garnet, amphibole, biotite, and spinel phases were analyzed in samples collected from the major lithologies present in the JRL (Table 2). Metasedimentary units are represented by sample SP-12, a garnet-sillimanite schist with quartz-plagioclase-K-feldspar microlithons, sillimanite mats, and garnet porphyroblasts. Relict kyanite is deformed.

Samples SP-143, SP-148, SP-149, and SP-154 were annotated as leucogneisses and metapelites; however, they are more accurately described as metatextitic amphibolites, based on the abundance of quartz-plagioclase leucosome. SP-143 has a matrix of elongate quartz-plagioclase pods with hybrid foliation produced by embayed hornblende and garnet porphyroblasts with inclusion-rich cores. SP-148 is nearly monomineralic, with minor plagioclase-quartz myrmekite and garnet in an interlocking K-feldspar matrix. SP-149 has abundant garnet porphyroblasts in a foliated hornblende-plagioclase-quartz matrix with relict kyanite. SP-154 contains inclusion-rich porphyroblastic garnets distributed in a interlocking quartz-plagioclase matrix with minor biotite.

Metabasites are represented by garnet amphibolite SP-153 from the northeastern JRL. Anhedral garnet porphyroblasts form the core of quartz-plagioclase augen, about which thin biotite-amphibole foliations anastomose.

Quartzofeldspathic gneisses are represented by sample SP-141, a weakly foliated quartz-plagioclase trondjhemitic gneiss (Weyand, 1989) with minor hornblende, biotite, and K-feldspar. DL-33B is a sample of transitional granulite “corona metagabbro” collected by Salt (1987), found as enclaves in the quartzofeldspathic gneisses.

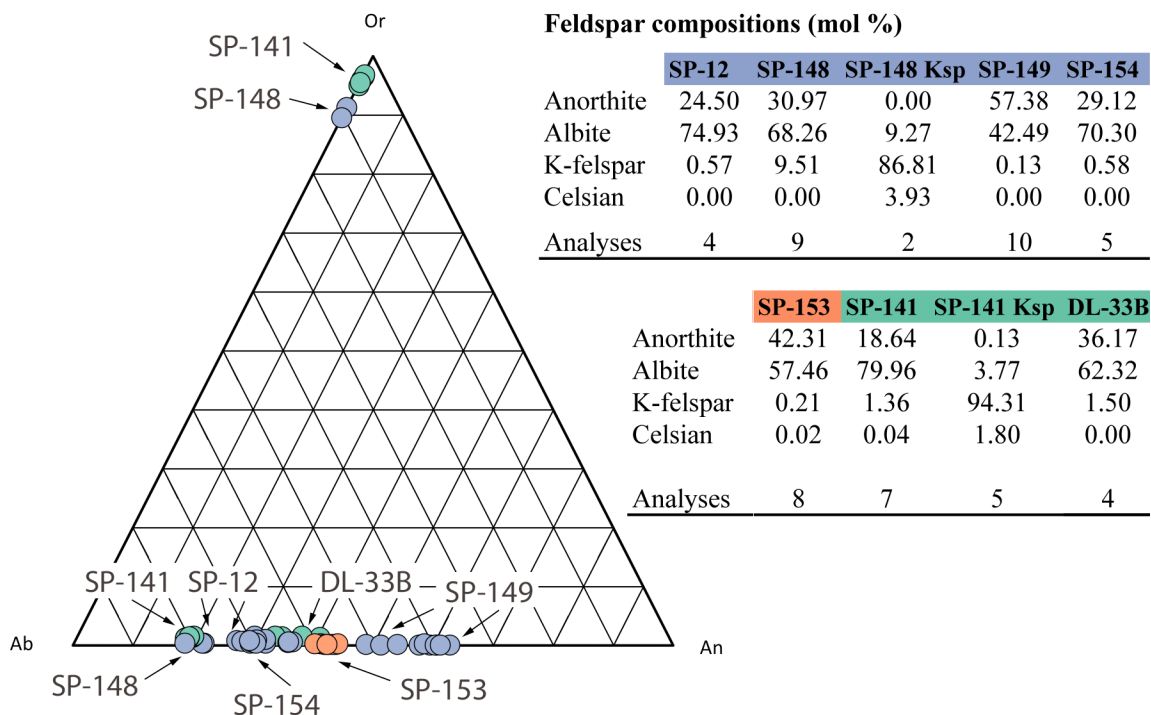


Figure 27: Ternary plot and table of feldspar compositions, recalculated and normalized to the anorthite-albite-K-feldspar system. Samples are grouped by lithology. Two K-feldspar occurrences are listed separately from plagioclase analyses as SP-148 Ksp and SP-141 Ksp. Complete compositional data is provided in appendix A.

Mineral Chemistry

Feldspars

Feldspar formulae were calculated on the basis of 8 oxygen atoms and the resulting compositions renormalized in the anorthite-albite-K-feldspar ternary system. Calculated formulae indicate oligoclasic to labradoritic compositions: An_{20} - An_{60} (Figure 27). The range of compositions does not appear to vary systematically with lithology but does reflect some intrasample variation.

In renormalizing compositions, the contribution of a celsian component was disregarded. The maximum abundance of a celsian component was limited to below 5

mol % for all analyses, and exceeded 2 mol % in seven of 51 total feldspar spot analyses. The highest celsian contents were measured in K-feldspar analyses from metatextitic amphibolite SP-148 (3.1-4.8 mol %) and quartzofeldspathic gneiss SP-141 (1.7-2.0 mol %).

The greatest intrasample variation is seen in SP-149, where composition varies nonsystematically up to 12 mol% between plagioclase adjacent to garnet and matrix plagioclase from the same subregion. This variation may reflect the development of local equilibria. For all other samples, plagioclase composition nonsystematically varies less than 7 mol%.

Feldspars from samples SP-148 and SP-141 were found to have two compositional modes: oligoclase to andesine plagioclase (An_{20} - An_{40}) and nearly pure K-feldspar (Or_{80} - Or_{90}). The oligoclasic-andesinic compositions of plagioclase in these samples represents the most sodic plagioclase compositions measured. Garnet amphibolite sample SP-153 has an intermediate plagioclase composition of An_{40} - An_{44} . The most anorthitic composition (An_{57}) was measured in metatextitic amphibolite sample SP-149.

Garnet

Garnet formulae were calculated on the basis of 12 oxygen atoms. The resulting compositions were renormalized in the pyralspite (pyrope-almandine-spessartine)-grossular quaternary system. Table 3 contains representative pyralspite-grossular normalized compositions by sample. Andradite, schorlomite, and uvarovite end-members were excluded on the basis of low abundance, as the total contribution was less than 2

Renormalized garnet compositions (mol %)					
	SP-12	SP-149	SP-154	SP-153	DL-33B
Almandine	71.45	59.90	69.21	62.53	56.29
Pyrope	15.30	24.07	4.25	8.45	20.19
Spessartine	9.95	1.26	2.00	3.30	1.42
Grossular	3.30	14.77	24.55	25.72	22.10
Analyses	8	15	15	9	6

Table 3: Renormalized average garnet compositions by sample. Andradite, schorlomite, and uvarovite endmembers were excluded, due to low abundances. Total contribution of all three endmembers was less than 0.5 mol% in samples other than SP-153. Up to 1.86 mol% andradite was found in garnet amphibolite SP-153. Low contributions of schorlomite and uvarovite was found in all samples. Complete compositional data is provided in appendix A.

mol % in any analysis.

Amphibolite samples SP-153, from Margo Lake, and SP-154, from Upper Falls Creek Lake, show a similar distinct composition. Both are dominantly almandine (61-71 mol%) with comparatively high grossular (23-28 mol%) and low pyrope (3-5 mol%) components. The pyrope content in these samples is the lowest of the analyzed garnets.

Garnet from garnet-sillimanite schist SP-12 has the highest almandine content analyzed (70-72 mol%) and low values for the other end-member components. Its composition is unique among the garnets analyzed, particularly for its highest spessartine and lowest grossular contents. No other garnets from metapelitic schists were analyzed.

Garnet compositions in transitional granulite sample DL-33B have the lowest almandine content (55-58 mol%) measured, equal amounts of pyrope and grossular (19-23 mol%), and trace spessartine.

Garnet from metatextitic amphibolite SP-149 has a composition similar to DL-33B, consisting of lower almandine (57-64 mol%), highest pyrope of all analyzed garnets

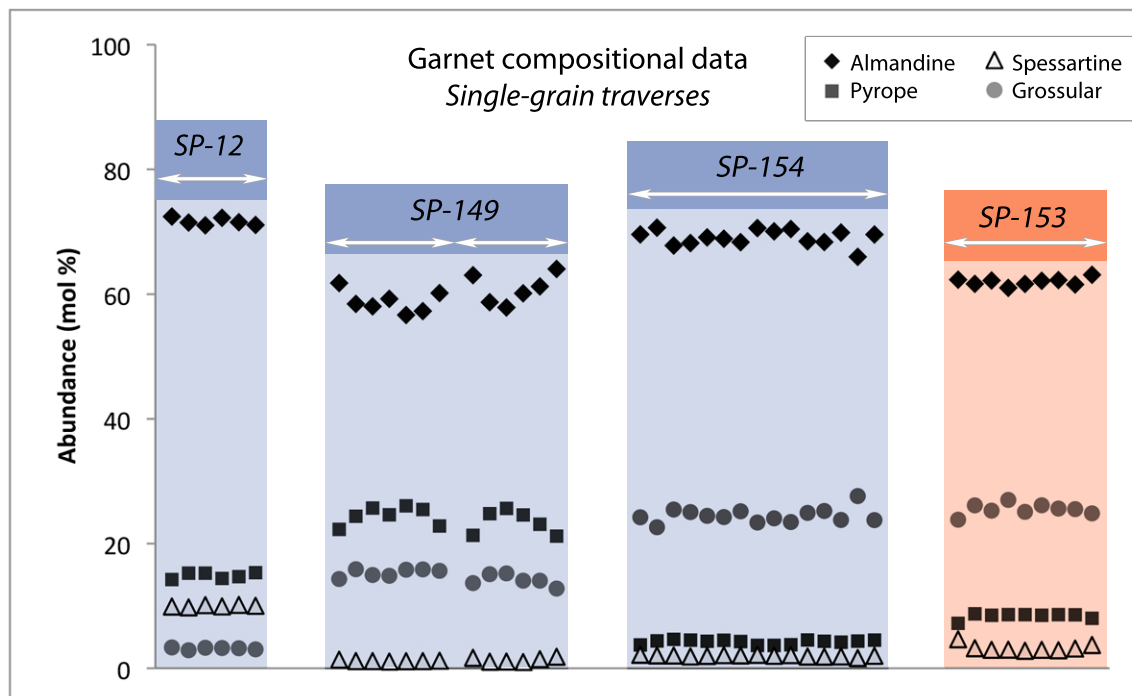


Figure 28: Single garnet grain transects normalized to pyrospite-grossular series. Order of analyses (left to right) reflects order of acquisition (rim-core-rim) and are grouped by sample. Two grains were transected from metatextitic amphibolite SP-149.

(22-26 mol%), low grossular (13-16 mol%) and trace spessartine.

Single grain transects were measured in garnet-sillimanite schist SP-12, metatextitic amphibolites SP-149 and SP-154, and garnet amphibolite SP-153. Figure 28 contains the results of these transects, grouped by sample. Compositional profiles for all transects are essentially flat, with the greatest variation in rim-core almandine content; typical variation does not exceed 3%. There is a minor anticorrelation between rim enrichment in almandine and 2-3% rim depletion in pyrope and grossular components.

The strongest zoning is documented in the two garnet transects of metatextitic amphibolite SP-149. The anticorrelated rim-core variation reached a maximum of 5 mol% in almandine and 4 mol% in pyrope contents.

Amphibole compositions (apfu)			
	SP-143	SP-149	SP-153
	Tschermakite	Tschermakite	Ferropargasite
Ca + Na (B-site)	2.00	2.00	2.00
Na + K (A-site)	0.41	0.35	0.52
Mg	2.27	2.56	1.40
Fe ²⁺	1.36	0.58	2.33
Fe ³⁺	0.58	1.01	0.62
Ti	0.12	0.10	0.15
Al ^{iv}	1.58	1.83	1.91
Al ^{vi}	0.67	0.74	0.48
Si	6.42	6.17	6.09
Analyses	n = 5	n = 6	n = 6

Table 4: Summary of amphibole compositional data. Note that formulae recalculation is performed on the basis of 23 oxygens and assigns all Ca to the B site. Nomenclature scheme is that of Hawthorne and Oberti (2007).

Amphibole

Compositional data for three samples, SP-143, SP-149, and SP-153 is shown in Table 4. Formulae were calculated on the basis of 23 oxygens; ferric iron contents were calculated from total iron content using charge balance; and all calcium was assigned to the B-site. Analyses were plotted in the appropriate compositional fields, shown in Figure 29, using the current IMA-recommended classification scheme of Hawthorne and Oberti (2007).

Samples SP-143 and SP-149 both fall in the tschermakite field. The tschermakite of SP-143, however, is on the boundary with magnesiohornblende, reflecting a more silicic and ferric composition than that of SP-149. Garnet amphibolite SP-153 plots in another set of fields, due to its higher alkali content than SP-143 and SP-149. It falls within the ferropargasite field but is near the boundary with mangesiohastingsite.

The tight clustering of analyses indicates little compositional variation within each sample. SP-149 has a single outlying analysis that is Si-enriched by 0.15 apfu; however,

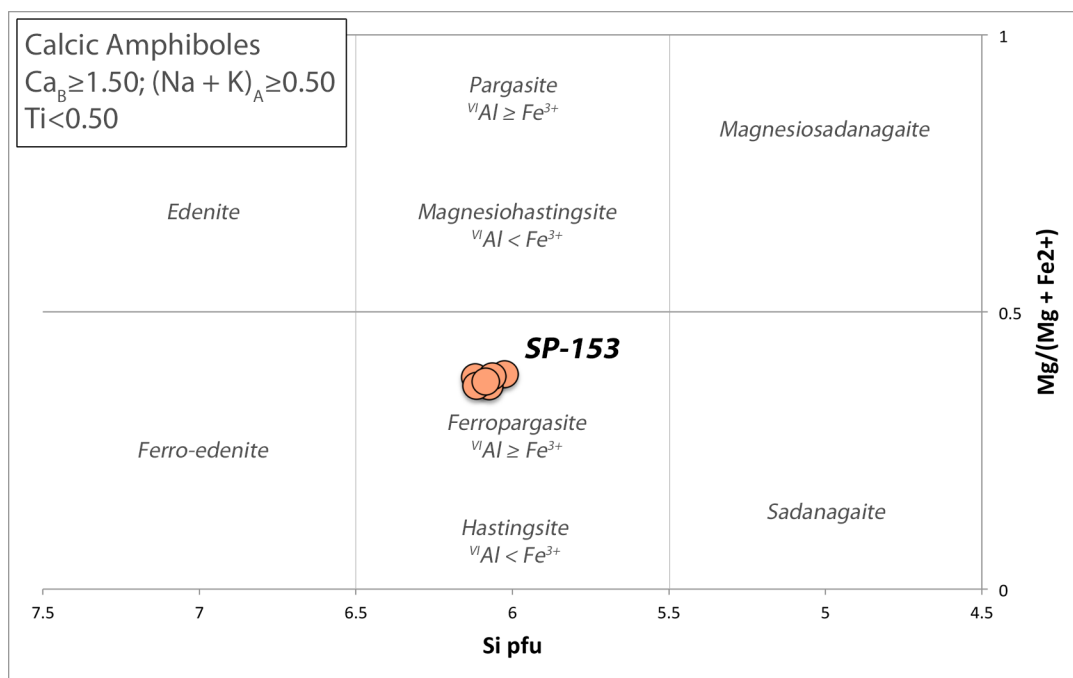
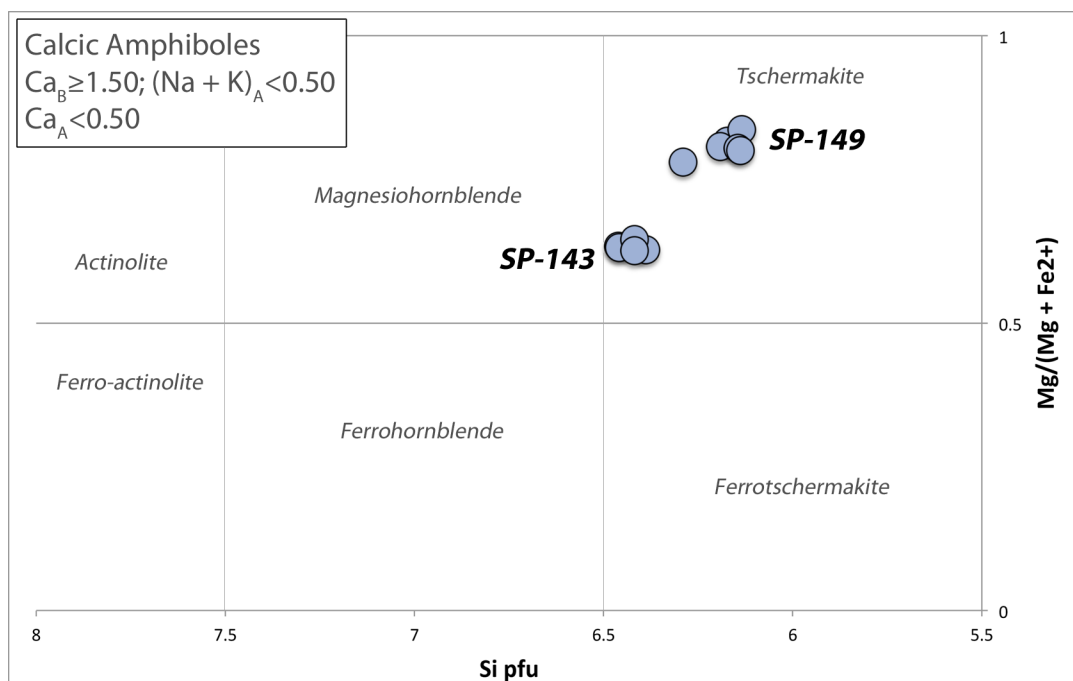


Figure 29: Normalized amphibole analyses for metatextitic amphibolites SP-143 and SP-149 and garnet amphibolite SP-153. Classification scheme diagram after Hawthorne and Oberti (2007). Complete compositional data is provided in appendix A.

this outlier was discarded. Utilizing the similarity in analyses, a median representative composition was selected for each sample and used in subsequent thermobarometric calculations.

Biotite

Formula recalculation for garnet-sillimanite schist SP-12 was performed on the basis of 22 oxygen atoms per formula unit and on the basis of 14 cations for garnet amphibolite SP-153. Henry et al. (2005) advocated normalizing to 14 cations for samples from lithologies that had undergone higher-grade metamorphism, based on previous studies (e.g. Bohlen et al., 1980) that found few to no octahedral vacancies in biotite from granulite facies rocks. Biotite compositions from garnet amphibolite SP-153 and metapelite SP-12 differ substantially in total aluminum and titanium versus magnesium number (Figure 30). Both samples fall closer to the siderophyllite-eastonite series than the annite-phlogopite series. The relatively iron-enriched biotite composition of SP-153



Figure 30: Recalculated biotite compositions. Panel A - plot of total aluminum content (apfu) versus magnesium number. Panel B - plot of total titanium content (apfu) versus magnesium number. Plot scheme after Henry et al. (2005).

Ilmenite compositions (apfu)									
Sample	Ti	Al	Fe²⁺	Fe³⁺	Mn	Mg	Nomenclature		Analyses
SP-154	0.95	0.00	1.04	0.21	0.01	0.00	Ilmenite	FeTiO ₃	2
SP-149	1.01	0.00	0.96	-0.02	0.01	0.03	Ilmenite	FeTiO ₃	3
SP-153	0.99	0.00	0.99	0.05	0.02	0.00	Ilmenite	FeTiO ₃	3

Table 5: Recalculated ilmenite compositions from metapelite sample SP-154, metatexitic amphibolite SP-149, and garnet amphibolite SP-153. The negative value for ferric iron abundance in SP-149 is attributed as an artifact of formulae recalculation.

would be expected for the more mafic bulk composition of garnet amphibolites (3.2 apfu average for SP-153 vs. 2.5 apfu maximum for SP-12).

SP-153 has a higher titanium content of approximately 0.49 atoms per formula unit. Individual analyses for SP-12 are significantly more scattered and correlate with differences in textural occurrence.

Ilmenite

The major element composition of opaque oxides was measured in SP-149, SP-154, and SP-153. Point analyses were selected to represent textural analyses (see Appendix B), including association with garnet, hornblende, and plagioclase.

Individual analyses within a single sample indicated nearly homogenous compositions. The composition of opaque oxides from all samples is nearly pure ilmenite, as shown in Table 5. There is a minor contribution of a magnetite component; however, this contribution is based on calculation of ferrous and ferric iron abundance from total iron content using charge balance. The extremely low abundance of manganese limits the suite of applicable thermobarometers utilizing ilmenite.

Ti-in-Biotite Thermometry Criteria and Parameters (Henry et al., 2005)		
Calibration Range	Sample Values	
<u>Biotite (per 22 oxygens)</u>	SP-12	SP-153
Mg #: 0.275-1.000	0.476	0.344
Ti: 0.04 - 0.60 atoms per formula unit	0.31 apfu	0.50 apfu
<u>Additional mineral phases</u>		
Ti-bearing oxides	Rutile	Ulvöspinel
Graphite	Likely	Possible
<u>P-T conditions</u>		
Temperature: 480 - 800 °C		
Pressure: 4 - 6 kbar		
<u>Precision</u>		
T < 700°C: ± 24°C		
T > 700°C: ± 12°C		

Table 6: Established compositional criteria and physical constraints for Ti-in-biotite thermometry (Henry et al., 2005). Values measured from SP-12 and SP-153 are listed for comparison.

Thermometry

Ti-in-Biotite Geothermometer

Henry et al. (2005) developed a thermometer based on the partitioning of Ti into octahedrally-coordinated sites in biotite as a function of increasing temperature. An empirical surface relating titanium content, magnesium number, and temperature was derived from analyses of titanium-bearing biotite in metapelitic schists from Massachusetts and Maine. Table 6 summarizes the compositional criteria and calibration parameters for Ti-in-biotite thermometry. The presence of graphite cannot be established for either sample. Therefore, the resulting Ti-in-biotite (TIB) temperatures are best interpreted as minimum estimates (Henry et al., 2005).

Calculated temperatures from garnet-sillimanite schist sample SP-12 were separated into three groups on the basis of distinct petrologic occurrences (Table

7). Two matrix biotite analyses yielded the highest mean temperatures of 702 °C. A biotite inclusion within garnet recorded an intermediate temperature of 658 °C. Two biotite analyses in contact with garnet yielded the lowest mean temperature of 617 °C. The lower values of biotites included in and adjacent to garnets have a precision of ± 24 °C, suggesting that the difference in temperature estimates is not significant. The temperatures yielded by matrix biotite fall on the threshold between precision values but remain significantly higher than those from biotite in association with garnet, regardless of selected precision. The range in calculated values fall within published error values as well. Thus, the matrix temperature is retained as a minimum estimate of peak conditions, while the temperatures calculated from biotite adjacent to garnet is interpreted to reflect reequilibration during cooling from peak conditions.

Matrix biotite analyses from garnet amphibolite sample SP-153 yielded temperatures from 711-729 °C. The increased Ti content of biotite from this metabasite sample is reflected in the higher calculated temperatures. At these values, the precision

Results of Ti-in-biotite thermometry (calibration: Henry et al., 2005)			
SP-12: Siderophyllite ($^{Ti} = 0.31$ apfu)			
	Matrix	Inclusion in garnet	Adjacent to garnet
Temperature	702 $\pm$ 12 °C	658 $\pm$ 24 °C	617 $\pm$ 24 °C
Range	696 - 709 °C	-	616 - 619 °C
Analyses	n = 2	n = 1	n = 2
SP-153: Siderophyllite ($^{Ti} = 0.49$ apfu)			
	Matrix		
Temperature	720 $\pm$ 12 °C		
Range	711 - 729 °C		
Analyses	n = 8		

Table 7: Calculated temperatures from the titanium-in-biotite thermometer of Henry et al. (2005). Various textural contexts are noted. Precision is taken from appropriate published values. Standard deviation for temperatures from sample SP-153 is 5.59 °C. Complete thermometric results are provided in appendix B.

of the thermometer increases to ± 12 °C. Although the TIB thermometer was calibrated using data from metapelitic biotite, application by Henry et al. (2005) to previously-published high-Ti biotite analyses from a mafic granulite found strong concordance with regional temperature estimates. The range of calculated temperature estimates falls within the published error values.

Two-Feldspar Geothermometer

The Putirka (2008) formulation of the two-feldspar thermometer is based on the early method of Barth (1951), which evaluated the partitioning of albite into K-feldspar and plagioclase. Subsequent formulations of the two-feldspar thermometer became more complex, incorporating additional parameters and ternary feldspar compositions (i.e. Benisek et al., 2004). However, Putirka (2008)'s model is calibrated with experimental data from 41 previously published experimental datasets, taken from Auzanneau et al. (2006), Elkins and Grove (1990), Gerke and Kilinc (1992), Koester et al. (2002), Patiño Douce (2005), Patiño Douce and Beard (1995), and Patiño Douce and Harris (1998). A number of the datasets are derived from melting of natural materials similar to the lithologies examined in this study, e.g. biotite gneisses and tonalites. The resulting thermometer is precise to 30 °C.

This thermometer can be applied only to quartzofeldspathic gneiss SP-141, with an average An₁₈ plagioclase and Or₉₄ K-feldspar. The relatively uniform grain size, interlocking grain boundaries between feldspars and quartz, and absence of disequilibrium textures (i.e. myrmekite) suggest that the matrix is at equilibrium. In the absence of an independent barometer, temperatures were calculated for 5 kbar pressure steps. The peak

Results of two-feldspar thermometry (calibration: Putirka, 2005)					
SP-148 (Plag = An₃₁, K-feldspar = Or₈₇)					
	T (0 kbar)	T (5 kbar)	T (10 kbar)	T (15 kbar)	Analyses
	-	-	-	-	3
Range	-	-	-	-	
SP-141 (Plag = An₁₉, K-feldspar = Or₉₄)					
	T (0 kbar)	T (5 kbar)	T (10 kbar)	T (15 kbar)	Analyses
	571 ± 30 °C	587 ± 30 °C	604 ± 30 °C	623 ± 30 °C	4
Range	525 - 632 °C	538 - 652 °C	553 - 673 °C	568 - 696 °C	

Table 8: Summary of two-feldspar solvus thermometry results, using the calibration of Putirka (2008). Note that temperature estimates for SP-148 could not be obtained. Complete thermometric results are provided in appendix B.

temperature is estimated to fall in the range of 587-604 °C over 5-10 kbar. Textural notes accompanying the spot analyses indicated that only two K-feldspar-plagioclase pairs were adjacent to each other and thus suitable for thermometry. Each pair of analyses were located in separate subregions of the sample and yield significantly different temperatures, as reflected in the ca. 100 °C range. Such variation may result from subsolidus reequilibration, although even the minimum P-T conditions calculated fall significantly above the wet granite solidus.

Textural relations in SP-148 indicate that K-feldspar and plagioclase are in disequilibrium with each other, particularly the presence of incipient plagioclase-quartz myrmekite at grain boundaries. Average compositions are An₃₁ for plagioclase and Or₈₇ for K-feldspar. Consequently, the composition of K-feldspar and plagioclase reflect the disequilibrium, rendering this sample unsuitable and unusable for Putirka (2008)'s thermometer. Complete results of two-feldspar thermometry are provided in appendix B.

Garnet-Biotite Exchange Geothermometer

The garnet-biotite (GARB) thermometer, based on the exchange of Fe and Mg

between the two phases, was applied to metapelite SP-12 and garnet amphibolite SP-153. Nine different calibrations were tested: Bhattacharya et al. (1992), Dasgupta et al. (1991) formulations 1 and 2, Ferry and Spear (1978), Hodges and Spear (1982), Holdaway (2000), Holdaway and Lee (1977), Perchuk and Lavrent'eva (1983), and Thompson (1976).

The Holdaway (2000) thermometer is based on the experimental datasets of Ferry and Spear (1978), Perchuk and Lavrent'eva (1983), and Gessman et al. (1997). The composite thermometer incorporates non-ideal quaternary mixing models for garnet and the effect of octahedrally-coordinated Ti and Al substitution in biotite, shown to be strongly temperature-dependent by Kleemann and Reinhardt (1994). These mixing parameters are especially pertinent with respect to the composition of garnet in SP-12 ($X^{\text{Mn}} = 0.10$), garnet in SP-153 ($X^{\text{Ca}} = 0.25$), and biotite in SP-153 ($\text{Ti}^{\text{vi}} = 0.49$). Variation in temperature estimates between the tested calibrations is, at most, 100 °C for sample SP-12 and 150 °C for SP-153. The Holdaway (2000) calibration yielded temperatures that fell near the median of all calibrations. Anomalous estimates for SP-12 were produced by the calibration of Dasgupta (1991), which were consistently 200 °C lower than all other calibrations. Thermometric data is provided in appendix B.

Temperatures were calculated in two groups to utilize the textural relationships between analyzed garnet and biotite grains. Table 9 summarizes the results of garnet-biotite thermometry as applied to garnet-sillimanite schist SP-12 and garnet amphibolite SP-153. Matrix biotite measurements were combined with garnet core analyses to obtain peak temperatures. Reequilibrium temperatures were calculated from measurements of

Results of garnet-biotite thermometry (calibration: Holdaway, 2000)		
SP-12		
	Garnet inner rim - matrix biotite	Garnet outer rim - adjacent biotite
Temperature	633 ± 25 °C	672 ± 25 °C
Range	611 - 664 °C	663 - 682 °C
Analyses	9	3
SP-153		
	Garnet core - matrix biotite	Garnet outer rim - matrix biotite
Temperature	719 ± 25 °C	683 ± 25 °C
Range	702 - 743 °C	662 - 710 °C
Analyses	56	16
Standard deviation	12 °C	15 °C

Table 9: Garnet-biotite thermometry applied to garnet-sillimanite schist SP-12 and garnet amphibolite SP-153. Calibration and error estimates of Holdaway (2000) were applied. Complete thermobarometric results are provided in appendix B.

biotite and adjacent garnet rims.

SP-12 yielded a garnet inner core-matrix biotite temperature of 633 ± 25 °C, lower than the garnet outer rim-adjacent biotite temperature of 672 ± 25 °C. Temperatures resulting from the synthesis of garnet inner rim with matrix biotite analyses would have been expected to exceed those from garnet outer rim-adjacent biotite analyses, as a result of continuing chemical exchange between the phases. Since only one of the eight garnet spot analyses clearly indicated it was taken in the core of the grain, others that were annotated “inner rim” were used in lieu of core analyses. The composition of analyzed biotite varies with occurrence, particularly with respect to Ti content. Garnet compositions reflect slight rim enrichment in Mn and rim depletion in Mg, on the order of 0.01 apfu. Variation in Fe content is minor and nonsystematic. The garnet inner core-matrix biotite temperature of 633 ± 25 °C is retained as a lower estimate of peak temperatures experienced by the metapelitic lithologies of the JRL area. However, relative concordance between garnet outer rim-adjacent biotite temperatures taken from

different subregions in the same thin section suggests that the development of local equilibrium may have been minor.

For garnet amphibolite SP-153, a total of eight matrix biotite analyses were combined with measurements across a single garnet grain. There is little variation in biotite composition between individual analyses. Garnet rim enrichment in Fe and Mn and depletion in Mg, on the order of 0.01 apfu, resulted in a mean temperature of 683 ± 25 °C, 36 °C lower than the mean temperature calculated from interior garnet and matrix biotite analyses, 719 ± 25 °C. The variation in calculated temperature for the combination of one garnet analysis with the eight biotite analyses is at most 30 °C. Since the set of lower temperatures result from the combination of garnet outer rim and matrix biotite analyses, rather than analyses of biotite adjacent to the garnet rims, the temperatures are omitted from further study. The peak temperature of 719 ± 25 °C is retained as an approximation of the peak temperatures experienced by garnet amphibolites in the JRL.

Hornblende-Plagioclase Geothermometer

The amphibole-plagioclase thermometers of Holland and Blundy (1994) rely on the temperature-sensitive exchange of Na-Ca and Si-Al between hornblende and plagioclase. The edenite-tremolite (Ed-Tr) thermometer utilizes an edenite exchange in the presence of excess silica. Consequently, it requires a silica-saturated bulk composition. The edenite-richterite (Ed-Ri) thermometer utilizes a plagioclase exchange and, therefore, requires plagioclase compositions between bytownite and oligoclase ($0.1 < X^{ab} < 0.9$). Both criteria are met by the assemblages of samples SP-149 and SP-153: no silica-undersaturated phases are present, disequilibrium textures between hornblende

Results of hornblende-plagioclase thermometry (calibration: Holland and Blundy, 1994)				
SP-149: Tschermakite-labradorite ($0.37 \leq X_{ab} \leq 0.51$) n=60				
Thermometer	0 kbar	5 kbar	10 kbar	15 kbar
Edenite-tremolite	$709 \pm 23^{\circ}\text{C}$	$740 \pm 19^{\circ}\text{C}$	$772 \pm 16^{\circ}\text{C}$	$804 \pm 14^{\circ}\text{C}$
Edenite-richterite	$658 \pm 17^{\circ}\text{C}$	$716 \pm 14^{\circ}\text{C}$	$776 \pm 12^{\circ}\text{C}$	$836 \pm 10^{\circ}\text{C}$
SP-153: Ferropargasite-andesine ($0.56 \leq X_{ab} \leq 0.6$) n = 48				
Thermometer	0 kbar	5 kbar	10 kbar	15 kbar
Edenite-tremolite	$855 \pm 35^{\circ}\text{C}$	$837 \pm 26^{\circ}\text{C}$	$818 \pm 17^{\circ}\text{C}$	$802 \pm 16^{\circ}\text{C}$
Edenite-richterite	$750 \pm 21^{\circ}\text{C}$	$781 \pm 17^{\circ}\text{C}$	$812 \pm 14^{\circ}\text{C}$	$843 \pm 11^{\circ}\text{C}$

Table 10: Results of edenite-tremolite and edenite-richterite thermometry (Holland and Blundy, 1994) as applied to metatexitic amphibolite SP-149 and garnet amphibolite SP-153. Values are calculated for 5 kbar pressure steps using the HBL-PLAG program and presented here as the mean $\pm$ one standard deviation. Input datasets were synthesized from amphibole and plagioclase analyses, containing n=60 and n=48 for samples SP-149 and SP-153, respectively. Bold text indicates the preferred values for upper and lower bounding temperature estimates.

and leucosomal material are not observed, and plagioclase compositions range from labradorite to andesine. The edenite-richterite thermometer is preferred, since it does not require quartz to proceed and thus would be less influenced by variations in bulk quartz content between lithologies.

The HBL-PLAG computer program was utilized to calculate temperatures from input datasets of representative hornblende and plagioclase compositions. Table 10 presents the mean calculated temperature and standard deviation for the datasets at each pressure step.

For metatexitic amphibolite SP-149, the estimated Ed-Ri temperatures are $716 \pm 40^{\circ}\text{C}$ at 5 kbar and $776 \pm 40^{\circ}\text{C}$ at 10 kbar. For garnet amphibolite sample SP-153, the estimated Ed-Ri temperatures are $781 \pm 40^{\circ}\text{C}$ at 5 kbar and $812 \pm 40^{\circ}\text{C}$ at 10 kbar.

In comparison to the Ed-Tr thermometer, the Ed-Ri thermometer yields lower temperatures at 5 kbar and identical temperatures at 10 kbar. The difference in values at

5 kbar is significant with respect to the calculated standard deviation but falls within the published ± 40 °C error.

Barometry

Garnet-Aluminosilicate-Plagioclase-Quartz Geobarometer

The garnet-aluminosilicate-plagioclase-quartz (GASP) barometer was first proposed by Ghent (1976) and has been widely applied to metapelitic lithologies. Garnet, plagioclase, and biotite analyses from garnet-sillimanite schist SP-12 were grouped into two datasets to approximate peak (core and matrix analyses) and reequilibration (rim analyses) conditions. Sillimanite was selected as the aluminosilicate polymorph for both peak and reequilibration conditions, due to the relict texture of kyanite present in SP-12.

The dominant feature of the resulting dataset, summarized in Table 11, is that the

Results of GASP-GARB thermobarometry		
SP-12		
	Garnet core - matrix biotite - plagioclase	Garnet rim - adjacent biotite - plagioclase
Pressure	3.78 ± 0.45 kbar	5.41 ± 0.3 kbar
Range	3.14 - 4.57 kbar	4.94 - 5.77 kbar
Temperature	621 ± 20 °C	659 ± 9 °C
Range	594 - 653 °C	648 - 672 °C
Analyses	16	8

Table 11: Results of GASP barometry, constrained by garnet-biotite thermometry. Thermodynamic data from the internally-consistent dataset of Holland and Powell (1998) were used for phases involved in the GASP equilibrium. Garnet mixing parameters were taken from Ganguly and Saxena (1984). For garnet-biotite thermometry, the calibration of Bhattacharya et al. (1992) was used. Sillimanite was selected as the appropriate aluminosilicate polymorph at peak conditions. Tests using kyanite as the peak aluminosilicate polymorph resulted in a systematic 0.3 kbar increase in calculated pressures. Complete thermobarometric data is provided in appendix B.

pressure and temperature estimate for the rim assemblages (5.41 kbar, 659 °C) exceeds that for the core assemblages (3.78 kbar, 621 °C) significantly. The assumption of sillimanite as the polymorph present during peak metamorphism was tested by selected kyanite as the polymorph with the core assemblage dataset and recalculating P-T values. The test results indicated a slight systematic increase in calculated pressures of only 0.3 kbar.

While the GARB thermometer calibration used here differed from the preferred calibration presented earlier, the results are similar, with higher temperatures calculated for rim assemblages. The GASP-GARB results appear to record increasing P-T conditions with mineral growth. However, this trajectory may also be an artifact of continuing retrograde exchange between the phases.

Computational Thermobarometry

TWQ Multi-Equilibria Calculations

The multi-equilibria approach of the thermobarometric program TWQ v2.3 (Berman, 1991) was applied to samples with compatible analyses of multiple phases (SP-12, SP-149, and SP-153). The program computed an averaged pressure and temperature for each sample by plotting in P-T space all possible equilibria for a given set of phases in a specified chemical system. Subsequent statistical analysis (weighting and dataset refinement) was performed on the resulting plot to yield a single equilibrium pressure and temperature from the intersections of all equilibria. Additionally, intersections between selected equilibria were calculated to compare with ‘classical’ thermobarometric results.

INDIVIDUAL THERMOMETERS AND BAROMETERS CALCULATED IN TWQ			
Geothermometer		Reference	Samples applied
Garnet-biotite		Holdaway (2000)	SP-12, SP-153
Garnet-hornblende		Graham & Powell (1984)	SP-149, SP-153
Geobarometer		Reference	Samples applied
Garnet-Al ₂ SiO ₅ -quartz-plagioclase		GASP Ghent (1976)	SP-12
Garnet-biotite-plagioclase-quartz		GBPQ Hoisch (1990)	SP-12, SP-153
Garnet-rutile-ilmenite-plagioclase-quartz		GRIPS Bohlen & Liotta (1986)	SP-149, SP-153
Garnet-amphibolite-plagioclase-quartz		GAPQ-89 Kohn & Spear (1989)	SP-149, SP-153
Garnet-amphibolite-plagioclase-quartz		GAPQ-90 Kohn & Spear (1990)	SP-149, SP-153
Reaction			
Garnet-biotite	3 almandine + 3 phlogopite = 3 annite + 3 pyrope		
Garnet-hornblende	4 ferropargasite + 3 pyrope = 4 pargasite + 3 almandine		
GASP	grossular + 2 aluminosilicate + quartz = 3 anorthite		
GBPQ-Mg	pyrope + 2 grossular + 3 eastonite + 6 quartz = 6 anorthite + 3 phlogopite		
GBPQ-Fe	almandine + 2 grossular + 3 siderophyllite + 6 quartz = 6 anorthite + 3 annite		
GRIPS	2 almandine + grossular + 6 rutile = 6 ilmenite + 3 anorthite + 3 quartz		
GAPQ-Mg (1989)	6 anorthite + 3 albite + 3 tremolite = 2 grossular + pyrope + 3 pargasite + 18 quartz		
GAPQ-Fe (1989)	6 anorthite + 3 albite + 3 Fe-tremolite = 2 grossular + almandine + 3 Fe-pargasite + 18 quartz		
GAPQ-Mg (1990)	6 anorthite + 3 tremolite = 2 grossular + pyrope + 3 tschermakite + 6 quartz		
GAPQ-Fe (1990)	6 anorthite + 3 Fe-tremolite = 2 grossular + almandine + 3 Fe-tschermakite + 18 quartz		

Table 12: Inventory of individual reaction curves calculated in winTWQ. The pargasite formulation of the garnet-hornblende thermometer (Graham and Powell, 1984) was selected, as it was medial between the tremolite and tschermakite formulations.

The set of individual calculated reactions is given in Table 12.

Representative assemblages were primarily selected on the basis of textural relationships and compositional trends. Where possible, a peak and a reequilibration dataset were created from pairings of core analyses and of rim analyses, respectively. Ideally, analyses for each pairing were selected from a single subregion, but the scatter of analyses between phases and subregions necessitated the occasional synthesizing of points from different subregions. Where pairings were synthesized from different subregions, best-representative analyses were selected.

The complex chemistry of amphibole species necessitated the consideration of six end-members: tremolite/ferroan tremolite, pargasite/ferroan pargasite, and

tschermakite/ferroan tschermakite. Thermodynamic data for these phases was compiled in database v1.02 (Berman, 1991); specific data for the amphibole endmembers was taken from Mader et al. (1994). Since the simultaneous consideration of all six amphibole endmembers resulted in an excessively large array, equilibrium P-T values were obtained for limited sub-assemblages with representative compositions of phases, taking 2 sets of amphibole end-members at a time. Ilmenite is treated as a pure phase since thermodynamic dataset v1.02 does not provide a solution model for this mineral. The validity of this approach is supported by low Mn-content of available ilmenite analyses.

Thermodynamic dataset v2.3 (Berman et al., 2007) was used for assemblages containing biotite, as it contained an updated solution model for biotite, including data for the siderophyllite-eastonite series. Individual equilibria were calculated using both datasets for garnet amphibolite SP-153, since both amphibole and biotite analyses were available.

SP-12 TWQ Results

The analyzed garnet-biotite-plagioclase assemblage of garnet-sillimanite schist SP-12, with the inclusion of pure phases quartz and sillimanite, in the KCFMASH chemical system reveals an equilibrium exceptionally sensitive to the Ca content of plagioclase. Garnet composition is nearly uniform, with maximum core-rim variations of ± 1 mol % for almandine ($0.70 < X^{\text{Fe}} < 0.72$), pyrope ($0.14 < X^{\text{Mg}} < 0.16$), spessartine ($0.09 < X^{\text{Mn}} < 0.10$), and grossular ($0.02 < X^{\text{Ca}} < 0.04$). Biotite analyses from the matrix, included in garnet, and adjacent to garnet, have three distinct compositions, with lowest Mg-numbers in analyses from grains adjacent to garnet ($0.432 < \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{\text{tot}}) <$

0.466) and highest from the inclusion analysis ($\text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{\text{tot}}) = 0.507$). Octahedral Al and Ti contents also varied with textural occurrence. Al contents were lowest in matrix analyses ($0.12 < {}^{\text{vi}}\text{Al}/({}^{\text{vi}}\text{Al} + {}^{\text{vi}}\text{R}^{2+}) < 0.13$) and highest in analyses from grains adjacent to garnet ($0.19 < {}^{\text{vi}}\text{Al}/({}^{\text{vi}}\text{Al} + {}^{\text{vi}}\text{R}^{2+}) < 0.27$). Ti contents were lowest in analyses from grains adjacent to garnet and highest in matrix analyses ($0.24 < {}^{\text{vi}}\text{Ti}^{2+} < 0.41$ apfu). Plagioclase compositions vary minimally between core and rim analyses (± 1 mol %). However, analyses from grains adjacent to garnet ($X^{\text{Ab}} = 0.78$) show albite enrichment relative to the matrix ($0.71 < X^{\text{ab}} < 0.72$).

Since the confident synthesis of plagioclase with appropriate garnet and biotite analyses can only be performed in one subregion, multiple synthetic datasets were tested to find the combination of analyses that produced the tightest clustering of equilibria curves, i.e. the assemblage with compositions closest to equilibrium. Pairings of core-matrix analyses were not found to definitely record peak conditions or complete equilibrium. Instead, the most-tightly clustered reaction curves with lowest standard deviation about an average P-T coordinate were produced by biotite analyses with higher total Fe and lower Al content. Increased anorthite content in plagioclase shifted the intersections between these tightly clustered thermometers and barometers 1.5 kbar higher. However, the garnet rim-adjacent biotite pairings generally revealed a broader distribution of reaction curves in P-T space and thus suggest greater disequilibrium. Reaction curves for garnet core-biotite matrix pairings were more tightly clustered about a single P-T point and TWQ results for one such pairing, in combination with the higher anorthite content of plagioclase in association with garnet, are retained as an estimate

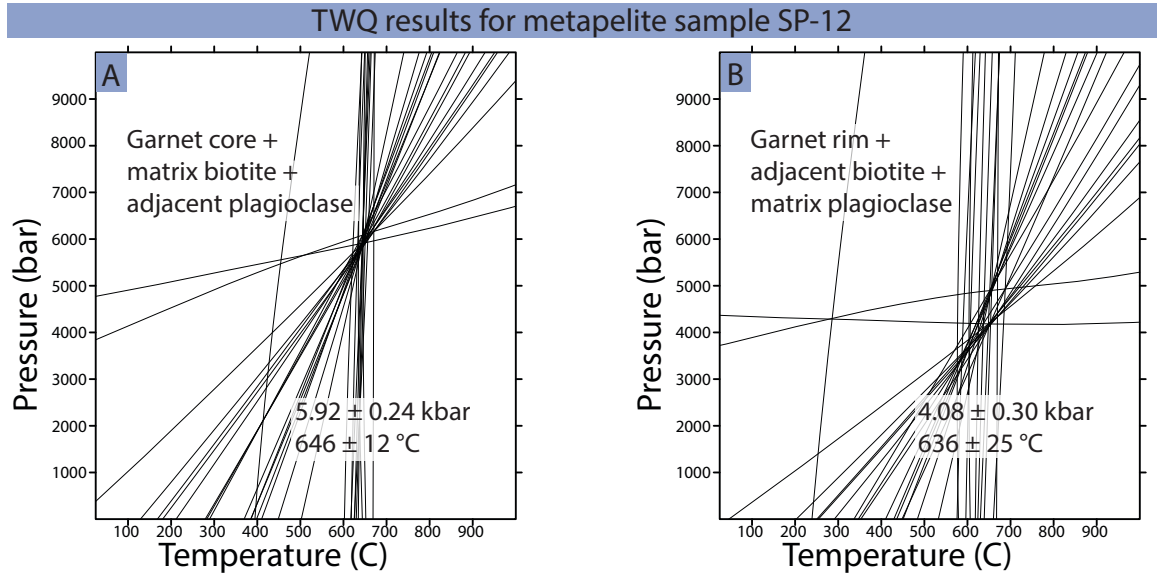


Figure 31: Results of TWQ weighted average P-T calculations for garnet-sillimanite schist SP-12. Equilibria are calculated for garnet-biotite-plagioclase analyses and pure phases quartz-sillimanite in the KCFMASH system. Panel A contains all curves calculated for the garnet core-matrix biotite- Ab_{78} plagioclase assemblage. Panel B contains all curves calculated for the garnet rim-adjacent biotite - Ab_{71} plagioclase assemblage.

of peak P-T conditions at 5.92 kbar and 646 °C (Figure 31).

Table 13 reports the intersections of individual barometers with the GARB thermometer. GASP-GARB estimates are slightly lower than the two, indistinguishable garnet-biotite-plagioclase-quartz (GBPQ)-GARB estimates, on the order of 0.2-0.3 kbar. These values indicate a nearly isothermal 1.0-1.5 kbar difference between average P-T conditions for peak and reequilibration assemblages in the KCFMASH system. Average P-T conditions calculated for all assemblages range from 4.08 ± 0.35 kbar and 612 ± 43 °C to 5.92 ± 0.24 kbar and 646 ± 12 °C. In the TiKCFMASH system, average pressures are within one standard deviation of each other (5.73-6.00 kbar) but average temperature is higher for the reequilibration assemblage (741 °C vs. 664 °C). For comparison, the

Results of TWQ P-T calculations applied to sample SP-12					
	Intersections used/total	P-T avg	GASP	GBPQ-Mg	GBPQ-Fe
Garnet core-matrix biotite-plagioclase (An ₇₈)	186 / 204	5.92 ± 0.24 kbar 646 ± 12 °C	6.02 kbar 651 °C	6.21 kbar 651 °C	6.20 kbar 651 °C
Garnet rim-adjacent biotite-plagioclase (An ₇₁)	132 / 209	4.08 ± 0.30 kbar 636 ± 25 °C	4.44 kbar 654 °C	4.97 kbar 656 °C	5.02 kbar 657 °C

Table 13: Average P-T and individual barometers calculated in the KCFMASH system for garnet-sillimanite schist SP-12. Barometers are used in conjunction with the garnet-biotite thermometer. Average P-T results for the same assemblages in the TiKCFMASH system are peak conditions of 6.00 ± 0.14 kbar and 664 ± 5 °C and reequilibration at 5.73 ± 0.16 kbar and 741 ± 12 °C. Complete thermobarometric results are provided in appendix B.

average P-T calculated from different peak and reequilibration assemblages, subsequently used for thermobarometric calculations performed in Program GTB (Spear and Kohn, 2014), indicates maximum conditions of 4.08 ± 0.35 kbar and 612 ± 43 °C and reequilibration at 5.63 ± 0.30 kbar and 644 ± 23 °C. Input datasets, additional plots, and complete results are provided in appendix B.

SP-149 TWQ Results

The garnet-amphibole-plagioclase-ilmenite assemblage, plus pure phases quartz and rutile, for metatexitic amphibolite SP-149 was considered in the TiNCKFMASH system. Garnet composition shows little variation between both individual subregions and core-rim compositions for almandine ($0.57 < X^{\text{Fe}} < 0.63$), pyrope ($0.22 < X^{\text{Mg}} < 0.26$), spessartine ($0.01 < X^{\text{Mn}} < 0.02$), and grossular ($0.13 < X^{\text{Ca}} < 0.16$). A representative amphibole composition was selected from six tschermakitic analyses with minor variation in Ca ($1.72 < \text{Ca}^{2+} < 1.73$ apfu), Na ($0.34 < \text{Na}^+ < 0.37$ apfu), K ($0.05 < \text{K}^+ < 0.07$ apfu), and Mg-number ($0.78 < \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+}) < 0.84$). Plagioclase shows

nonsystematic variation between both subregions and core-rim ($0.40 < X^{\text{Ab}} < 0.51$). A representative pure ilmenite composition was used, since analyses indicated a nearly pure composition (Table 5). Although thermodynamic database v2.34 does include a solid solution model for ilmenite (Berman et al., 2007), Pownceby et al. (1987)'s garnet-ilmenite thermometer could not be applied to this sample, due to low spessartine content in garnet ($X^{\text{mn}}=0.01$) and pyrophanite content in ilmenite ($X^{\text{mn}}=0.0$). The suite of available point analyses permitted the combination of core and matrix analyses from the same subregion into synthetic datasets for peak and reequilibration conditions. A single representative assemblage for each set of conditions was selected, based on the clustering of reaction curves in P-T space. The same composition of amphibole and ilmenite was used for both assemblages.

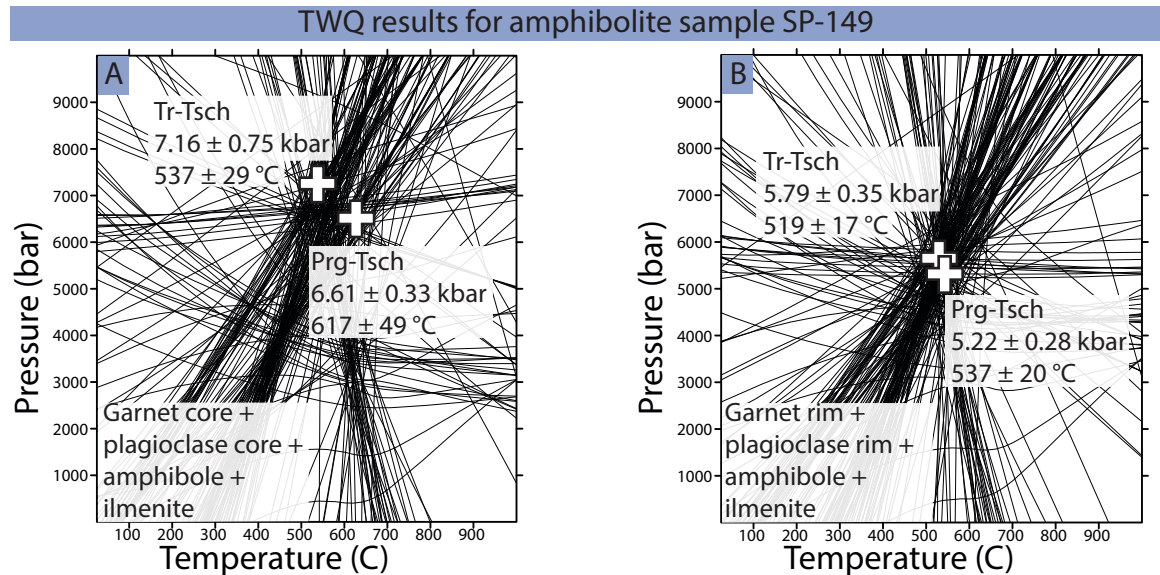


Figure 32: Results of TWQ weighted average P-T calculations for metatextitic amphibolite SP-149. Equilibria are calculated for garnet-amphibole-plagioclase analyses with pure phase quartz in the NaCFMASH system. Due to computing restraints, average P-T values were only calculated for assemblages assigned the tremolite-tschermakite (Tr-Tsch) and pargasite-tschermakite (Prg-Tsch) endmembers.

The size of the array resulting from complete consideration of all six amphibole end-members in addition to the other phases rendered calculation of a P-T weighted average beyond the capabilities of the program. However, P-T averages were calculated for two subsets, which contained albite-almandine-anorthite-grossular-ilmenite-pyroxene-quartz-rutile plus tremolite-ferroan tremolite-tschermakite-ferroan tschermakite or pargasite-ferroan pargasite-tschermakite-ferroan tschermakite in the TiNCKFMASH system. Figure 32 contains the average P-T results for peak and reequilibration assemblages. The calculated average peak and reequilibration P-T conditions utilizing the pargasite-tschermakite end-members have higher pressures but lower temperatures than those calculated with the tremolite-tschermakite end-members. Combining the two average values results in peak conditions at 6.61-7.17 kbar and 537-617 °C and reequilibration at 5.22-5.79 kbar and 519-537 °C.

Results of TWQ average P-T calculations applied to sample SP-149

	Intersections	Tremolite-Tschermakite P-T average	Intersections	Pargasite-Tschermakite P-T avg
Garnet core-plagioclase core-amphibole-ilmenite	241 / 530	6.61 ± 0.33 kbar 617 ± 49 °C	81 / 220	7.16 ± 0.75 kbar 537 ± 29 °C
Garnet rim-plagioclase rim-amphibole-ilmenite	458 / 534	5.22 ± 0.28 kbar 537 ± 20 °C	88 / 239	5.79 ± 0.35 kbar 519 ± 17 °C

Results of TWQ selected barometers applied to SP-149

	GRIPS	GAPQ-Mg (1989)	GAPQ-Fe (1989)	GAPQ-Mg (1990)	GAPQ-Fe (1990)
Garnet core-plagioclase core-amphibole-ilmenite	6.08 kbar 634 °C	6.86 kbar 638 °C	7.13 kbar 639 °C	7.89 kbar 643 °C	8.11 kbar 644 °C
Garnet rim-plagioclase rim-amphibole-ilmenite	5.34 kbar 560 °C	5.12 kbar 559 °C	5.54 kbar 561 °C	5.72 kbar 562 °C	6.11 kbar 564 °C

Table 14: Average P-T and individual barometers calculated for metatextitic amphibolite SP-149. Barometers are used in conjunction with the garnet-pargasite thermometer. Complete thermobarometric results are provided in appendix B.

Individual barometers were calculated using intersection with the garnet-pargasite thermometer, medial between the garnet-tremolite and garnet-tschermakite formulations of the garnet-hornblende thermometer (GRHB). The results are presented in Table 14. A wider range of peak P-T values (6.08-8.11 kbar and 559-564 °C) than for reequilibration (5.12-6.11 kbar and 634-644 °C) is recorded. Applicable hornblende-plagioclase thermometry was calculated separately, as neither extant version of the internally-consistent thermodynamic database includes data for edenite and richterite.

SP-153 TWQ Results

For garnet amphibole SP-153, five analysed phases (garnet-biotite-plagioclase-ilmenite-amphibole) were combined with pure phases rutile, ilmenite, and quartz in the TiNaKCFMASH system. Minimal variation between subregions in all phases permitted the use of a single synthetic dataset of core-matrix and rim-adjacent analyses for possible peak and reequilibration conditions. Garnet core-rim variation was very limited for almandine ($0.61 < X^{\text{Fe}} < 0.63$), pyrope ($0.07 < X^{\text{Mg}} < 0.09$), spessartine ($0.03 < X^{\text{Mn}} < 0.05$), and grossular ($0.24 < X^{\text{Ca}} < 0.27$). A single annitic composition for biotite was selected from eight matrix analyses with minimal variation in Mg-number ($0.33 < \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{\text{tot}}) < 0.35$), octahedral Al ($0.03 < {}^{\text{vi}}\text{Al}/({}^{\text{vi}}\text{Al} + {}^{\text{vi}}\text{R}^{2+}) < 0.06$), and Ti ($0.46 < {}^{\text{vi}}\text{Ti}^{2+} < 0.52$ apfu). Plagioclase showed minor, nonsystematic variation in albite content ($0.55 < X^{\text{Ab}} < 0.59$). Ilmenite analyses were essentially pure, containing only trace amounts of Mn ($0.02 < \text{Mn}^{2+} < 0.03$ apfu), whether from grains included in amphibole, associated with garnet and amphibole, or in the matrix. The spessartine content in garnet ($X^{\text{mn}}=0.03$) and pyrophanite content in ilmenite ($X^{\text{mn}}=0.01$) was insufficient to evaluate the garnet-

ilmenite thermometer of Pownceby et al. (1987). The composition of individual amphibole analyses showed little variation in Ca ($1.82 < \text{Ca}^{2+} < 1.91$ apfu), Na ($0.48 < \text{Na}^+ < 0.54$ apfu), K ($0.21 < \text{K}^+ < 0.23$ apfu), and Mg-number ($0.51 < \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+}) < 0.67$). Thus, a single representative ferropargasitic composition was used. Point analyses from various subregions permitted the combination of core-matrix and rim-adjacent grain analyses into one synthetic input dataset each for possible peak and reequilibration assemblages.

Bulk equilibria conditions for the sub-assemblage containing tremolite-ferroan tremolite-tschermakite-ferroan tschermakite amphibole end-members is presented in Figure 33. An average P-T could not be calculated for the tremolite-pargasite or tschermakite-pargasite sub-assemblages. Peak conditions of 10.05 kbar and 781 °C and

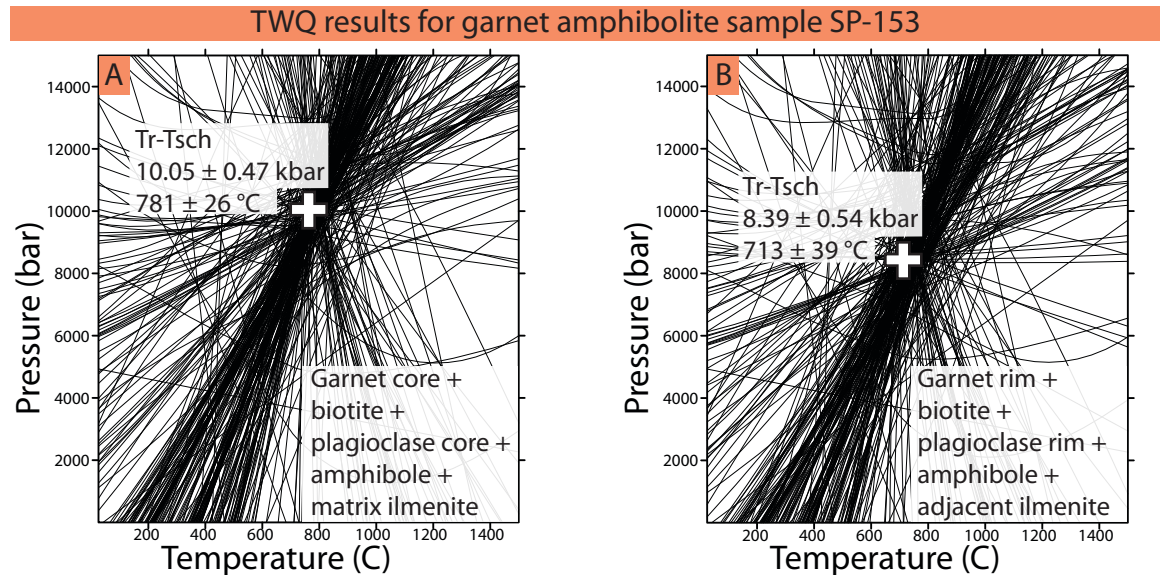


Figure 33: Results of TWQ weighted average P-T calculations for garnet amphibolite SP-153. Equilibria are calculated for garnet-amphibolite-biotite analyses and pure phases quartz-rutile-ilmenite in the TiNaCKFMASH system. Due to computing constraints, average P-T coordinates were only calculated for assemblages assigned the tremolite-tschermakite (Tr-Tsch) end-members.

Results of TWQ P-T calculations applied to sample SP-153					
	Intersections	Tremolite- Tschermakite P-T average	Thermodynamic dataset v2.3 using garnet-biotite thermometer		
			GRIPS	GBPQ-Mg	GBPQ-Fe
Garnet-biotite-plagioclase- amphibole-ilmenite core	688	10.05 ± 0.47 kbar 781 ± 26 °C	11.10 kbar 807 °C	12.04 kbar 811 °C	12.46 kbar 812 °C
Garnet-biotite-plagioclase- amphibole-ilmenite rim	510	8.39 ± 0.54 kbar 713 ± 39 °C	9.91 kbar 742 °C	9.71 kbar 74 °C	9.95 kbar 742 °C

Thermodynamic dataset v1.02, using garnet-pargasite thermometer					
	GRIPS	GAPQ-Mg (1989)	GAPQ-Fe (1989)	GAPQ-Mg (1990)	GAPQ-Fe (1990)
Core	9.97 kbar 763 °C	9.40 kbar 761 °C	9.04 kbar 759 °C	9.58 kbar 762 °C	9.13 kbar 759 °C
Rim	8.67 kbar 693 °C	7.58 kbar 688 °C	7.37 kbar 687 °C	7.35 kbar 687 °C	7.09 kbar 685 °C

Table 15: Results of average P-T and individual barometers calculated for garnet amphibolite SP-153. Thermodynamic dataset v1.02 (Berman, 1988) includes six amphibolite endmembers and is used in conjunction with the garnet-pargasite thermometer. Dataset v2.3 (Berman et al., 2007) includes data for the eastonite-siderophyllite series in conjunction with the GBPQ barometers. Results of the GRIPS barometer is also included for comparison.

reequilibration at 8.39 kbar and 713 °C are the highest calculated of the three samples.

The results of intersection between individual barometers and the GRHB thermometer are presented in Table 15. The garnet-pargasite formulation is preferred, as it is the medial of the three GRHB thermometer formulations. The garnet-amphibole-plagioclase-quartz (GAPQ)-garnet-pargasite intersections for core and rim compositions are retained as representative of the conditions experienced by SP-153. Results from GBPQ-GARB are discarded, as the conditions are physically infeasible, exceeding known P-T values for biotite dehydration.

Classical Thermobarometry

GTB Calculations

The calculation of multiple “classical” thermometers and barometers was performed by the computer application Program GTB (Spear and Kohn, 2014) on three samples with analyses of multiple phases: garnet-sillimanite schist SP-12, metatextitic amphibolite SP-149, and garnet amphibolite SP-153. These same samples were previously used for TWQ multiequilibria calculations.

The GARB thermometer calibration of Kleeman and Reinhardt (1994) was selected from among 12 calibrations available in GTB: Ferry and Spear (1978); Ferry and Spear (1978) with the garnet solution model of Berman (1990); Hodges and Spear (1982); Ganguly and Saxena (1984) using either asymmetric or symmetric garnet solution models; Perchuk and Lavrent'eva (1984); Indares and Martignole (1985) using the garnet solution model of either Hodges and Spear (1978) or Ganguly and Saxena (1984); Patiño Douce et al. (1993); Gessman et al. (1997); and Holdaway et al. (1997). Of the calibrations available, only Kleeman and Reinhardt (1994) both incorporated mixing of Al and Ti on octahedral sites in biotite and utilized Berman (1990) for the garnet solution model. The garnet solution model was selected to facilitate comparison of thermobarometric results between GTB and TWQ programs. Compositional data for analysed biotite indicates the significant contribution of octahedral Ti (Figure 30).

The GASP barometer calibration of Hodges and Crowley (1985) was selected from five calibrations available: Newton and Haselton (1981); Hodges and Spear (1982); Ganguly and Saxena (1984); and Koziol (1989). Hodges and Crowley (1985) presented

INDIVIDUAL THERMOMETERS AND BAROMETERS CALCULATED IN GTB		
Geothermometer	Calibration	
Garnet-biotite	Kleeman & Reinhardt (1994)	
Garnet-hornblende	Graham & Powell (1984)	
Hornblende-plagioclase	Holland & Blundy (1994)	
Geobarometer	Calibration	
Garnet-Al ₂ SiO ₅ -quartz-plagioclase	GASP	Hodges & Crowley (1985)
Garnet-amphibolite-plagioclase-quartz	GAPQ	Kohn & Spear (1990)
Garnet-biotite-plagioclase-quartz	GBPQ	Hoisch (1990)
Garnet-rutile-ilmenite-plagioclase-quartz	GRIPS	Bohlen & Liotta (1986)
Garnet-rutile-Al ₂ SiO ₅ -ilmenite-quartz	GRAIL	Bohlen et al. (1983)
Reaction		
Garnet-biotite	3 almandine + 3 phlogopite = 3 annite + 3 pyrope	
Garnet-hornblende	4 ferropargasite + 3 pyrope = 4 pargasite + 3 almandine	
Hornblende-plagioclase	edenite + 4 quartz = tremolite + albite	
GASP	grossular + 2 aluminosilicate + quartz = 3 anorthite	
GAPQ-Mg	6 anorthite + 3 tremolite = 2 grossular + pyrope + 3 tschermakite + 6 quartz	
GAPQ-Fe	6 anorthite + 3 Fe-tremolite = 2 grossular + almandine + 3 Fe-tschermakite + 18 quartz	
GBPQ-Mg	pyrope + 2 grossular + 3 eastonite + 6 quartz = 6 anorthite + 3 phlogopite	
GBPQ-Fe	almandine + 2 grossular + 3 siderophyllite + 6 quartz = 6 anorthite + 3 annite	
GRIPS	2 almandine + grossular + 6 rutile = 6 ilmenite + 3 anorthite + 3 quartz	
GRAIL	3 ilmenite + aluminosilicate + 2 quartz = almandine + rutile	

Table 16: Inventory of individual reaction calibrations calculated in GTB. Note that the GRIPS barometer could not be calculated for SP-149 and SP-153.

a modified version of Newton and Haselton (1981)'s barometer, using the Al-avoidance model for plagioclase and only symmetric mixing along the pyrope-grossular join in an otherwise ideal mixing model for ternary garnets. The negligible influence of the spessartine component in garnet is supported by medial P-T conditions estimated by application of the Hodges & Crowley (1985) calibration to rocks of the JRLT.

For the remaining thermometers and barometers, single calibrations were available. Table 16 contains a summary of all thermometers, barometers, and calibrations used. The garnet-rutile-ilmenite-plagioclase-quartz (GRIPS) barometer of Bohlen and Liotta (1986) could not be applied to samples SP-149 and SP-153. GTB identified stoichiometric problems with biotite in the SP-12 peak assemblage and with amphibole in

SP-149 and SP-153 assemblages. The identified input datasets consequently were verified for compositional accuracy and utilized. GTB does not provide for the computation of exact intersections between thermometers and barometers; however, linear solutions were recalculated from P-T output and tabulated.

Peak and reequilibration assemblages of representative mineral compositions were synthesized from individual point analyses, ideally taken from the core and rim of each mineral. As with the synthetic datasets prepared for TWQ input, analyses from the same thin section subregion were combined where possible. Strong compositional zoning is not frequent in the minerals of the samples utilized and for some species, there is only a single composition measured. The details of mineral compositions in synthetic datasets will be discussed separately with each sample.

The GTB program utilized input datasets of cation abundances per mineral, rather than weight percent oxides per mineral in TWQ. Since formulae were corrected for ferric iron at the time of recalculation, no additional corrections were applied in GTB for GARB thermometry or GRIPS/garnet-rutile-aluminosilicate-ilmenite (GRAIL) barometry. Complete input datasets, output plots, and results are provided in appendix B.

SP-12 GTB Results

The same suite of mineral point analyses utilized in TWQ computational thermobarometry was utilized, but the combination of individual analyses into synthetic input composition datasets was performed exclusively on the basis of textural association. Core analyses were combined with matrix analyses for possible peak assemblages and rim analyses were combined with analyses from adjacent grains for possible

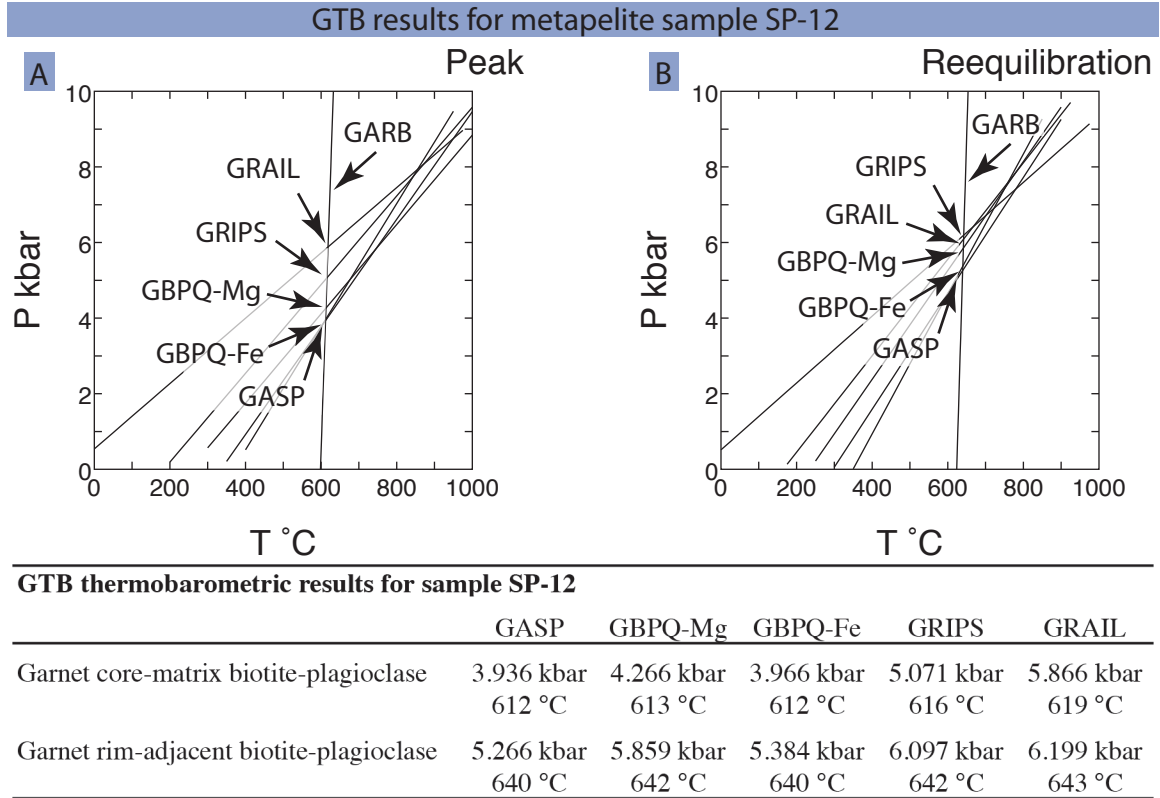


Figure 34: GTB plots for garnet-sillimanite schist SP-12. The peak garnet-biotite-plagioclase assemblage utilizes individual analyses from the same subregion. Garnet ($X^{\text{Fe}} = 0.70$; $X^{\text{Mg}} = 0.17$; $X^{\text{Mn}} = 0.10$; $X^{\text{Ca}} = 0.03$), biotite ($\text{Mg}/(\text{Mg} + \text{Fe}^{\text{tot}}) = 0.49$; $^{\text{vi}}\text{Al}/(^{\text{vi}}\text{Al} + ^{\text{vi}}\text{R}^{2+}) = 0.12$; $\text{Ti} = 0.41$ apfu), and plagioclase ($X^{\text{Ab}} = 0.71$). The reequilibration assemblage combines garnet and biotite analyses from the same subregion with texturally equivalent plagioclase from a different subregion. Garnet ($X^{\text{Fe}} = 0.72$; $X^{\text{Mg}} = 0.14$; $X^{\text{Mn}} = 0.10$; $X^{\text{Ca}} = 0.03$), biotite ($\text{Mg}/(\text{Mg} + \text{Fe}^{\text{tot}}) = 0.43$; $^{\text{vi}}\text{Al}/(^{\text{vi}}\text{Al} + ^{\text{vi}}\text{R}^{2+}) = 0.19$; $\text{Ti} = 0.24$ apfu), and plagioclase ($X^{\text{Ab}} = 0.78$). Additionally, pure ilmenite and sillimanite were included for GRIPS and GRAIL calculations.

reequilibration assemblages. For comparison, GTB classical thermobarometry was also applied to the peak and reequilibration assemblages for SP-12 identified in TWQ, which were selected on the basis of both textural association and broadness of reaction curve distribution in P-T space. Additional plots and results are provided in appendix B.

The preferred peak and reequilibration reaction curves are plotted in Figure 34.

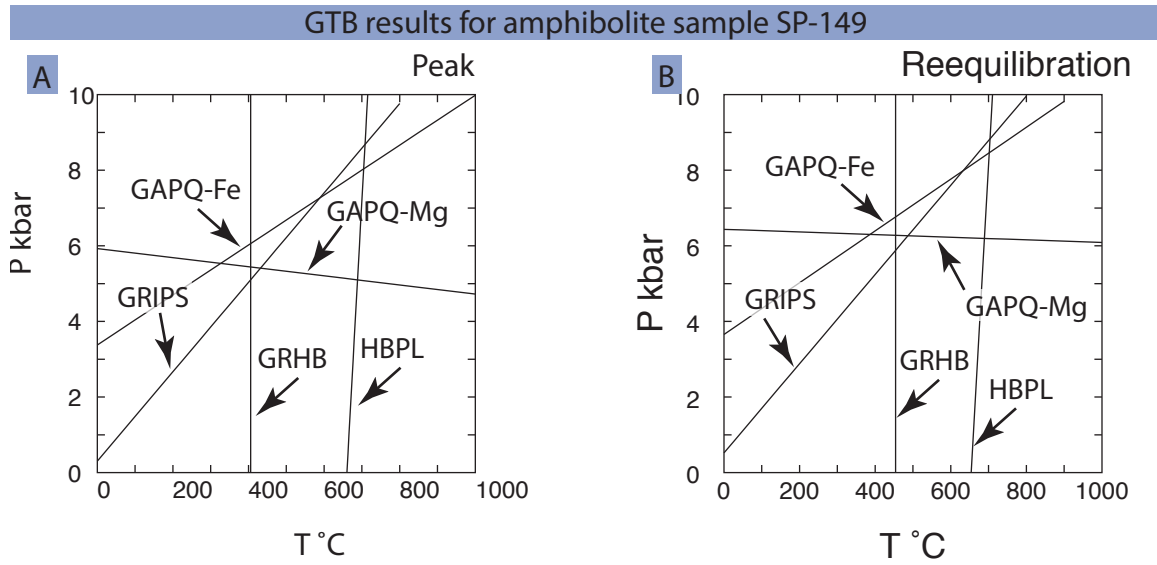
P-T conditions calculated for the possible peak assemblage are 3.936-5.866 kbar and

612-619 °C, while for the reequilibration assemblage, 5.266-6.199 kbar and 640-643 °C. Similar to the independently calculated GASP-GARB results using the Holland and Powell (1998) dataset and the Bhattacharya et al. (1992) GARB calibration, the results for the core-matrix assemblage expected to yield peak P-T conditions are, in fact, significantly lower than those for the rim-adjacent grain assemblage expected to yield reequilibration conditions. However, for both assemblages, the lowest pressures are returned by GASP and GBPQ-Fe barometers, while GRIPS and GRAIL return the highest pressures. Since pure ilmenite was utilized for the calculation of GRIPS and GRAIL barometers, these pressures can only be interpreted as an upper bound for conditions experienced by garnet-sillimanite schist SP-12.

SP-149 GTB Results

A limited thermobarometric suite is applicable to metatextitic amphibolite SP-149. The same possible peak and reequilibration garnet-plagioclase-amphibole-ilmenite assemblages selected for TWQ calculations were used for P-T calculations in GTB. Representative compositions for tschermakitic amphibole and nearly pure ilmenite were used in both assemblages. Garnet and plagioclase core analyses, as well as garnet and plagioclase rim analyses, were taken from the same subregion and combined with the representative amphibole and ilmenite assemblages. Dominantly almandine-pyrope garnet varied 1-5 mol% in individual components.

Calculated P-T values are similar for both peak and reequilibration assemblages, as shown in Figure 35. Garnet-hornblende thermometry returns temperature estimates for core (407 °C) and rim assemblages (454 °C) that are substantially lower than hornblende-



GTB thermobarometric results for sample SP-149

	Garnet-hornblende thermometer			Hornblende-plagioclase thermometer		
	GBPQ-Mg	GBPQ-Fe	GRIPS	GBPQ-Mg	GBPQ-Fe	GRIPS
Garnet core-plagioclase	5.439 kbar	6.064 kbar	5.112 kbar	5.099 kbar	8.036 kbar	8.685 kbar
core-amphibole-ilmenite	407 °C	407 °C	407 °C	689 °C	705 °C	709 °C
Garnet rim-plagioclase	6.278 kbar	6.771 kbar	5.886 kbar	6.197 kbar	8.466 kbar	8.834 kbar
rim-amphibole-ilmenite	455 °C	455 °C	455 °C	689 °C	702 °C	704 °C

Figure 35: GTB results for metatextitic amphibole SP-149. Single representative tschermakitic amphibole ($\text{Ca}^{2+} = 1.72$, $\text{Na}^{+} = 0.37$, $\text{K}^{+} = 0.07$) and pure ilmenite compositions were used in possible peak (core-core) and reequilibration (rim-rim) assemblages of garnet-plagioclase-amphibole-ilmenite analyses from one subregion. Peak garnet ($X^{\text{Fe}} = 0.63$; $X^{\text{Mg}} = 0.21$; $X^{\text{Mn}} = 0.02$; $X^{\text{Ca}} = 0.14$) and plagioclase ($X^{\text{Ab}} = 0.42$). Reequilibration garnet ($X^{\text{Fe}} = 0.58$; $X^{\text{Mg}} = 0.26$; $X^{\text{Mn}} = 0.01$; $X^{\text{Ca}} = 0.15$) and plagioclase ($X^{\text{Ab}} = 0.41$). Complete input datasets are provided in appendix B.

plagioclase values (689-709 °C). The GAPQ-Mg barometer returns anomalously low values in conjunction with both thermometers and has a negative slope when applied to both assemblages. P-T conditions are thus estimated from the GAPQ-Fe and GRIPS barometers in conjunction with the hornblende-plagioclase thermometer as 8.036-8.685 kbar and 705-709 °C for the ‘peak’ garnet core-plagioclase core-amphibole-ilmenite assemblage and 8.466-8.834 kbar and 702-704 °C for the ‘reequilibration’ garnet rim-plagioclase rim-amphibole-ilmenite assemblage. The narrow P-T range agrees with minor

compositional variation between ‘peak’ and ‘reequilibration’ assemblages.

The anomalously low temperatures calculated by garnet-hornblende thermometry likely result from chemical disequilibrium between the two phases. Hornblende-plagioclase temperatures are lower than those calculated independently with the HBL-PLAG program, utilizing discreet pressure steps. The HBL-PLAG temperatures were estimated as 716-776 °C over the interval 5-10 kbar.

SP-153 GTB Results

The largest suite of thermometers and barometers was applied to garnet

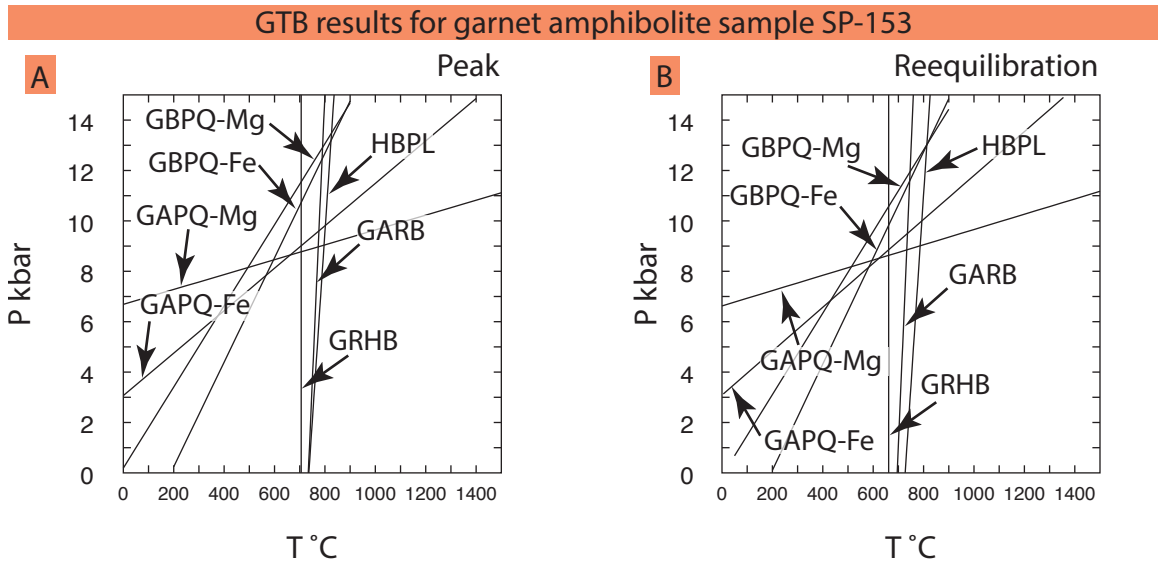


Figure 36: GTB results for garnet amphibolite SP-153. Single representative compositions of ferropargasitic amphibole ($\text{Ca}^{2+} = 1.89$; $\text{Na}^{+} = 0.52$; $\text{K}^{+} = 0.21$) and annitic biotite ($\text{Mg}/(\text{Mg} + \text{Fe}^{\text{tot}}) = 0.35$; $^{\text{vi}}\text{Al}/(^{\text{vi}}\text{Al} + ^{\text{vi}}\text{R}^{2+}) = 0.05$; $\text{Ti} = 0.48$ apfu) were used in possible peak (core-core) and reequilibration (rim-rim) assemblages of garnet-biotite-plagioclase-amphibole-ilmenite analyses. Garnet core ($X^{\text{Fe}} = 0.61$; $X^{\text{Mg}} = 0.09$; $X^{\text{Mn}} = 0.03$; $X^{\text{Ca}} = 0.27$), matrix ilmenite ($\text{Fe}^{2+} = 0.98$ apfu; $\text{Mn}^{2+} = 0.03$), and plagioclase core ($X^{\text{Ab}} = 0.56$). Garnet rim ($X^{\text{Fe}} = 0.62$; $X^{\text{Mg}} = 0.07$; $X^{\text{Mn}} = 0.05$; $X^{\text{Ca}} = 0.24$), adjacent ilmenite ($\text{Fe}^{2+} = 0.99$ apfu; $\text{Mn}^{2+} = 0.02$), and plagioclase rim ($X^{\text{Ab}} = 0.59$). Complete input datasets are provided in appendix B.

GTB thermobarometric results for sample SP-149

	Garnet-biotite thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	8.972 kbar 773 °C	9.606 kbar 776 °C	12.920 kbar 791 °C	12.451 kbar 789 °C	11.413 kbar 784 °C
	Garnet-hornblende thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	8.772 kbar 706 °C	9.011 kbar 706 °C	11.551 kbar 706 °C	12.729 kbar 706 °C	10.229 kbar 706 °C
	Hornblende-plagioclase thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	9.040 kbar 796 °C	9.818 kbar 801 °C	12.484 kbar 826 °C	13.178 kbar 824 °C	11.882 kbar 815 °C
	Garnet-biotite thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	8.851 kbar 733 °C	9.550 kbar 736 °C	11.934 kbar 747 °C	11.590 bar 745 °C	11.281 kbar 744 °C
	Garnet-hornblende thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	8.633 kbar 662 °C	8.898 kbar 662 °C	10.577 kbar 662 °C	9.830 kbar 662 °C	9.578 kbar 662 °C
	Hornblende-plagioclase thermometer				
	GAPQ-Mg	GAPQ-Fe	GBPQ-Mg	GBPQ-Fe	GRIPS
	9.012 kbar 786 °C	10.047 kbar 793 °C	13.025 kbar 813 °C	13.016 kbar 813 °C	11.778 kbar 805 °C

Table 17: Results calculated from intersections between individual thermometers and barometers for garnet amphibolite SP-153.

amphibolite SP-153, utilizing the same combinations of core-matrix and rim-rim pairings of mineral analyses previously selected in TWQ. Single representative analyses for biotite and amphibole were used. A single composition for ilmenite would have also been applicable, since there was minimal variation among analyses. Dominantly almandine-grossular garnet varies 1-3 mol% for individual components and plagioclase shows a

minor rim enrichment in albite of 3 mol%. The GRIPS curve could not be plotted in GTB but intersections with thermometers were recalculated from the P-T output. Figure 36 contains all thermometers and barometers plotted for possible peak and reequilibration assemblages. Table 17 contains the calculated intersections between all thermometers and barometers. Minimum P-T conditions estimated by GARB-GAPQ are 8.851 kbar and 733 °C, which falls on the biotite dehydration curve. All other P-T estimates utilizing GARB exceed the biotite dehydration curve. Similarly, the intersections between the GPBQ barometer and all thermometers are in excess of the biotite dehydration curve. Consequently, the hornblende-plagioclase (HBPL) thermometer-GRIPS barometer pairing was selected for estimates of peak conditions and the GRHB-GAPQ barometer was selected for an estimate of reequilibration conditions. A GRIPS-HBPL value of 11.882 kbar and 815 °C is retained as a maximum for peak conditions. Minimum GAPQ-GRHB conditions of 8.633-8.898 kbar and 662 °C are retained for reequilibration.

Summary of Thermobarometric Results

Independently calculated thermometers and barometers are considered in comparison with TWQ and GTB results for three samples: SP-12, SP-149, and SP-153. While thermobarometric calculations from pairings of core and matrix analyses were intended to capture peak metamorphic conditions experienced early in the growth of minerals, garnet-sillimanite schist SP-12 showed a reversal of expected conditions, manifesting in GARB, GASP-GARB, TWQ, and GTB results. Higher pressures and temperatures are recorded from core-matrix assemblages than rim-adjacent grain

pairings. This may be a result of continued Fe-Mg exchange between the phases during retrogression. However, TIB thermometry does record a higher temperature for matrix biotite (702 °C) than biotite adjacent to garnet (617 °C). The GARB calibration of Holdaway (2000) calculated an increase from a core temperature of 633 °C to a rim temperature of 672 °C. The GASP-GARB thermobarometer, using the Holland and Powell (1998) dataset and the Bhattacharya et al. (1992) calibration, estimates ‘peak’ conditions of 3.78 kbar and 621 °C and ‘reequilibration’ at 5.41 kbar and 659 °C. GTB calculation of GASP-GARB has similar results, with conditions estimated from the core-matrix assemblage of 3.94 kbar and 612 °C and conditions from the rim-adjacent assemblage of 5.27 kbar and 640 °C. TWQ’s average P-T calculation, applied to the same ‘peak’ and ‘reequilibration’ assemblages, follows the same pattern and returns conditions of 4.08 kbar and 612 °C for core-matrix pairings and 5.63 kbar and 644 °C for rim-adjacent pairings. However, using different assemblages, selected for attainment of equilibrium, returns peak conditions of 5.92 kbar and 646 °C and reequilibration conditions of 4.08 kbar and 636 °C.

Results from metatexitic garnet amphibolite SP-149 follow the expected trend of higher P-T conditions calculated from core-matrix pairings and lower P-T conditions from rim-adjacent grain pairings. Amphibole-plagioclase thermometry indicates maximum conditions of 716-776 °C over the interval 5-10 kbar. TWQ average P-T values, calculated with amphibole compositions limited to the tremolite-tschermakite end-members in the NaCFMASH system, indicate peak conditions of 6.61 kbar and 617 °C and reequilibration at 5.22 kbar and 537 °C. Higher P-T values of 7.89 kbar and

643 °C for peak and 5.72 kbar and 562 °C for reequilibration were calculated for the individual thermobarometer GAPQ-GRHB in TWQ. The same thermobarometer in GTB returned peak values of 5.44 kbar and 407 °C and reequilibration P-T of 6.28 kbar and 455 °C. The preferred GRIPS-GRHB thermobarometer in GTB calculated peak P-T of 8.89 kbar and 709 °C and reequilibration at 8.83 kbar and 704 °C.

Garnet amphibolite SP-153 also demonstrated the expected higher P-T values in core-core assemblages and lower P-T values in rim-adjacent pairings. The difference in P-T estimates can be attributed to minor compositional variation in garnet and plagioclase only. Both TIB and GARB thermometry record a maximum biotite temperature of 720 °C. HBPL thermometry estimates a higher temperature of 781-812 °C over the interval 5-10 kbar. TWQ's average peak P-T condition of 10.05 kbar and 781 °C agrees with HBPL values, while reequilibration is estimated at 8.39 kbar and 713 °C. Similar results, 1 kbar and 30 °C lower, were obtained from GAPQ-GRHB thermobarometry in TWQ. In GTB, two different thermometer-barometer pairs were used to eliminate anomalous results from reactions involving biotite. Peak conditions in GTB were obtained, using the GRIPS-HBPL thermobarometer, of 11.88 kbar and 815 °C. The GASP-GRHB thermobarometer in GTB was used to calculate reequilibration P-T conditions of 8.63 kbar and 662 °C.

TWQ Results Summary

Figure 37 plots the determined peak and reequilibration conditions calculated in TWQ for peak core-matrix and reequilibration rim-adjacent grain assemblages of SP-149 and SP-153. As previously discussed, the assemblage for SP-12 was selected

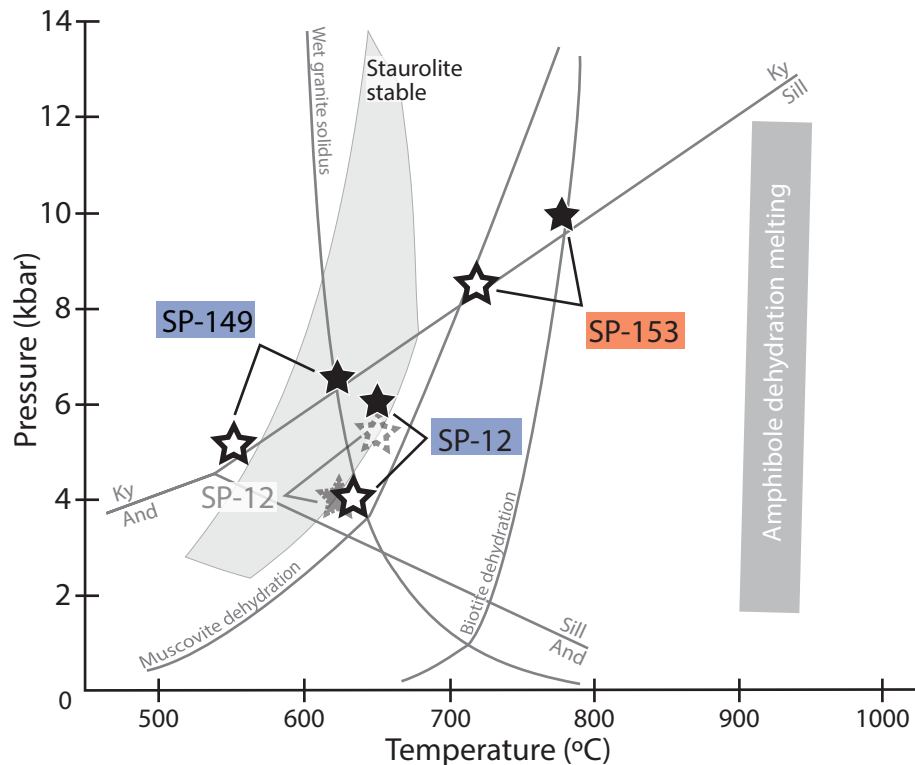


Figure 37: Summary of TWQ thermobarometry calculations for peak (solid star) and reequilibration (open star) assemblages of garnet-sillimanite schist SP-12, garnet-hornblende leucogneiss SP-149, and garnet amphibolite SP-153. P-T coordinates are calculated from intersections between GASP/GBPQ and GARB curves (SP-12) and between GAPQ and garnet-pargasite curves for SP-149 and SP-153. Grey stars for SP-12 indicate average P-T calculated for peak and reequilibrium assemblages that do not maximize equilibrium but are from the same sample subregion. Complete thermobarometric data is provided in appendix B. Positions of reaction curves: aluminosilicate fields from Pattison (1992); amphibole from Cheney et al. (2004) after Pattinson (2003); biotite dehydration from Le Breton and Thompson (1988); wet granite solidus from Luth (1976); muscovite dehydration from Spear et al. (1999); staurolite stability field from Spear et al. (1999) after Thompson and Connolly (1995).

from all available analyses to maximize equilibrium and thus does not preserve textural relations; however, results from textural assemblages are also presented. All samples plot at the kyanite-sillimanite boundary or below, in the sillimanite field. SP-153 traverses the biotite dehydration curve during decompressive cooling. SP-12 remains below the muscovite breakdown curve; however, the composition of the metapelite is sensitive to

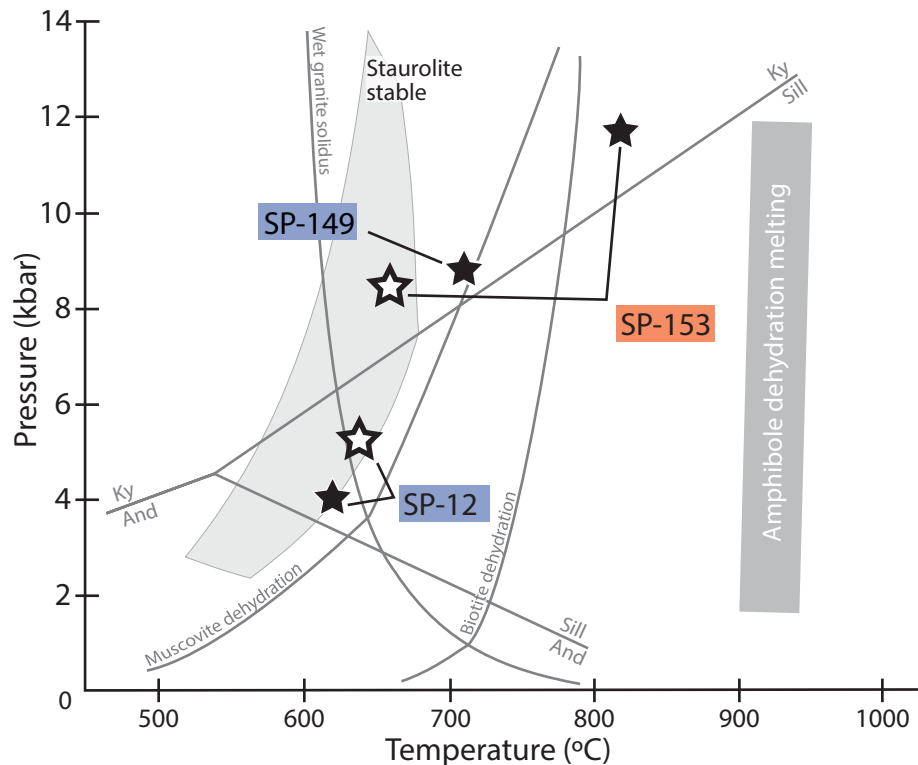


Figure 38: Summary of GTB thermobarometry calculations for peak (solid star) and reequilibration (open star) assemblages of garnet-sillimanite schist SP-12, garnet-hornblende leucogneiss SP-149, and garnet amphibolite SP-153. P-T calculations from GASP-GARB for SP-12, GRIPS-GRHB for SP-149, and GRIPS-HBPL for peak SP-153 and GAPQ-GRHB for reequilibration SP-12. Complete thermobarometric data is provided in appendix B. Positions of reaction curves: aluminosilicate fields from Pattison (1992); amphibole from Cheney et al. (2004) after Pattinson (2003); biotite dehydration from Le Breton and Thompson (1988); wet granite solidus from Luth (1976); muscovite dehydration from Spear et al. (1999); staurolite stability field from Spear et al. (1999) after Thompson and Connelly (1995).

changing P-T conditions throughout its evolution, during which retrogression may have obliterated the record of peak conditions. The results of TWQ's average P-T calculations broadly agree with individual reaction curves calculated separately and in GTB.

GTB Results Summary

Figure 38 contains the P-T conditions calculated for selected peak and

reequilibration assemblages of SP-12, SP-149, and SP-153. Garnet-sillimanite schist SP-12 records increasing pressures and temperatures from core-matrix to rim-adjacent mineral assemblages, possibly resulting from continuing Fe-Mg exchange after peak conditions. SP-149 records nearly constant P-T in the kyanite field. SP-153 records cooling and decompression from peak conditions near the onset of amphibolite dehydration melting, crossing the biotite dehydration curve. This P-T path segment follows a steeply adiabatic trajectory, similar to that of Alpine-style orogenies (Spear, 1993).

Thermobarometric Synthesis

The metabasites record simultaneous decompression and cooling from peak metamorphism in the upper amphibolite-lower granulite facies, where amphibole dehydration occurs. Thus, quantitative thermobarometry supports textural evidence for *in situ* melting of pargasitic amphibole to produce quartz-albitic plagioclase leucosome.

The complex mineralogy of the metapelite is reflected in possibly contradictory results. Regardless of prograde or retrograde direction, the rock experienced maximum upper amphibolite-facies conditions near initiation of biotite dehydration melting. The metapelite thus falls along the same P-T trajectory as the metabasites, recording the waning phase of regional metamorphism.

DISCUSSION

The results of this study demonstrate the protracted tectonic evolution of the Jerome Rocks Lakes (JRL) area, beginning with intrusion of a Mesoarchæan TTG suite and deposition of pelitic and quartz-rich sediments. Several, unresolved Archæan episodes of high-grade metamorphism and anatexis under locally variable fluid conditions followed, accompanied by penetrative progressive deformation. Preceding metamorphic events were overprinted and obscured by final granulite-facies metamorphism, of character similar to the late Palæoproterozoic Big Sky orogeny that has been identified in the Tobacco Root range by Harms et al. (2004). The tectonic evolution of the JRL area concluded with final exhumation during the Cretaceous Laramide orogeny.

To understand the metamorphic and tectonic processes that operated in the JRL, thermobarometric and structural results must be integrated with the widespread partial melting document. Therefore, a review of the major melt-producing metamorphic reactions operating in the mid- and lower crust is necessary.

Petrogenetic Processes

The nature of mid-crustal metamorphic processes is largely controlled by the relative abundance of aqueous fluids. Processes involving CO₂ rich fluids, such as charnockitization and CO₂-flushing (e.g. Janardhan et al., 1982), are not considered by this study. Generally, the conditions of the middle and lower continental crust fall in the amphibolite and granulite facies. This is easily demonstrated by schematically plotting

in P-T space the proposed Archæan and Phanerozoic geotherms over a generalized facies model, a diagram common in introductory petrology texts (e.g. Winter, 2010). Under these increasing P-T conditions, metamorphic reactions become partial melting reactions, particularly those involving the breakdown of hydrous phases. For brevity, three phases are considered here: muscovite, biotite, and a general amphibole. The breakdown of other hydrous phases such as chlorite and staurolite has been investigated (e.g. Thompson and Connolly, 1995) but are unlikely contributors to the peak metamorphic character of the Spanish Peaks. The terminology of partial melting used here follows the convention of Sawyer (2006), where neosome indicates the “new rock” formed through partial melting, divided into leucosome and residuum, where applicable. Palæosome refers to lithologies unaffected by partial melting.

Thompson (1983) and Powell (1983) were among the first to shift the dominant model of mid-crustal petrogenesis away from water-saturated conditions. Thompson (1983) found that preceding studies provided little evidence to substantiate the general assumption of a free volatile phase and proposed instead that, through iterative metamorphism, the bulk of middle and lower crust attained vapor-absent conditions. However, the likelihood of local increases in volatile concentration was not dismissed. Powell (1983) proposed that metamorphic processes in the granulite facies did not occur with input from an indefinite external reservoir of fluid. Melt-producing reactions were concluded to iteratively reduce the activity of water as well. Melt is defined, for the purposes of this study, as a silicate liquid phase containing quartz, plagioclase, and possibly K-feldspar, depending on the melt-producing reaction.

A simplified model developed by Clemens and Vielzeuf (1987) provided the first semi-quantitative estimates of melt production via dehydration of hydrous phases. Using model rock compositions with standardized amounts of muscovite, biotite, and amphiboles, the melt fraction resulting from complete breakdown of the hydrous phases under vapor-absent conditions was calculated. The results indicated that a biotite-rich (16 wt%) intermediate composition was the most fertile, yielding 50 vol% melt. However, a model two-mica schist and amphibole-rich mafite could produce similarly large volumes of melt. Muscovite melting was found to contribute very little volume. Amphibole breakdown, producing a large volume of melt, required temperatures exceeding 900 °C. Under crustal conditions, the vapor-absent breakdown of biotite was thus considered the most significant process for melt production and biotite-rich rocks the most fertile. These results also demonstrated that vapor-absent melting could, in fact, contribute extensively to crustal modification and differentiation.

However, the compelling case for bulk vapor-absent conditions in the middle and lower continental crust also must be reconciled with the water contents of silicic liquids. Estimation of water contents in silicic eruptive and plutonic rocks by Whitney (1988) indicated 2-4 wt% water; however, the 0.1% pore space of high-grade metamorphic rocks can contain a maximum of only 0.3 wt% water (Winter, 2010). Any model for widespread vapor-present melting of the crust must include a mechanism for the introduction and transport of fluids, such as the pumping and cycling of fluid through shear zones to rework large volumes of rock (Mogk, 1992).

A number of different partial melting reactions have been identified to operate

Selected vapor-present and dehydration melting reactions

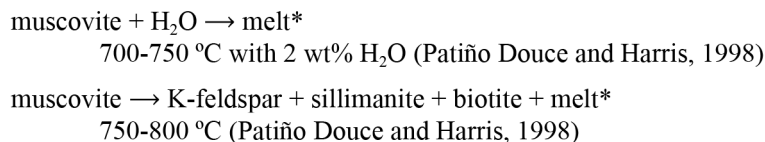
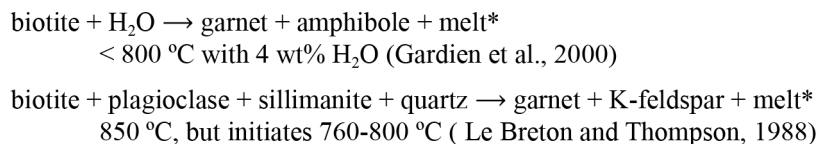
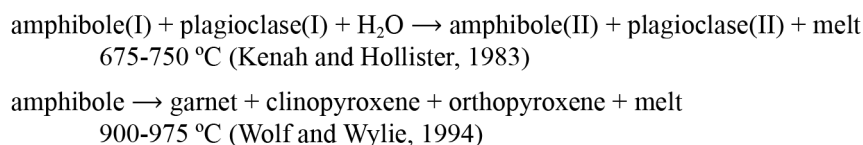
Muscovite**Biotite****Amphibole**

Table 18: Vapor-present and dehydration reactions selected from experimental studies on natural materials with measured temperatures of melting. Asterisk indicates K feldspar-containing melts.

under mid-crustal P-T conditions, depending on the hydrous phases involved and the presence of water. Vapor-absent melting of hydrous phases generally is recognized by the prograde growth of anhydrous phases, while vapor-present melting reaction is recognized by the prograde growth of hydrous phases. Table 18 provides a summary of representative partial melting reactions, illustrating the general differences between vapor-present and vapor-absent melting: namely, temperature of reaction and composition of the residuum.

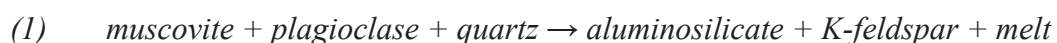
Partial Melting in the JRL

All rocks present in the JRL have undergone a significant and variable amount of partial melting; protolith composition and activity of water determines the anatectic

reaction that occurred at peak conditions. Metasedimentary protolith compositions are inferred to include arkosic sand, argillaceous psammites, and mudstones (pelites). Amphibolites and garnet amphibolites are inferred to represent metamorphosed metabasites. The protolith of the grey gneisses around the JRL and Lake Solitude is a high-Al trondhjemite with zircon crystallization ages of ca. 3030 Ma (Weyand, 1989).

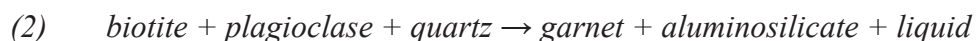
The observed gradient in anatectic degree, increasing upslope to the headwall, affects both garnet amphibolites and metasedimentary schists. This pattern is not reciprocated in the trondhjemitic gneisses. The amount of partial melting in the garnet amphibolite ranges from incipient, producing a salt-and-pepper matrix with mm-size garnets, to extensive, producing a monomineralic hornblende melanosome with cm-size garnets and wispy leucosome such as that seen in photograph C of Figure 17. A similar range of textures is observed in the metapelitic units; however, the least migmatized units still manifest well-developed granitic leucosomes. Foliation in the most migmatized units is barely preserved, resulting in diatexites with biotite schlieren. Concordant injections of garnet-bearing K-feldspar leucosome up to a meter thick are also observed to intrude the garnet amphibolites. Thus, field observations from the JRL support the conclusion of Clemens and Vielzeuf (1987), among others, that metapelites produce a significant volume of melt. The complete breakdown of muscovite and biotite, yielding 50% melt in the model of Clemens and Vielzeuf (1987), would easily exceed the rheologically critical melt percentage. This value, typically estimated as ca. 20% (Azri, 1978), is a hypothetical minimum amount of melt that must be generated in order for the melt to escape its source and become a magma.

Initial burial of the JRL rocks to peak pressures in the kyanite field is inferred from the presence of staurolite inclusions in kyanite grains in the metaquartzite unit. Only minor muscovite is observed in the metasedimentary lithologies and is interpreted as secondary. During burial, early muscovite dehydration is inferred to have occurred according to the general reaction after Thompson (1983):



The model of Clemens and Vielzeuf (1987) predicts only a small volume of melt (ca. 5 vol%) would be generated from the vapor-absent breakdown of muscovite in a hypothetical pelitic composition containing 10 wt% muscovite. This small volume of relatively low T melt is not expected to have migrated, remaining *in situ* until the rheologically critical melt percentage was exceeded during biotite dehydration melting. Free water produced by the breakdown of muscovite would dissolve in the unsegregated melt.

Along the same prograde path at increased P and T, the breakdown of biotite is inferred to have produced a large volume of melt in the metapelites. A generalized reaction for the production of garnet, sillimanite, and a granitic liquid from breakdown of biotite is:



Clemens and Vielzeuf (1987) calculated the production of 20-30 vol% melt from a two-mica pelite containing 20 wt% biotite. The requisite vapor-absent complete breakdown of biotite is expected to occur at ca. 850 °C and 10 kbar (Le Breton and Thompson, 1988). The low peak temperature of 640 °C obtained from thermobarometry

of metapelite SP-12 may reflect waning metamorphic conditions after breakdown of biotite, which recrossed the biotite stability field. Perplexingly, the occurrence of a different, tschermakitic amphibole composition in melanocratic layers of metapelite may represent the residuum of early, prograde vapor-present biotite breakdown. These disparate lines of evidence are difficult to resolve in a single estimate for the conditions of biotite breakdown.

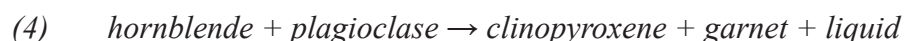
Peak metamorphic conditions likely culminated in the breakdown of hornblende. The absence of pyroxene from the peak assemblage of the garnet amphibolites indicates that hornblende breakdown occurred in two stages: initial dehydration reactions produced garnet amphibolites and were followed by continued breakdown of the garnet amphibolites via vapor-absent melting. This incongruent vapor-absent melting of hornblende produced a plagioclase-quartz melt with a garnet residuum via the general reaction:



Clemens and Vielzeuf (1987) estimate the production of 30-40 vol% melt from the complete vapor-absent breakdown of a model basite containing 80 wt% amphibole. However, this requires temperatures in excess of 900 °C. Microtextural evidence indicates only incipient breakdown of pargasitic amphibolite. The lower degree of anatexis produced *in situ* melts only, which are observed as quartz-plagioclase augen.

The mineralogy of clinopyroxene-garnet-plagioclase-hornblende lenses in the quartzofeldspathic gneisses is diagnostic of transitional granulites. Two modes of clinopyroxene, relict porphyroclasts and matrix neoblasts, indicates metamorphism

after intrusion and crystallization of a mafic protolith. Hornblende surrounding the clinopyroxene porphyroclasts was formed via subsolidus hydration. Subsequent metamorphism produced garnet coronæ around the hornblende and clinopyroxene neoblasts in the matrix. A general reaction for the dehydration of hornblende in the presence of quartz and plagioclase is:



The reaction discussed by Pattison (2003) also requires the involvement of quartz and produces vapor at subsolidus conditions. Small lenses of quartz-plagioclase observed in thin section to embay hornblende suggest that this reaction occurred above the solidus, producing small amounts of a silicate melt rather than a mobile volatile phase. Subsequent ductile deformation is recorded in grain-size reduction of the granulite at the gneiss-granulite contact. Additionally, Pattison (2003)'s comparison of experimental and natural data found that this transitional assemblage could develop at conditions in the amphibolite facies when stabilized by iron-rich mineral compositions, grossular-rich garnet, anorthite-rich plagioclase, and low titanium content in hornblende. Geochemical and thermobarometric investigation would provide quantitative constraints for the peak metamorphic conditions experienced by these enclaves and likely clarify the complicated evolution of the surrounding trondhjemitic gneisses. However, it can be inferred that the vapor-absent peak conditions, which resulted in the clinopyroxene-garnet-melt assemblage, were likely widespread in the surrounding gneisses as well.

The mean estimates from thermobarometry of JRL samples show lower temperatures than accepted standard conditions for vapor-absent melting of major

hydrous phases. For example, metapelite SP-12, which lacks primary muscovite, records peak conditions of 5-6 kbar and 640 °C, close to standard estimates of muscovite dehydration melting at 5 kbar and 665 °C. However, there is also substantial textural evidence for biotite breakdown in this sample, which under similar vapor-absent conditions would initiate at 850 °C. The peak conditions recorded by garnet amphibolite SP-153 reach ca. 10 kbar and 800 °C, below the 920 °C required for vapor-absent breakdown of amphiboles at 10 kbar.

Petrographic and field observations suggest that locally vapor-present melting did occur in the quartzofeldspathic gneisses immediately adjacent to garnet amphibolite units. Coarse peritectic hornblende was observed to form in association with K-feldspar-plagioclase-quartz leucosomes. The stabilization of hornblende resulting from the breakdown of biotite or another amphibole requires the presence of a mobile aqueous phase. The source for such a vapor phase may have been the subsolidus dehydration of adjacent metabasites; however, the absence of clinopyroxene indicates the suprasolidus breakdown of hornblende.

Mogk (1992) concluded that quartzofeldspathic gneisses in Gallatin Canyon, east of the JRL, were extensively migmatized via vapor-present incongruent breakdown of biotite, producing hornblende-rich melanosomes and granitic leucosomes. Channeling and cycling of water-rich fluids through shear zones is suggested as a potential mechanism for migmatizing a large volume of crust with a small total volume of fluid.

In the JRL, mobilization of early melt may have led to a feedback loop, generating additional melt via vapor-absent reactions that then coalesced into larger bodies, altering

the rheological properties of the diminishing palæosome. Further aggregation of melt would facilitate the localization of strain into weaker areas. Thus, while vapor-absent conditions may dominate in the mid-crust, deformation may be largely accommodated along weaker zones formed by vapor-present melting.

Deep burial of JRL metasedimentary lithologies resulted in widespread partial melting, producing a large volume of granitic liquid with the potential to escape the system. However, the granitic melts appear to have remained *in situ*, migrating on meter-scales only. Locally water-fluxed melting of the surrounding quartzofeldspathic gneisses accompanied the prograde path. Continued heating in the mid-crust led to incipient melting of metabasites and production of a small volume of trondhjemitic-tonalitic liquid. While the melting of biotite-rich rocks to produce granitic magma appears to be a viable mechanism for local melting, these melts are produced close to the granite minimum solidus and, thus, have little potential for migrating outside the system (Mogk, 1992). The vapor-absent breakdown of hornblende also does not seem a likely process for large-scale crustal differentiation, at least at the depths recorded in the JRL metabasites. Additional heat flux, possibly from a mantle source, seems to be necessary for generation of appropriately high temperatures to produce larger melt fractions.

Structure of the JRL

Bedrock mapping reveals substantially more complex spatial relations between individual lithologic units than previously documented by Kellogg and Williams (2000). Metapelitic schist and metatexite layers 1-10 m thick are intimately interleaved with

metatextitic garnet amphibolites of similar dimensions, with each outcrop manifesting varying scales of deformation and degrees of anatexis and melt segregation. These metasedimentary units abruptly terminate to the northwest and southeast against volumetrically dominant quartzofeldspathic (trondhjemitic) gneisses, which contain meter-scale enclaves of transitional granulite and minor amphibolite. This association of TTG-derived gneiss and mafic granulite is a fine-scale manifestation of typical Mesoarchæan bimodal TTG-amphibolite suites, which conspicuously lack rocks of intermediate composition, indicating two processes of magma generation (Barker and Arth, 1976). Examples are found globally, including throughout the West Greenland craton (Polat et al., 2009) and the Limpopo Belt (Smit and Van Reenen, 2014). In the Sweetwater province of the Wyoming craton, such associations are common and interpreted in the context of a long-lived active southern cratonic margin (Chamberlain et al., 2003). Contacts between individual units do not elucidate original depositional or intrusive relationships between lithologies. Widespread shearing and grain-size reduction at contacts indicates that deformation during the last high-grade metamorphic event affected the entire JRL area.

A steeply-dipping northeast regional foliation is axial planar with plunging, reclined intrafolial isoclinal folds measured in all units. Lineation data indicate that fold hinges in all lithologies are distributed within the mean foliation plane. Mineral and stretching lineations are oblique or subparallel to dip direction. Folding is concentrated in the metapelites and quartzofeldspathic gneisses, a manifestation of rheological contrasts between layers. Late quartz pegmatites crosscut all structures. While Spencer and Kozak

(1975) interpreted the regional foliation and isoclinal folds to represent two separate deformation events, they are more likely produced by a single, progressive deformation event at elevated P-T conditions, as suggested by Salt (1987).

The D2 event of Kellogg and Mogk (2009), which refolded earlier isoclinal folds near the Crooked Creek shear zone, does not appear to manifest in the JRL. Later deformation in the JRL is inferred from the observation of at least one north-south trending outcrop scale open fold, which refolded foliation and F1 isoclinal folds. Elsewhere in the Spanish Peaks, broad, open folds shallowly plunging to the north have been documented to refold regional foliation and earlier fold generations (Kellogg and Mogk, 2009; Spencer and Kozak, 1975).

Regional Tectonics

The presence of relict kyanite in multiple metasedimentary lithologies of the JRL requires early high-pressure conditions to stabilize this aluminosilicate polymorph. Presence of early kyanite and staurolite in the Gallatin Peak terrane was interpreted by Salt (1987) as evidence for a prograde metamorphic path through moderate (staurolite-grade) conditions. Early, higher-temperature conditions above the stability of staurolite for the JRL terrane were thus inferred from its observed absence. However, Salt (1987) did not map the metaquartzite with staurolite-included kyanite described in this study and concluded that the two terranes differed in their early metamorphic history.

The identification of staurolite inclusions in kyanite from the JRL thus suggests that the two terranes may not have differed greatly in their early metamorphic history.

Additionally, the preservation of a phase with a limited stability field as an inclusion in the high-pressure aluminosilicate polymorph permits a simple calculation of the maximum geothermal gradient experienced during prograde metamorphism. The intersection of the andalusite-kyanite polymorphic transition curve and the staurolite-out reaction occurs at ca. 7.5 kbar and 625 °C, which corresponds to ca. 25 km depth and a maximum linear geotherm of 24 °C/km. However, such a calculation neglects the thermal delay commonly observed in P-T-t paths of Alpine orogenies, arising from burial rates in excess of the adiabat during prograde metamorphism (Spear, 1993). Therefore, this estimation must be considered in concert with physical evidence: the presence of kyanite. The existence of stable, cool, and thick continental crust with modern thicknesses is inferred from early, prograde growth of the high-pressure aluminosilicate polymorph and a probable shallow geotherm similar to documented Proterozoic-Phanerozoic values.

Peak temperatures were attained in the sillimanite field, after the high-pressure growth of kyanite. Sillimanite records the isobaric or slightly decompressive heating of the buried metasedimentary units to peak temperatures after peak pressures were attained. Peak conditions of 5-6 kbar and ca. 630 °C, in the mid-amphibolite facies, are calculated, followed by decompressive cooling through ca. 4 kbar and 615 °C, in the upper greenschist facies.

The bulk composition of the metabasites is relatively robust to the many pressure-temperature steps experienced; however, substantial uncertainty in the amphibolite activity models used in quantitative thermobarometry results in significantly scattered P-T estimates. The shape of the prograde path is not preserved in relict early phases,

but is inferred as identical to that of the metasedimentary units, with peak temperatures occurring after peak pressure was reached. Peak conditions of ca. 10 kbar and 800 °C are in excess of the amphibolite facies conditions of 7-8 kbar and ca. 750 °C reported by Salt (1987). Waning conditions passed through ca 8.5 kbar and 660 °C. The reequilibration conditions are similar to the peak temperatures in the metapelites but are 2.5 kbar higher. Growth of biotite likely occurred during decompression as conditions returned to biotite's stability field, further suggested by the measured uniform biotite composition. The slope of the retrograde path matches that calculated for the metasedimentary lithologies.

The P-T-D path for the JRL area is inferred to follow a clockwise trajectory in three general stages, based on the combination of thermobarometric constraints with structural observations (Figure 39). Peak pressure is attained during rapid burial to mid-crustal depths along a steep Alpine-type path, accompanied by formation of early isoclinal folds and subsequent rotation of folds into the developing regional foliation S1 during deformation event D1. F1 folds were produced during the latter part of D1, resulting in the isoclinal folds observed in the diatexites. Peak pressure is followed by isobaric to slightly decompressive heating towards peak temperature, which outlasts the deformation of D1 and results in undeformed leucosomes in the garnet amphibolites. Retrogression follows a steeply adiabatic path. This geometry is typical of P-T histories in continent-continent collisions (Spear, 1993).

The timing of this metamorphic event can be constrained through comparison with previous studies. Recent thermochronologic investigations in the Spanish Peaks (e.g. Ault et al., 2012; Condit et al., 2013a) call into question the accuracy of a proposed

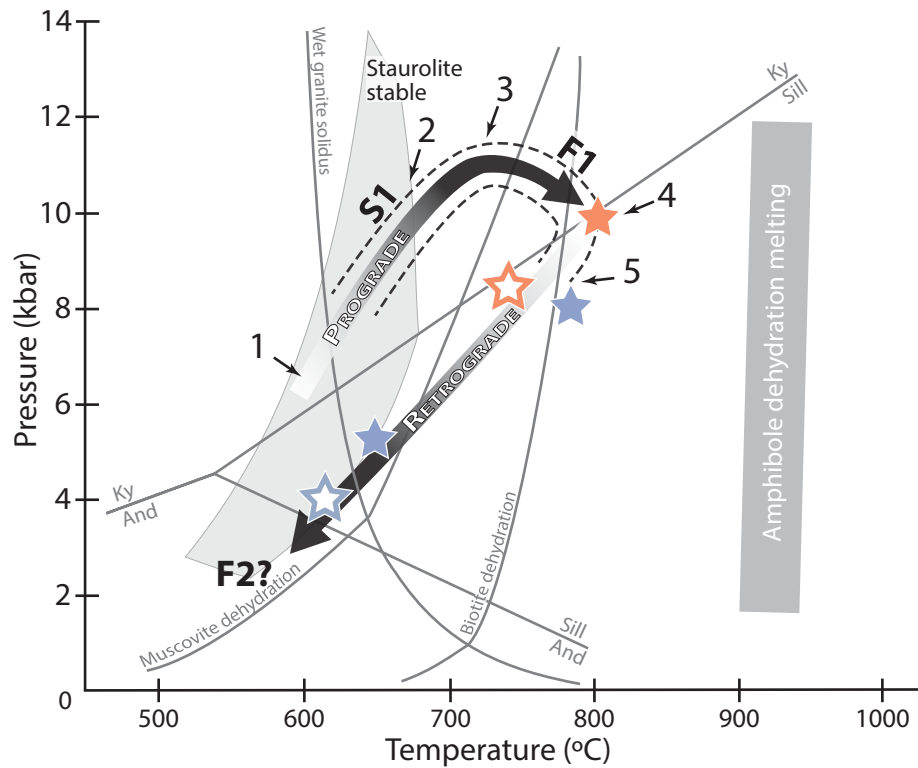


Figure 39: P-T-D trajectory of the JRL area, based on petrologic and thermobarometric data from garnet amphibolite and metapelitic samples. Prograde and retrograde metamorphic trajectories and their direction are indicated by large arrows. The relative timing of D1 along the prograde metamorphic path is indicated by dashed lines, where progressive ductile strain results in regional foliation S1 and isoclinal folds F1. Results from quantitative thermobarometry are indicated by filled stars (core-matrix pairings) and outlined stars (rim-adjacent pairings). Numbered points indicate petrologic constraints for metamorphic trajectory: 1, early high pressure indicated by growth of kyanite; 2, inclusions of staurolite in kyanite; 3, peak pressure attained; 4, peak temperature attained; 5, undeformed leucosomes in garnet amphibolites, indicating cessation of ductile shearing associated with D1. Positions of reaction curves: aluminosilicate fields from Pattison (1992); amphibole from Cheney et al. (2004) after Pattinson (2003); biotite dehydration from Le Breton and Thompson (1988); wet granite solidus from Luth (1976); muscovite dehydration from Spear et al. (1999); staurolite stability field from Spear et al. (1999) after Thompson and Connolly (1995).

cessation of thermal activity after ca. 2700 Ma, as advocated by Weyand (1989) on the basis of sphene closure at an assumed temperature of 450 °C.

The peak conditions recorded in the amphibolitic rocks of the JRL may be

correlative with granulite facies metamorphism reported in the northern Spanish Peaks at 1753 Ma (Ault et al., 2012). If the amphibolite facies conditions obtained from thermobarometry of metapelite SP-12 reflect subsequent near-isothermal cooling through ca. 4 kbar and 615 °C, this regional event may be correlative with the Big Sky orogeny, which attains peak conditions in the Tobacco Root Range of 11–12 kbar and 750–800 °C. A lower metamorphic grade would be consistent with the inboard location of the Madison Range with respect to the colliding continental block and a subsequent regional cessation of thermotectonic activity. The observed paucity of retrograde textures and phases (e.g. chlorite, sericite) suggests that final exhumation was rapid. Preservation of corona and symplectite textures in undeformed metamorphosed dykes of the Gallatin Peak terrane were interpreted by Salt (1987) to indicate lack of reequilibration due to rapid uplift.

The metamorphic character of the Jerome Rock Lakes area is congruent with evidence for Palæoproterozoic tectonism documented elsewhere in the Spanish Peaks and throughout the Montana metasedimentary terrane (MMT). As in the Tobacco Root Range, probable preceding episodes of metamorphism in the JRL are likely also obscured by the last granulite facies event. The conditions recorded indicate a similar style to the Big Sky orogeny, produced in a continent-continent collisional environment.

The collage of subcratonic blocks, separated by numerous ductile shear zones, that form the northern Madison Range indicates the complex nature of Archæan cratonic boundaries. The results of mapping, petrology, and geochronology continue to constrain the occurrence and timing of metamorphic, magmatic, and deformation events in the MMT, refining the 3.5 Ga and possibly longer history of the Wyoming Province.

CONCLUSIONS

The Jerome Rock Lakes (JRL) area has experienced a protracted history, from deposition of sediments to high grade metamorphism, ductile deformation, and partial melting. Bedrock mapping reveals the intensively interleaving of individual metasedimentary and garnet amphibolite units at a significantly finer scale than previously reported. Analysis of structural features reveals a main deformation event D1 that occurred during northwest-southeast directed shortening, which produced a regional foliation and coplanar isoclinal folds. A much later episode D2 is identified by the presence of large open cross folds.

A shallow geotherm is inferred from inclusions of staurolite in kyanite-bearing metaquartzite, preserved during prograde metamorphism. The widespread occurrence of kyanite in the metasedimentary units of the JRL area also indicates that these units were buried to depths in excess of 20 km.

Four melting-producing reactions are proposed for the JRL area. In the metasedimentary units, early muscovite dehydration is inferred, followed by widespread biotite dehydration melting, which produced a substantial volume of deformed K-feldspar leucosome. Throughout the metabasitic garnet amphibolites, incipient hornblende dehydration occurred at peak conditions, generating minor undeformed plagioclase leucosomes. Hornblende dehydration also occurred in mafic enclaves within the quartzofeldspathic gneisses, producing minor plagioclase leucosomes and clinopyroxene. Localized vapor-present breakdown of biotite occurred in the quartzofeldspathic gneisses, producing small K-feldspar leucosomes.

The main tectonic event that was responsible for the observed metamorphic and structural character of the JRL attained peak pressures of 10 kbar, accompanied by extensive ductile deformation. Continued heating after the cessation of deformation attained peak temperatures of 780-815 °C, which are substantially lower than those expected from the vapor-absent melting reactions observed. Waning from peak conditions in the granulite facies followed a steeply adiabatic to isothermal decompressive path and is inferred to have occurred rapidly, based on the absence of retrograde textures. The clockwise trajectory of the P-T path indicates a continental collision, similar to that occurring in the Himalayas today.

This metamorphic overprint resembles the Big Sky orogeny (Harms et al., 2004), seen in the Tobacco Root Mountains to the north. The consensus of metamorphic conditions between this study and other recent investigations in the Madison Range suggests that a widespread high-grade event affected the entire area at ca. 1.7 Ga. Thus, it is likely that the Big Sky orogeny also affected the rocks of the Madison Range.

Further investigation of the JRL area would benefit from additional thermobarometry to resolve the discrepancy between the metamorphic conditions implied by the observed, dominantly vapor-absent melting reactions and those calculated by quantitative thermobarometric methods. Geochronology of igneous and detrital zircons would provide protolith ages, clarifying the relationships between individual lithologies, while geochronology of metamorphic minerals would quantitatively constrain the timing of deformation and metamorphism in the JRL, possibly confirming a Palæoproterozoic age for the last major orogenic event.

REFERENCES CITED

- Allmendinger, R.W., Cardozo, N., Fisher, D.W., 2012, Structural geology algorithms: Vectors and tensors: New York, Cambridge University Press, 302 p.
- Aranovich, L.Y., and Berman, R.G., 1996, Optimized standard state and solution properties of minerals: Part II. Comparisons, predictions, and applications: Contributions to Mineralogy and Petrology, v. 126, p. 25-37.
- Arzi, A.A., 1978, Critical phenomena in the rheology of partially melted rocks: Tectonophysics, v. 44, p. 173-184.
- Ault, A.K., Flowers, R.M., Mahan, K.H., 2012, Quartz shielding of a sub-10 micrometer zircons from radiation damage-enhanced Pb-loss: An example from a metamorphosed mafic dike, northwestern Wyoming craton: Earth and Planetary Science Letters, v. 339-340, p. 57-66.
- Auzanneau, E., Vielzuef, D., Schmidt, M.W., 2006, Experimental evidence of decompression melting during exhumation of subducted continental crust: Contributions to Mineralogy and Petrology, v. 152, p. 125-148.
- Barker, F., Arth, J.G., 1976, Generation of trondhjemitic-tonalitic liquids and Archean bimodal trondhjemite-basalt suites: Journal of Geology, v. 4., p. 596-600.
- Barth, T.F., 1951, The feldspar geologic thermometer: Neues Jahrbuch für Mineralogie, v. 82, p. 143-154.
- Benisek, A., Kroll, H., Cemic, L., 2004, New developments in two-feldspar thermometry: American Mineralogist, v. 89, p. 1496-1504.
- Berman, R.G., 2007, winTWQ (version 2.3): a software package for performing internally-consistent thermobarometric calculations: Geological Survey of Canada, Open File 5462, [https:// http://geogatis.gc.ca/api/en/nrcan-rncan/ess-sst/259c8635-73bc-5fb2-8ced-6346bf9eb899.html](https://http://geogatis.gc.ca/api/en/nrcan-rncan/ess-sst/259c8635-73bc-5fb2-8ced-6346bf9eb899.html) (accessed November 20, 2014).
- Berman, R.G., 1991, Thermobarometry using multi-equilibrium calculations: A new technique, with petrological applications: Canadian Mineralogist, v. 29, p. 833-855.
- Berman, R.G., 1990, Mixing properties of Ca-Mg-Fe-Mn garnets: American Mineralogist, v. 75, p. 328-344.
- Berman, R.G., 1988, Internally-consistent thermodynamic data for minerals in the system $\text{Na}_2\text{O}-\text{H}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{H}_2\text{O}-\text{CO}_2$: Journal of Petrology, v. 29, p. 445-522.

- Berman, R.G., Aranovich, L.Y., Rancourt, D.G., and Mercier, P.H.J., 2007, Reversed phase equilibrium constraints on the stability of Mg-Fe-Al biotite: *American Mineralogist*, v. 92, p. 139-150.
- Berman, R.G., and Aranovich, L.Y., 1996, Optimized standard state and solution properties of minerals: Part I. Model calibration for olivine, orthopyroxene, cordierite, garnet, and ilmenite in the system FeO-MgO-CaO-Al₂O₃-TiO₂-SiO₂: *Contributions to Mineralogy and Petrology*, v. 126, p. 1-24.
- Bhattacharya, A., Mohanty, L., Maji, A., Sen, S.K., and Raith, M., 1992, Non-ideal mixing in the phlogopite-annite binary: constraints from experimental data on Mg-Fe partitioning and a reformulation of the biotite-garnet geothermometer: *Contributions to Mineralogy and Petrology*, v. 111, p. 87-93.
- Blundy, J.D., and Holland, T.J.B., 1990, Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer: *Contributions to Mineralogy and Petrology*, v. 104, p. 208-224.
- Bohlen, S.R., and Liotta, J.J., 1986, A barometer for garnet amphibolites and garnet granulites: *Journal of Petrology*, v. 27, p. 1025-1034.
- Bohlen, S.R., Wall, V.J., and Boettcher, A.L., 1983, Experimental investigations and geological applications of equilibria in the system FeO-TiO₂-Al₂O₃-SiO₂-H₂O: *American Mineralogist*, v. 68, p. 1049-1058.
- Bohlen, S.R., Peacor, D.R., Essene, E.J., 1980, Crystal chemistry of a metamorphic biotite and its significance in water barometry: *American Mineralogist*, v. 65, p. 55-62.
- Burger, H.R., 2004, General geology and tectonic setting of the Tobacco Root Mountains, in Brady, J.B., Burger, H.R., Cheney, J.T., and Harms, T.A., eds., *Precambrian geology of the Tobacco Root Mountains, Montana*, v. 377: Boulder, Colorado, Geological Society of America, p. 1-14.
- Cardozo, N., and Allmendinger, R.W., 2013, Spherical projections with OSXStereonet: *Computers and Geosciences*, v. 51, p. 193-205.
- Chamberlain, K.R., Frost, C.D., and Frost, B.R., 2003, Early Archean to Mesoproterozoic evolution of the Wyoming Province: Archean origins to modern lithospheric structure: *Canadian Journal of Earth Science*, v. 40, p. 1357-1374.
- Cheney, J.T., Webb, A.A.G., Coath, C.D., and McKeegan, K.D., 2004, In situ ion microprobe ²⁰⁷Pb/²⁰⁶Pb dating of monazite from Precambrian metamorphic suites,

- Tobacco Root Mountains, Montana, in Brady, J.B., Burger, H.R., Cheney, J.T., and Harms, T.A., eds., *Precambrian geology of the Tobacco Root Mountains, Montana*, Geological Society of America Special Publications, v. 377: Geological Society of America, p. 151-179.
- Clemens, J.D., and Vielzeuf, D., 1987, Constraints on melting and magma production in the crust: *Earth and Planetary Science Letters*, v. 86, p. 287-306.
- Condit, C.B., Mahan, K.H., Ault, A.K., Flowers, R.M., Johnson, J.E., 2013a, New petrologic and geochronological constraints on Paleoproterozoic tectonometamorphism along the NW margin of the Wyoming craton, M. Madison Range, SW Montana: *Geological Society of America Abstracts with Programs*, v. 45, no. 5, p. 37.
- Condit, C.B., Mahan, K.H., Ault, A.K., Flowers, R.M., 2013b, New evidence for an exhumed crustal section from the Paleoproterozoic Big Sky orogeny, N. Madison Range, SW Montana: *Geological Society of America Abstracts with Programs*, v. 45, no. 7, p. 310.
- Dasgupta, S., Sengupta, P., Guha, D., and Fukuoka, M., 1991, A refined garnet-biotite Fe-Mg exchange thermometer and its application in amphibolites and granulites: *Contributions to Mineralogy and Petrology*, v. 109, p. 130-137.
- Elkins, L.T., and Grove, T.L., 1990, Ternary feldspar experiments and thermodynamic models: *American Mineralogist*, v. 75, p. 544-559.
- Erslev, E.A., and Sutter, J.F., 1990, Evidence for Proterozoic mylonitization in the northwestern Wyoming province: *Geological Society of America Bulletin*, v. 102, p. 1681-1694.
- Ferry, J.M., and Spear, F.S., 1978, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet: *Contributions to Mineralogy and Petrology*, v. 66, p. 113-117.
- Foster, D.A., Mueller, P.A., Mogk, D.W., Wooden, J.L., and Vogl, J.J., 2006, Proterozoic evolution of the western margin of the Wyoming craton: Implications for the tectonic and magmatic evolution of the northern Rocky Mountains: *Canadian Journal of Earth Sciences*, v. 43, p. 1601-1619.
- Fuhrman, M.L., and Lindsley, D.H., 1988, Ternary feldspar modeling and thermometry: *American Mineralogist*, v. 73, p. 201-215.
- Ganguly, J., and Saxena, S.K., 1984, Mixing properties of aluminosilicate garnets:

Constraints from natural and experimental data and applications to geothermobarometry: *American Mineralogist*, v. 69, p. 88-97.

Gardien, V., Thompson, A.B., Ulmer, P., 2000, Melting of biotite+plagioclase+quartz gneisses: The role of H₂O in the stability of amphibole: *Journal of Petrology*, v. 41, p. 651-666.

Giletti, B.J., 1966, Isotopic ages from southwestern Montana: *Journal of Geophysical Research*, v.71, p. 4029-4036.

Giletti, B.J., 1971, Discordant isotopic ages and excess argon in biotites: *Earth and Planetary Science Letters*, v. 10, p. 157-164.

Gerke, T.L., and Kilinc, A.I., 1992, Enrichment of SiO₂ in rhyolites by fractional crystallization: An experimental study of peraluminous granitic rocks from the St. Francois Mountains, Missouri, USA: *Lithos*, v. 29, p. 273-283.

Gessman, C.K., Spiering, B., Raith, M., 1997, Experimental study of the Fe-Mg exchange between garnet and biotite: Constraints on the mixing behavior and analysis of the cation-exchange mechanism: *American Mineralogist*, v. 82, p. 1225-1240.

Ghent, E.D., 1976, Plagioclase-garnet-Al₂SiO₅-quartz: A potential geobarometer-thermometer: *American Mineralogist*, v. 61, p.71-714.

Graham, C.M., and Powell, R., 1984, A garnet-hornblende geothermometer: Calibration, testing, and application to the Pelona Schist, southern California: *Journal of Metamorphic Geology*, v. 2, p. 13-31.

Hammarstrom, J.H., Zen, E-A, 1986, Aluminum in hornblende: An empirical igneous geobarometer: *American Mineralogist*, v. 71, p. 1297-1313.

Harms, T.A., Burger, H.R., Blednick, D.G., Cooper, J.M., King, J.T., Owen, D.R., Lowell, J., Sincock, M.J., Kranenburg, S.R., Pufall, A., and Picornell, C.M., 2004, Character and origin of Precambrian fabrics and structures in the Tobacco Root Mountains, Montana, in Brady, J.B., Burger, H.R., Cheney, J.T., and Harms, T.A., eds., *Precambrian geology of the Tobacco Root Mountains, Montana*, Geological Society of America Special Publications, v. 377: Geological Society of America, p. 203-226.

Harrower, M., and Brewer, C.A., 2011, Colorbrewer.org: An online resource for selecting colour schemes for maps, in Dodge, M., Kitchin, R., Perkins, C., eds., *The Map Reader: Theories of mapping practice and cartographic representation*, Chichester, John Wiley and Sons, 503p.

- Hawthorne, F.C., and Oberti, R., 2007, Classification of the amphiboles: Reviews in Mineralogy and Geochemistry, v. 67, p. 55-88.
- Henry, D.J., Guidotti, C.V., Thomson, J.A., 2005, The Ti-saturation surface for low-to-medium pressure metapelitic biotites: implications for geothermometry and Ti-substitution mechanisms: American Mineralogist, v. 90, p. 316-328.
- Hodges, K.V., and Crowley, P.D., 1985, Error estimation and empirical geothermobarometry for pelitic systems: American Mineralogist, v. 70, p. 702-709.
- Hodges, K.V., and Spear, F.S., 1982, Geothermometry, geobarometry, and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire: American Mineralogist, v. 67, p. 1118-1134.
- Hoisch, T.D., 1990, Empirical calibration of six geobarometers for the mineral assemblage quartz+muscovite+biotite+plagioclase+garnet: Contributions to Mineralogy and Petrology, v. 104, p. 225-234.
- Holdaway, M.J., and Lee, S. M., 1977, Fe-Mg cordierite stability in high-grade pelitic rocks based on experimental, theoretical, and natural observations: Contributions to Mineralogy and Petrology, v. 63, p. 175-198.
- Holdaway, M.J., 2000, Application of new experimental and garnet Margules data to the garnet-biotite geothermometer: American Mineralogist, v. 85, p. 881-892.
- Holland, T.J.B., and Blundy, J.D., 1994, Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry: Contributions to Mineralogy and Petrology, v. 116, p. 433-447.
- Holland, T.J., and Powell, 1998, An internally consistent thermodynamic data set for phases of petrological interest: Journal of Metamorphic Geology, v. 16, p. 309-343.
- Hollister, L.S., Grissom, G.C., Peters, E.K., Stowell, H.H., Sisson, V.B., 1987, Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons: American Mineralogist, v. 72, p. 231-239.
- Indares, A., Martignole, J., 1985, Biotite-garnet geothermometry in granulite-facies rocks: The influence of Ti and Al in biotite: American Mineralogist, v. 70, p. 272-278.
- Janardhan, A.S., Newton, R.C., Hansen, E.C., 1982, The transformation of amphibolite

- facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India: *Contributions to Mineralogy and Petrology*, v. 79, p. 130-149.
- Johnson, M.C., Rutherford, M.J., 1989, Experimental calibration of the aluminum-in-hornblende geobarometer with application to Long Valley caldera (California) volcanic rocks: *Geology*, v. 17, p. 837-841.
- Johnson, J.W., West, D.O., Condit, C.B., Mahan, K.H., 2014, Strain localization in the Spanish Creek mylonite, northern Madison Range, southwest Montana, USA: *Rocky Mountain Geology*, v. 49, p. 91-114.
- Kellogg, K.S., Snee, L.W., and Unruh, D., 2003, The Mesoproterozoic Beaverhead impact structure and its tectonic setting, Montana-Idaho: $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb isotopic constraints: *Journal of Geology*, v. 111, p. 639-652.
- Kellogg, K.S., and Harlan, S.S., 2007, New $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations and paleomagnetic results bearing on the tectonic and magmatic history of the northern Madison Range and Madison Valley region, southwestern Montana, U.S.A.: *Rocky Mountain Geology*, v. 42, no. 2, p. 157-174.
- Kellogg, K.S., and Mogk, D.W., 2009, Structural development of high-temperature mylonites in the Archean Wyoming province, northwestern Madison Range, Montana: *Rocky Mountain Geology*, v. 44, no. 2, p. 85-102.
- Kellogg, K.S., and Williams, V.S., 2000, Geologic map of the Ennis 30' x 60' quadrangle, Madison and Gallatin counties, Montana, and Park County, Wyoming: United States Geologic Survey Geologic Investigations, v. I-2690.
- Kenah, C., Hollister, L.S., 1983, Anatexis in the Central Gneiss Complex, British Columbia, in Atherton, M.P., Gribble, C.D., eds., *Migmatites, Melting, and Metamorphism*: Cheshire, Shiva Publishing, 336 p.
- Kleeman, U., and Reinhardt, J., 1994, Garnet-biotite thermometry revisited: the effect of Al^{VI} and Ti in biotite: *European Journal of Mineralogy*, v. 6, p. 925-941.
- Koester, E., Pawley, A.R., Fernandes, L.A., Porcher, C.C., Soliani Jr., E., 2002, Experimental melting of cordierite gneiss and the petrogenesis of syntranscurrent peraluminous granites in southern Brazil: *Journal of Petrology*, v. 43, p. 1595-1616.
- Kohn, M.J., and Spear, F.S., 1990, Two new geobarometers for garnet amphibolites, with application to southeastern Vermont: *American Mineralogist*, v. 75, p. 89-96.

- Kohn, M.J., and Spear, F.S., 1989, Empirical calibration of geobarometers for the assemblage garnet + hornblende + plagioclase + quartz: *American Mineralogist*, v. 74, p. 77-84.
- Koziol, A.M., 1989, Recalibration of the garnet-plagioclase- Al_2SiO_5 -quartz (GASP) geobarometer and application to natural parageneses: *Eos (Transactions of the American Geophysical Union)*, v. 70, p. 493.
- Le Breton, N., Thompson, A.B., 1988, Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis: *Contributions to Mineralogy and Petrology*, v. 99, p. 226-237.
- Lageson, D.R., Kellogg, K.S., and O'Neill, J.M., 1997, Potential for catastrophic landslide failure of northwest flank of Jumbo Mountain, Spanish Peaks Wilderness, Montana, in Lageson, D.R., and Parker, A., eds., *The edge of the Crazyes: Geology where mountains meet the prairies: Tobacco Root Geologic Society 22nd annual field conference with the Montana Geological Society*, v. 27: Tobacco Root Geologic Society, Missoula, Montana, University of Montana, p. 13-18.
- LeMieux, S., Ross, G.M., Cook, F.A., 2000, Crustal geometry and tectonic evolution of the Archean crystalline basement beneath the southern Alberta Plains, from new seismic reflection and potential-field studies: *Canadian Journal of Earth Sciences*, v. 37, p. 1473-1491.
- Luth, W.C., 1976, Granitic rocks, in Bailey, D.K. and MacDonald, R., eds., *The evolution of the crystalline rocks*: London, Academic Press, 484 p.
- Mader, U.K., Percival, J.A., and Berman, R.G., 1994, Thermobarometry of garnet-clinopyroxene-hornblende granulites from the Kapuskasing structural zone: *Canadian Journal of Earth Sciences*, v. 31, p. 1134-1145.
- McMullin, D.W.A., Berman, R.G., and Greenwood, H.J., 1991, Calibration of the SGAM thermometer for pelitic rocks using data from phase equilibrium experiments and natural assemblages, v. 29, p. 889-908.
- Mogk, D.W., 1992, Ductile shearing and migmatization at mid-crustal levels in an Archean high-grade gneiss belt, northern Gallatin Range, Montana, USA: *Journal of Metamorphic Geology*, v. 10, p. 427-438.
- Mogk, D.W., 1990, A model for the granulite-migmatite association in the Archean basement of southwestern Montana in Vielzeuf, D., and Vidal, Ph., eds, *Granulites and crustal evolution*, NATO ASI Series C, v. 311: Netherlands, Kluwer Academic

Publishers, p. 133-155.

- Mogk, D.W., 1988, Archean allochthonous unit in the northern and western Beartooth Mountains, Montana, in Lewis, S.E., and Berg, R.B., eds., *Precambrian and Mesozoic plate margins; Montana, Idaho and Wyoming, with field guides for the 8th International Conference on Basement Tectonics*, v. 96: Montana Bureau of Mines and Geology, p. 43-52.
- Mogk, D.W., and Henry, D.J., 1988, Metamorphic petrology of the northern Archean Wyoming Province, southwestern Montana: Evidence for Archean collisional tectonics in Ernst, W.G., ed., *Metamorphism and Crustal Evolution of the western U.S.*, Rubey Volume VII: Upper Saddle River, Prentice Hall, p. 362-382.
- Mogk, D.W., Mueller, P.A., Wooden, J.L., 1992, The nature of Archean terrane boundaries: An example from the northern Wyoming Province: *Precambrian Research*, v. 55, p. 155-168.
- Mogk, D.W., Mueller, P.A., Wooden, J.L., 1988, Archean tectonics of the North Snowy Block, Beartooth mountains, Montana: *Journal of Geology*, v. 96, p. 125-141.
- Mueller, P.A., Wooden, J.L., and Mogk, D.W., 2011, 2450 Ma metamorphism recorded in 3250 Ma gneisses, Gallatin Range, Montana: *Northwest Geology*, v. 40, p. 1-8.
- Mueller, P.A., Wooden, J.L., Mogk, D.W., Henry, D.J., Bowes, D.R., 2010, Rapid growth of an Archean continent by arc magmatism: *Precambrian Research*, v. 183, p. 70-88.
- Mueller, P.A., Wooden, J.L., Nutman, A.P., Mogk, D.W., 1998, Early Archean crust in the northern Wyoming province: Evidence from U-Pb ages of detrital zircons: *Precambrian Research*, v. 91, p. 295-307.
- Mueller, P.A., Wooden, J.L., Mogk, D.W., Nutman, A.P., Williams, I.S., 1996, Extended history of a 3.5 Ga trondhjemitic gneiss, Wyoming Province, USA: Evidence from U-Pb systematics in zircon: *Precambrian Research*, v. 78, p. 41-52.
- Mueller, P.A., Heatherington, A.L., Weyand, E., Wooden, J.L., Mogk, D.W., and Nutman, A.P., 1995, Geochemical evolution of Archean crust in the northern Madison Range, Montana: Evidence from U-Pb and Sm-Nd systematics: *Geological Society of America Abstracts with Programs*, v. 27, p. 49.
- Mueller, P.A., Shuster, R.D., Wooden, J.L., Erslev, E.A., and Bowes, D.R., 1993, Age and composition of Archean crystalline rocks from the southern Madison Range, Montana: implications for crustal evolution in the Wyoming craton: *Geological*

Society of America Bulletin, v. 105, p. 437-446.

- Newton, R.C., and Haselton, H.T., 1981, Thermodynamics of the garnet-plagioclase-Al₂SiO₅-quartz geobarometer in Newton, R.C., Navrotsky, A., Wood, B.J., eds, Thermodynamics of minerals and melts, Advances in Physical Geochemistry, v. 1: New York, Springer-Verlag, p. 131-147.
- Passchier, C.W., and Trouw, R.A.J., 2005, Microtectonics: New York, Springer, 366 p.
- Patiño Douce, A.E., 2005, Vapor-absent melting of tonalite at 15-32 kbar: Journal of Petrology, v. 46, p. 275-290.
- Patiño Douce, A.E., and Beard, J.S., 1995, Dehydration melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar: Journal of Petrology, v. 36, p. 707-738.
- Patiño Douce, A.E., and Harris, N., 1998, Experimental constraints on Himalayan anatexis: Journal of Petrology, v. 36, p. 689-710.
- Patiño Douce, A.E., Johnston, A.D., Rice, J.M., 1993, Octahedral excess mixing properties in biotite: A working model with applications to geobarometry and geothermometry: American Mineralogist, v. 78, p. 113-131.
- Pattison, D.M., 2003, Petrogenetic significance of orthopyroxene-free garnet + clinopyroxene + plagioclase $\pm$ quartz-bearing metabasites with respect to the amphibolite and granulite facies: Journal of Metamorphic Geology, v. 21, p. 21-34.
- Pattinson, D.M., 1992, Stability of andalusite and sillimanite and the Al₂SiO₅ triple point: Constraints from the Ballachulish aureole, Scotland: Journal of Geology, v. 100, p. 423-446.
- Perchuk, L.L., and Lavrent'eva, I.V., 1983, Experimental investigation of exchange equilibria in the system cordierite-garnet-biotite in Saxena, S.K., ed, Kinetics and equilibrium in mineral reactions, New York, Springer, p. 199-239.
- Polat, A., Kerrich, R., Windley, B., 2009, Archaean crustal growth processes in southern West Greenland and the southern Superior Province: Geodynamic and magmatic constraints, in Cawood, P.A., Kröner, A., eds., Earth accretionary systems in space and time, Geological Society Special Publications, v. 318: London, Geological Society, p. 155-191.
- Powell, R., 1983, Processes in granulite-facies metamorphism, in Atherton, M.P., Gribble, C.D., eds., Migmatites, Melting, and Metamorphism: Cheshire, Shiva Publishing,

336 p.

- Pownceby, M.I., Wall, V.J., and O'Neill, H.S., 1987, Fe-Mn partitioning between garnet and ilmenite: experimental calibration and applications: *Contributions to Mineralogy and Petrology*, v. 97, p. 116-126.
- Putirka, K.D., 2008, Thermometers and barometers for volcanic systems in Minerals, inclusions, and volcanic processes, v. 69: Washington, D.C., Mineralogical Society of America, p. 61-120.
- Ramsay, J.G., and Huber, M., 1987, The techniques of modern structural geology, volume 2: Folds and fractures: New York, Academic Press, 391 p.
- Roberts, H., Dahl, P., Kelley, S., Frei, R., 2002, New ^{207}Pb - ^{206}Pb and ^{40}Ar - ^{39}Ar ages from SW Montana, USA: Constraints on the Proterozoic and Archaean tectonic and depositional history of the Wyoming Province: *Precambrian Research*, v. 117, p. 119-143.
- Salt, K.J., 1987, Archean geology of the Spanish Peaks area, southwestern Montana: unpublished MSc thesis, Montana State University, Bozeman, 86 pp.
- Sawyer, E.W., 2006, Atlas of migmatites: *Canadian Mineralogist*, Special Publication v. 9: Ottawa, NRC Research Press, 371 p.
- Schmidt, C.J., and Garihan, J.M., 1986, Middle Proterozoic and Laramide tectonic activity along the southern margin of the Belt Basin, in Roberts, S.M., ed., *Belt Supergroup: a guide to Proterozoic rocks of western Montana and adjacent areas*, v. 94: Butte, Montana, Montana Bureau of Mines and Geology, p. 217-235.
- Schmidt, M.W., 1992, Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer: *Contributions to Mineralogy and Petrology*, v. 110, p. 304-310.
- Sears, J.W., Chamberlain, K.R., Buckley, S.N., 1998, Structural and U-Pb geochronological evidence for 1.47 Ga rifting in the Belt basin, western Montana: *Canadian Journal of Earth Science*, v. 35, p. 467-475.
- Smit, C.A., and Van Reenen, D.D., 2014, Role of fluids in the exhumation of the Southern Marginal Zone of the Limpopo Complex, South Africa: *Precambrian Research*, v. 253, p. 81-95.
- Spear, F.S., 1993, Metamorphic phase equilibria and pressure-temperature-time paths: Washington, D.C., Mineralogical Society of American, 799 p.

- Spear, F.S., and Kohn, M. J., 2014, Program GTB: Geothermobarometry: Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, http://ees2.geo.rpi.edu/metapetaren/software/gtb_prog/gtb.html.
- Spear, F.S, Kohn, M.J., Cheney, J.T., 1999, P-T paths from anatectic pelites: *Contributions to Mineralogy and Petrology*, v. 134, p. 17-32.
- Spencer, E.W., and Kozak, S.J., 1975, Precambrian evolution of the Spanish Peaks area, Montana: *Geological Society of America Bulletin*, v. 86, p. 785-792.
- Thompson, A.B., 1983, Fluid-absent metamorphism: *Journal of the Geological Society*, v. 140, p. 533-547.
- Thompson, A.B., 1976, Mineral reactions in pelitic rocks: II. Calculation of some P-T-X (Fe-Mg) phase relations: *American Journal of Science*, v. 276, p. 425-454.
- Thompson, A.B., and Connolly, J.A., 1995, Melting of the continental crust: Some thermal and petrologic constraints on anatexis in continental collision zones and other settings: *Journal of Geophysical Research*, v. 100, p. 15565-15579.
- Weyand, E.L., 1989, U-Pb zircon geochronology of Archean rocks from the Spanish Peaks area, Madison Range, Montana: unpublished MSc thesis, University of Florida, Gainesville, 122 p.
- Whitney, J.S., 1988, The origin of granite: The role and source of water in the evolution of granitic magmas: *Geological Society of America Bulletin*, v. 100, p. 1886-1897.
- Winter, J.D., 2010, *Principles of Igneous and Metamorphic Petrology*: Upper Saddle River, Pearson Prentice Hall, 720 p.
- Wolf, M.B., Wyllie, P.J., 1994, Dehydration-melting of amphibolite at 10 kbar: The effects of temperature and time: *Contributions to Mineralogy and Petrology*, v. 115, p. 369-383.
- Wu, C.-M., Zhang, J., Ren, L.-D., 2004, Empirical garnet-biotite-plagioclase-quartz (GBPQ) geobarometry in medium- to high-grade metapelites: *Journal of Petrology*, v. 45, p. 1907-1921.

APPENDICES

APPENDIX A

COMPOSITIONAL DATA

AMPHIBOLE OXIDE DATA

Oxides (wt %)												
Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cl	Total
SP-143	44.310	1.110	12.900	15.450	0.080	10.610	11.420	1.420	0.520	0.040	0.000	97.860
	43.760	1.120	13.040	15.940	0.070	10.520	11.580	1.480	0.550	0.100	0.010	98.170
	44.200	1.160	12.700	15.590	0.080	10.610	11.380	1.450	0.580	0.020	0.000	97.770
	43.910	1.190	12.880	15.570	0.060	10.650	11.290	1.470	0.550	0.100	0.000	97.670
	43.620	1.040	12.990	15.740	0.040	10.360	11.380	1.430	0.560	0.060	0.010	97.230
SP-149	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	42.550	0.950	15.010	13.080	0.090	11.830	11.090	1.260	0.360	0.140	0.000	96.360
	41.820	0.860	14.930	13.080	0.080	11.770	10.980	1.200	0.340	0.110	0.000	95.170
	42.970	0.860	14.720	12.320	0.070	11.730	11.190	1.180	0.330	0.150	0.000	95.520
	42.660	0.790	15.050	13.330	0.030	11.680	11.090	1.280	0.260	0.020	0.000	96.190
SP-153	42.250	0.890	15.360	13.290	0.050	11.540	11.030	1.310	0.360	0.080	0.000	96.160
	42.290	0.980	15.510	13.110	0.100	11.540	11.080	1.310	0.390	0.110	0.000	96.420
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	39.280	1.160	13.250	22.340	0.190	5.930	10.930	1.670	1.090	0.030	0.020	95.890
	39.070	1.370	13.110	23.320	0.210	6.080	11.340	1.600	1.130	0.040	0.020	97.290
	38.800	1.460	13.090	22.300	0.190	5.970	11.380	1.770	1.160	0.010	0.030	96.160
	38.970	1.360	12.900	22.760	0.210	6.130	11.340	1.690	1.100	0.110	0.030	96.600
	39.340	1.170	13.180	22.570	0.190	5.930	11.390	1.680	1.110	0.050	0.020	96.630
	39.280	1.320	13.090	22.740	0.200	6.050	11.380	1.740	1.080	0.080	0.030	96.990

AMPHIBOLE STRUCTURAL FORMULAE

Sample	Site occupancies (apfu) calculated for 23 oxygens															
	Si	Al ^{iv}	Al ^{vi}	Ti	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Na	K	F	Cl	OH	Total	
SP_143	6.461	1.539	0.678	0.122	0.551	1.333	0.010	2.306	1.784	0.401	0.097	0.018	0.000	1.982	17.282	
	6.389	1.611	0.633	0.123	0.589	1.358	0.009	2.290	1.811	0.419	0.102	0.046	0.002	1.951	17.333	
	6.459	1.541	0.646	0.128	0.558	1.347	0.010	2.311	1.782	0.411	0.108	0.009	0.000	1.991	17.301	
	6.419	1.581	0.638	0.131	0.627	1.277	0.007	2.321	1.768	0.417	0.103	0.046	0.000	1.954	17.287	
	6.418	1.582	0.671	0.115	0.580	1.357	0.005	2.272	1.794	0.408	0.105	0.028	0.002	1.970	17.307	
SP_149	6.173	1.827	0.740	0.104	1.011	0.576	0.011	2.559	1.724	0.354	0.067	0.064	0.000	1.936	17.145	
	6.135	1.865	0.716	0.095	1.102	0.503	0.010	2.574	1.726	0.341	0.064	0.051	0.000	1.949	17.131	
	6.290	1.710	0.829	0.095	0.786	0.722	0.009	2.560	1.755	0.335	0.062	0.069	0.000	1.931	17.151	
	6.191	1.809	0.765	0.086	1.014	0.604	0.004	2.527	1.724	0.360	0.048	0.009	0.000	1.991	17.133	
	6.145	1.855	0.778	0.097	1.009	0.608	0.006	2.502	1.719	0.369	0.067	0.037	0.000	1.963	17.155	
SP_153	6.139	1.861	0.792	0.107	0.968	0.623	0.012	2.497	1.723	0.369	0.072	0.050	0.000	1.950	17.164	
	6.119	1.881	0.552	0.136	0.688	2.222	0.025	1.377	1.824	0.504	0.217	0.015	0.005	1.980	17.545	
	6.025	1.975	0.408	0.159	0.800	2.207	0.027	1.398	1.874	0.478	0.222	0.020	0.005	1.975	17.574	
	6.074	1.926	0.490	0.172	0.505	2.415	0.025	1.393	1.909	0.537	0.232	0.005	0.008	1.987	17.678	
	6.064	1.936	0.430	0.159	0.679	2.283	0.028	1.422	1.891	0.510	0.218	0.054	0.008	1.938	17.619	
	6.115	1.885	0.530	0.137	0.561	2.373	0.025	1.374	1.897	0.506	0.220	0.025	0.005	1.970	17.623	
	6.086	1.914	0.476	0.154	0.616	2.330	0.026	1.397	1.889	0.523	0.213	0.039	0.008	1.953	17.625	

AMPHIBOLE NOMENCLATURE

Sample	Nomenclature				
	(Ca+Na) B-site	Na B-site	(Na+K) A-site	$\frac{Mg}{(Mg+Fe^{2+})}$	$\frac{Fe^{3+}}{(Fe^{3+}+Al^{VI})}$
SP_143	2.000	0.216	0.282	0.634	0.448
	2.000	0.189	0.333	0.628	0.482
	2.000	0.218	0.301	0.632	0.463
	2.000	0.232	0.287	0.645	0.496
	2.000	0.206	0.307	0.626	0.464
SP_149	2.000	0.276	0.145	0.816	0.577
	2.000	0.274	0.131	0.837	0.606
	2.000	0.245	0.151	0.780	0.487
	2.000	0.276	0.133	0.807	0.570
	2.000	0.281	0.155	0.805	0.565
SP_153	2.000	0.277	0.164	0.800	0.550
	2.000	0.176	0.545	0.383	0.555
	2.000	0.126	0.574	0.388	0.662
	2.000	0.091	0.678	0.366	0.508
	2.000	0.109	0.619	0.384	0.613
	2.000	0.103	0.623	0.367	0.514
	2.000	0.111	0.625	0.375	0.564

BIOTITE OXIDE DATA

Oxides (wt %)

Sample	FeO	TiO ₂	Na ₂ O	CaO	F	SiO ₂	K ₂ O	Al ₂ O ₃	MgO	BaO	Cl	MnO	Cr ₂ O ₃	Total
SP-12	19.179	3.642	0.196	0.028	0.000	34.983	9.815	19.747	10.182	0.000	0.000	0.000	0.000	97.772
	15.245	2.126	2.223	0.846	0.181	38.483	7.049	20.188	7.475	0.000	0.000	0.000	0.000	93.816
	18.582	2.538	0.207	0.000	0.035	35.256	9.838	20.328	10.741	0.000	0.000	0.000	0.000	97.525
	19.656	2.112	0.172	0.106	0.623	36.686	6.734	18.938	8.370	0.000	0.000	0.000	0.000	93.397
	19.224	3.280	0.234	0.000	0.703	35.345	9.492	19.544	10.289	0.000	0.000	0.000	0.000	98.111
SP-153	25.795	4.160	0.133	0.035	0.000	34.990	9.134	14.745	7.238	0.390	0.024	0.106	0.042	96.792
	25.137	4.065	0.133	0.018	0.000	34.770	9.127	15.191	7.028	0.432	0.019	0.079	0.029	96.028
	24.159	4.082	0.116	0.020	0.000	34.905	9.313	15.021	7.323	0.536	0.015	0.125	0.044	95.659
	24.250	4.078	0.136	0.055	0.013	34.956	8.994	15.013	7.189	0.435	0.009	0.102	0.105	95.335
	24.495	4.434	0.123	0.001	0.000	35.022	9.045	15.185	7.361	0.473	0.000	0.106	0.057	96.302
	24.631	4.332	0.097	0.015	0.064	34.808	8.944	15.121	7.301	0.451	0.018	0.075	0.057	95.914
	23.959	4.200	0.128	0.000	0.000	34.943	8.961	15.234	7.266	0.437	0.006	0.043	0.023	95.200
	24.972	3.878	0.159	0.021	0.026	34.862	8.996	14.766	7.306	0.449	0.028	0.094	0.082	95.639

BIOTITE STRUCTURAL FORMULAE

Site Occupancies (apfu) calculated for 24 anions																								
Sample	Si		Al		Fe ³⁺		Total		Al		Ti		Fe ²⁺		Cr ³⁺		Mn		Mg		Vacancy		Total	
	T-site		T-site		T-site		T-site		R-site		R-site		R-site		R-site		R-site		R-site		R-site		R-site	
SP-12	5.198	2.802	0.000	0.000	8.000		8.000		0.657	0.407	2.383	0.000	2.255	0.298	6.000		0.000	0.000	2.255	0.298	6.000		0.000	6.000
	5.747	2.253	0.000	0.000	8.000		8.000		1.301	0.239	1.904	0.000	1.664	0.892	6.000		0.000	0.000	1.664	0.892	6.000		0.000	6.000
	5.230	2.770	0.000	0.000	8.000		8.000		0.785	0.283	2.305	0.000	2.375	0.251	6.000		0.000	0.000	2.375	0.251	6.000		0.000	6.000
	5.624	2.376	0.000	0.000	8.000		8.000		1.045	0.243	2.520	0.000	1.913	0.279	6.000		0.000	0.000	1.913	0.279	6.000		0.000	6.000
	5.259	2.741	0.000	0.000	8.000		8.000		0.686	0.367	2.392	0.000	2.282	0.274	6.000		0.000	0.000	2.282	0.274	6.000		0.000	6.000
SP-153	5.461	2.539	0.000	0.000	8.000		8.000		0.174	0.488	3.367	0.005	1.684	0.268	6.000		0.014	0.014	1.684	0.268	6.000		0.000	6.000
	5.454	2.546	0.000	0.000	8.000		8.000		0.263	0.480	3.298	0.004	1.643	0.303	6.000		0.010	0.010	1.643	0.303	6.000		0.000	6.000
	5.482	2.518	0.000	0.000	8.000		8.000		0.263	0.482	3.173	0.005	1.715	0.345	6.000		0.017	0.017	1.715	0.345	6.000		0.000	6.000
	5.497	2.503	0.000	0.000	8.000		8.000		0.280	0.482	3.189	0.013	1.685	0.336	6.000		0.014	0.014	1.685	0.336	6.000		0.000	6.000
	5.455	2.545	0.000	0.000	8.000		8.000		0.242	0.519	3.191	0.007	1.709	0.318	6.000		0.014	0.014	1.709	0.318	6.000		0.000	6.000
	5.452	2.548	0.000	0.000	8.000		8.000		0.243	0.510	3.226	0.007	1.705	0.299	6.000		0.010	0.010	1.705	0.299	6.000		0.000	6.000
	5.488	2.512	0.000	0.000	8.000		8.000		0.308	0.496	3.147	0.003	1.701	0.339	6.000		0.006	0.006	1.701	0.339	6.000		0.000	6.000
	5.490	2.510	0.000	0.000	8.000		8.000		0.230	0.459	3.289	0.010	1.715	0.284	6.000		0.013	0.013	1.715	0.284	6.000		0.000	6.000

Site Occupancies (apfu) calculated for 24 anions

Sample												
	Ca A-site	Ba A-site	Na A-site	K A-site	Vacancy A-site	Total A-site	OH X-site	F X-site	Cl X-site	Total X-site		
SP-12	0.004	0.000	0.056	1.861	0.079	2.000	4.000	0.000	0.000	4.000		
	0.135	0.000	0.644	1.343	0.000	2.122	3.915	0.085	0.000	4.000		
	0.000	0.000	0.060	1.862	0.079	2.000	3.984	0.016	0.000	4.000		
	0.017	0.000	0.051	1.317	0.615	2.000	3.698	0.302	0.000	4.000		
	0.000	0.000	0.067	1.802	0.131	2.000	3.669	0.331	0.000	4.000		
SP-153	0.006	0.024	0.040	1.819	0.111	2.000	3.994	0.000	0.006	4.000		
	0.003	0.027	0.040	1.826	0.104	2.000	3.995	0.000	0.005	4.000		
	0.003	0.033	0.035	1.866	0.062	2.000	3.996	0.000	0.004	4.000		
	0.009	0.027	0.041	1.804	0.118	2.000	3.991	0.006	0.002	4.000		
	0.000	0.029	0.037	1.797	0.137	2.000	4.000	0.000	0.000	4.000		
	0.003	0.028	0.029	1.787	0.153	2.000	3.964	0.032	0.005	4.000		
	0.000	0.027	0.039	1.795	0.139	2.000	3.998	0.000	0.002	4.000		
	0.004	0.028	0.049	1.807	0.113	2.000	3.980	0.013	0.007	4.000		

BIOTITE NOMENCLATURE

Sample	Mg			NOMENCLATURE	
	$\frac{\text{Mg}}{(\text{Mg}+\text{Fe}^{\text{US}})}$	$\frac{\text{Mg}}{(\text{Mg}+\text{Fe}^{2+})}$	$\frac{\text{viAl}}{(\text{viAl}+\text{viR}^{2+})}$	Rieder et al. (1998)	after Tischendorf et al. (2007)
SP-12	0.486	0.486	0.124	Biotite	Annite
	0.466	0.466	0.267	Biotite	Siderophyllite
	0.507	0.507	0.144	Biotite	Phlogopite
	0.432	0.432	0.191	Biotite	Annite
	0.488	0.488	0.128	Biotite	Annite
SP-153	0.333	0.333	0.033	Biotite	Annite
	0.333	0.333	0.050	Biotite	Annite
	0.351	0.351	0.051	Biotite	Annite
	0.346	0.346	0.054	Biotite	Annite
	0.349	0.349	0.047	Biotite	Annite
	0.346	0.346	0.047	Biotite	Annite
	0.351	0.351	0.060	Biotite	Annite
	0.343	0.343	0.044	Biotite	Annite

*The lithium parameter cannot be applied due to analytic limitations, so the nomenclature here considers only Mg-number and octahedrally-coordinated Al content parameters.

FELDSPAR OXIDE DATA

Sample	Textural context	Oxides (wt %)							
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	BaO	Na ₂ O	K ₂ O	Total
SP-12	Circle 1 grain rim	62.040	24.899	0.035	5.706		8.508	0.138	101.326
	Circle 1 grain core	61.852	25.163	0.003	5.922		8.243	0.119	101.302
	Circle 2 near bio-gar	62.724	23.741	0.076	4.515		8.989	0.068	100.113
	Circle 2 near bio-gar	63.140	23.913	0.048	4.582		9.299	0.080	101.062
SP-148	Circle 1 plag touching gar	59.326	25.636	0.198	7.595	0.000	7.543	0.088	100.386
	Circle 1 matrix plag not touching gar	60.685	24.816	0.078	6.471	0.000	8.269	0.162	100.481
	Circle 1 matrix plag not touching gar	63.920	22.756	0.097	3.940	0.000	9.562	0.071	100.346
	Circle 1 plag touching gar	59.716	25.397	0.108	6.876	0.000	8.084	0.072	100.253
	Circle 2 matrix plag	60.268	24.594	0.156	6.219	0.000	8.056	0.272	99.565
	Kspar	62.613	18.937	0.126	0.000	2.615	0.925	14.603	99.819
	Circle 3 plag touching gar	59.591	24.955	0.068	6.765	0.000	8.001	0.182	99.562
	Circle 3 matrix plag	58.809	25.917	0.052	7.666	0.000	7.388	0.108	99.940
	Circle 3 plag next to kspar not gar	58.748	25.819	0.068	7.626	0.000	7.538	0.104	99.903
	Circle 3 kspar touching above plag	63.263	18.648	0.045	0.000	1.703	1.139	14.765	99.563
	Matrix plag far from garnet	60.026	24.970	0.021	6.412	0.000	8.113	0.172	99.714
SP-149	Circle 1 plag touching garnet	53.004	29.457	0.125	12.499	0.000	4.713	0.016	99.814
	Circle 1 same plag in corner, core	53.212	29.538	0.087	12.100	0.000	4.922	0.018	99.877
	Circle 1 matrix plag not touching gar	55.226	28.068	0.078	10.330	0.000	5.987	0.027	99.716
	Circle 2 (blue) plag touching gar	54.493	28.531	0.103	10.838	0.000	5.692	0.018	99.675
	Circle 2 (blue) same, core	54.559	28.740	0.057	11.310	0.000	5.330	0.035	100.031
	Circle 2 (blue) matrix plag	52.706	29.197	0.071	12.199	0.000	4.778	0.047	98.998
	Circle 3 plag touching gar	52.451	29.698	0.148	12.610	0.000	4.519	0.015	99.441
	Circle 3 matrix plag not touching gar	52.645	29.678	0.082	12.705	0.000	4.612	0.021	99.743

Sample	Textural context	Oxides (wt %)									
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	BaO	Na ₂ O	K ₂ O	Total		
SP-149 cont.	Circle 4 plag not touching gar	51.562	30.445	0.235	13.184	0.000	4.317	0.016	99.759		
	Circle 4 matrix plag	52.164	29.978	0.056	12.723	0.000	4.471	0.015	99.407		
SP-154	Circle 1 plag not touching gar, in qtz	60.963	24.373	0.160	5.993	0.000	8.538	0.122	100.149		
	Circle 1 same, rimshot next to bio	60.710	24.870	0.118	6.309	0.000	8.384	0.069	100.460		
	Matrix plag not near garnet	60.610	24.602	0.104	6.284	0.000	8.281	0.119	100.000		
	Small circle grain rimshot	60.280	24.511	0.031	6.428	0.000	8.145	0.076	99.471		
	Small circle same OMITTED	11.991	4.018	0.377	2.767	0.000	2.106	0.051	21.310		
	Small circle same, core of plag grain near gar but not touching	60.785	24.734	0.066	6.240	0.000	8.357	0.140	100.322		
SP-153	Circle 1 plag in contact with gar	57.012	27.764	0.100	9.285	0.000	6.590	0.033	100.784		
	Circle 1 plag away from gar	57.098	26.938	0.014	8.913	0.000	6.631	0.040	99.634		
	Circle 1 new grain in matrix not touching gar	56.723	27.534	0.018	8.992	0.060	6.517	0.027	99.871		
	Circle 1 plag rimshot next to small gar	54.480	27.477	1.113	8.990	0.008	6.314	0.042	98.424		
	Circle 1 same, mm along strike, core	57.412	27.267	0.066	8.605	0.000	6.788	0.043	100.181		
	Circle 2 plag in contact with gar	56.677	27.409	0.191	8.887	0.000	6.832	0.040	100.036		
	Circle 3 matrix plag	55.203	28.696	0.036	8.117	0.000	6.651	0.044	98.747		
	Circle 2 matrix plag not touching gar	55.836	27.739	0.061	8.832	0.015	6.660	0.029	99.172		
DL-33B	Circle 1 large plag	58.557	26.987	0.089	8.641		6.870	0.244	101.390		
	Circle 1 large plag grain core	60.449	25.829	0.045	7.267		7.590	0.263	101.440		
	Circle 2 plag next to gar	61.216	25.839	0.112	6.909		7.624	0.271	101.970		
	Circle 3 plag next to hornblende	58.976	26.348	0.102	7.856		7.107	0.290	100.680		
SP-141	Circle 1 plag next to hornblende	64.025	22.777	0.184	4.153	0.020	9.477	0.243	100.879		
	Circle 1 same, core	63.861	22.832	0.133	4.159	0.085	9.412	0.288	100.770		

Sample	Textural context	Oxides (wt %)									
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	BaO	Na ₂ O	K ₂ O	Total		
SP-141 cont.	Circle 1 plag next to hornblende	63.567	22.630	0.103	3.926	0.008	9.661	0.227	100.122		
	Circle 1 kspar	64.107	18.741	0.072	0.014	0.942	0.433	15.693	100.002		
	Kspar next to hornblende	64.281	18.790	0.079	0.018	0.963	0.539	15.849	100.519		
	Circle 1 plag next to kspar	63.367	23.079	0.060	4.033	0.000	9.722	0.214	100.475		
	Circle 2 kspar	64.588	18.542	0.083	0.043	1.084	0.362	15.893	100.595		
	Circle 2 plag adjacent to previous kspar	63.993	22.932	0.148	3.939	0.017	9.682	0.240	100.951		
	Circle 2 kspar	64.196	18.543	0.066	0.026	0.938	0.330	15.845	99.944		
	Circle 2 plag next to previous kspar	64.029	22.912	0.090	4.034	0.045	9.551	0.247	100.908		
	Circle 2 matrix plag	64.015	22.802	0.099	3.999	0.000	9.461	0.266	100.642		
	Circle 2 kspar	64.257	18.853	0.066	0.018	0.967	0.486	15.823	100.470		

Calculated Site Occupancies (apfu)

Sample	Calculated Site Occupancies (apfu)											
	Si T-site	Al T-site	Fe ³⁺ T-site	Total T-site	Fe ³⁺ M-site	Fe ²⁺ M-site	Mg M-site	Ca M-site	Ba M-site	Na M-site	K M-site	Total M-site
SP-149 cont	2.394	1.590	0.003	3.987	0.000	0.000	0.000	0.619	0.000	0.407	0.001	1.027
	2.350	1.635	0.008	3.993	0.000	0.000	0.000	0.644	0.000	0.381	0.001	1.026
	2.380	1.612	0.002	3.993	0.000	0.000	0.000	0.622	0.000	0.395	0.001	1.018
SP-154	2.710	1.277	0.005	3.992	0.000	0.000	0.000	0.285	0.000	0.736	0.007	1.028
	2.691	1.299	0.004	3.995	0.000	0.000	0.000	0.300	0.000	0.721	0.004	1.024
	2.699	1.291	0.003	3.993	0.000	0.000	0.000	0.300	0.000	0.715	0.007	1.021
	2.698	1.293	0.001	3.992	0.000	0.000	0.000	0.308	0.000	0.707	0.004	1.019
	2.625	1.037	0.062	3.723	0.000	0.000	0.000	0.649	0.000	0.894	0.014	1.557
	2.698	1.294	0.002	3.994	0.000	0.000	0.000	0.297	0.000	0.719	0.008	1.024
SP-153	2.540	1.458	0.002	4.000	0.001	0.000	0.000	0.443	0.000	0.569	0.002	1.014
	2.569	1.428	0.000	3.997	0.000	0.000	0.000	0.430	0.000	0.578	0.002	1.010
	2.547	1.457	0.000	4.005	0.001	0.000	0.000	0.433	0.001	0.567	0.002	1.003
	2.497	1.484	0.019	4.000	0.019	0.000	0.000	0.441	0.000	0.561	0.002	1.005
	2.567	1.437	0.000	4.004	0.002	0.000	0.000	0.412	0.000	0.588	0.002	1.003
	2.544	1.450	0.005	4.000	0.001	0.000	0.000	0.427	0.000	0.595	0.002	1.024
	2.504	1.534	0.000	4.038	0.001	0.000	0.000	0.395	0.000	0.585	0.003	0.982
DL-33B	2.528	1.480	0.000	4.008	0.002	0.000	0.000	0.428	0.000	0.585	0.002	1.015
	2.588	1.406	0.003	3.997	0.000	0.000	0.000	0.409	0.000	0.589	0.014	1.012
	2.658	1.339	0.001	3.998	0.000	0.000	0.000	0.342	0.000	0.647	0.015	1.004
	2.673	1.330	0.000	4.003	0.004	0.000	0.000	0.323	0.000	0.645	0.015	0.984
	2.619	1.379	0.002	4.000	0.002	0.000	0.000	0.374	0.000	0.612	0.016	1.002

FELDSPAR NOMENCLATURE

Sample	ENDMEMBER COMPOSITIONS (mole %)			
	Albite	Anorthite	Orthoclase	Celsian
SP-12	72.396	26.831	0.773	0.000
	71.098	28.227	0.675	0.000
	77.970	21.642	0.388	0.000
	78.250	21.307	0.443	0.000
SP-148	63.934	35.575	0.491	0.000
	69.187	29.921	0.892	0.000
	81.130	18.474	0.396	0.000
	67.755	31.848	0.397	0.000
	69.022	29.445	1.533	0.000
	8.362	0.000	86.860	4.778
	67.466	31.524	1.010	0.000
	63.170	36.223	0.608	0.000
SP-149	63.769	35.652	0.579	0.000
	10.171	0.000	86.755	3.074
	68.932	30.106	0.962	0.000
	40.522	59.388	0.091	0.000
	42.356	57.542	0.102	0.000
	51.113	48.736	0.152	0.000
SP-154	48.678	51.221	0.101	0.000
	45.936	53.866	0.198	0.000
	41.367	58.365	0.268	0.000
	39.305	60.610	0.086	0.000
	39.599	60.283	0.119	0.000
	37.173	62.736	0.091	0.000
	38.838	61.076	0.086	0.000
	71.567	27.760	0.673	0.000
	70.360	29.259	0.381	0.000

Sample	ENDMEMBER COMPOSITIONS (mole %)			
	Albite	Anorthite	Orthoclase	Celsian
SP-154 cont.	69.988	29.350	0.662	0.000
	69.335	30.239	0.426	0.000
	57.405	41.680	0.915	0.000
	70.242	28.984	0.774	0.000
SP-153	56.120	43.696	0.185	0.000
	57.249	42.524	0.227	0.000
	56.591	43.150	0.154	0.105
	55.820	43.921	0.244	0.014
	58.661	41.095	0.245	0.000
	58.049	41.728	0.224	0.000
	59.567	40.174	0.259	0.000
	57.598	42.211	0.165	0.026
DL-33B	58.192	40.448	1.360	0.000
	64.437	34.094	1.469	0.000
	65.609	32.857	1.534	0.000
	61.061	37.300	1.639	0.000
SP-141	79.399	19.228	1.340	0.034
	78.979	19.286	1.590	0.144
	80.632	18.108	1.247	0.013
	3.952	0.071	94.240	1.738
	4.825	0.089	93.344	1.742
	80.403	18.432	1.165	0.000
	3.272	0.215	94.532	1.981
	80.548	18.109	1.314	0.029
	3.011	0.131	95.128	1.730
	79.912	18.652	1.360	0.076
	79.867	18.656	1.477	0.000
	4.377	0.090	93.773	1.760

GARNET OXIDE DATA

Sample	Textural context	Oxides (wt %)												
		SiO ₂	Al ₂ O ₃	TiO ₂	V ₂ O ₃	Cr2O3	FeO (measured)			MgO	CaO	FeO (calculated)		Fe ₂ O ₃ (calculated)
SP-12	Circle 1 gar, rim	37.652	21.497	0.009	0.000	0.005	30.864	4.283	3.957	1.337	30.864	0.000	99.604	
	Circle 1 gar, core	37.342	21.455	0.026	0.000	0.072	31.101	4.187	4.189	1.296	31.101	0.000	99.668	
	Circle 3 gar, rimshot	37.245	21.187	0.000	0.000	0.024	31.397	4.242	3.462	1.157	31.397	0.000	98.714	
	Circle 3 same, inner rim	37.505	21.338	0.000	0.000	0.185	31.374	4.236	3.758	1.199	31.374	0.000	99.595	
	Circle 3 same, inner rim	37.425	21.289	0.031	0.000	0.058	31.195	4.401	3.760	1.225	31.195	0.000	99.384	
	Circle 3 same, inner rim	37.920	21.394	0.000	0.000	0.055	32.229	4.374	3.607	1.195	32.229	0.000	100.774	
	Circle 3 same, rim	37.137	21.451	0.124	0.000	0.000	31.329	4.400	3.613	1.231	31.329	0.000	99.285	
	Circle 3 same, inner rim	37.322	21.292	0.072	0.000	0.094	31.489	4.387	3.809	1.229	31.489	0.000	99.694	
SP-149	Circle 3 gar, traverse, y-axis rimshot	39.118	21.758	0.029	0.000	0.052	28.478	0.635	5.763	5.329	28.478	0.000	101.162	
	Circle 3 gar, traverse, inner rim	39.168	22.056	0.004	0.000	0.040	27.194	0.537	6.368	5.822	27.194	0.000	101.189	
	Circle 3 same, traverse	39.008	21.972	0.029	0.000	0.026	26.929	0.531	6.690	5.478	26.929	0.000	100.663	
	Circle 3 same, traverse	39.285	22.081	0.046	0.000	0.033	27.520	0.503	6.413	5.462	27.520	0.000	101.343	
	Circle 3 same, traverse	39.386	22.113	0.067	0.000	0.047	26.406	0.530	6.816	5.876	26.406	0.000	101.241	
	Circle 3 same, traverse	39.083	22.159	0.030	0.000	0.050	27.170	0.537	6.680	5.875	26.782	0.431	101.627	
	Circle 3 same, traverse end, rimshot	38.870	21.896	0.029	0.000	0.021	27.545	0.555	5.863	5.640	27.545	0.000	100.419	
	Circle 2 gar next to bio, rimshot	38.654	21.970	0.054	0.000	0.092	28.745	0.659	5.736	4.839	28.745	0.000	100.749	
	Circle 2 same, core	39.508	22.045	0.029	0.000	0.130	26.593	0.418	6.755	5.906	26.593	0.000	101.384	
	Circle 1 sm garnet, traverse, rimshot	38.955	21.912	0.051	0.000	0.047	28.935	0.767	5.493	5.003	28.935	0.000	101.163	
	Circle 1 same, traverse	39.391	22.047	0.042	0.000	0.071	27.128	0.486	6.431	5.565	27.128	0.000	101.161	
	Circle 1 same, traverse	39.201	22.088	0.028	0.000	0.036	26.628	0.501	6.622	5.535	26.628	0.000	100.639	
	Circle 1 same, traverse	39.198	22.057	0.016	0.000	0.059	27.616	0.458	6.338	5.120	27.616	0.000	100.862	
	Circle 3 same, traverse, inner rim	39.230	21.936	0.006	0.000	0.047	28.112	0.663	5.948	5.092	28.112	0.000	101.034	
	Circle 3 same, traverse, rimshot	38.734	21.879	0.014	0.000	0.031	28.839	0.826	5.356	4.543	28.839	0.000	100.222	

Sample	Textural context	Oxides (wt %)											
		SiO ₂	Al ₂ O ₃	TiO ₂	V ₂ O ₃	Cr2O3	FeO (measured)	MnO	MgO	CaO	FeO (calculated)	Fe ₂ O ₃ (calculated)	Total
SP-154	Circle 1 gar leuco matrix, traverse, rim	37.800	21.038	0.061	0.000	0.038	30.951	0.950	0.935	8.516	30.951	0.000	100.289
	Circle 1 same, traverse, inner rim	38.052	20.887	0.032	0.000	0.021	31.305	0.905	1.093	8.889	31.276	0.032	101.187
	Circle 1 same, traverse	38.069	21.128	0.025	0.000	0.000	30.070	0.898	1.156	8.841	30.070	0.000	100.187
	Circle 1 same, traverse	37.997	21.168	0.065	0.000	0.045	30.326	0.838	1.129	8.816	30.326	0.000	100.384
	Circle 1 same, traverse	37.964	20.894	0.041	0.000	0.002	30.560	0.867	1.076	8.785	30.560	0.000	100.189
	Circle 1 same, traverse	37.848	21.290	0.030	0.000	0.061	30.540	0.925	1.115	8.490	30.540	0.000	100.299
	Circle 1 same, traverse	37.779	21.308	0.050	0.000	0.005	30.542	0.911	1.075	8.841	30.542	0.000	100.511
	Circle 1 gar, traverse, inner rim	37.389	20.756	0.043	0.000	0.012	31.046	0.934	0.909	8.701	31.033	0.015	99.791
	Circle 1 gar, traverse end, rimshot	37.524	21.086	0.026	0.000	0.042	31.249	0.884	0.921	8.443	31.249	0.000	100.175
	Circle 1 sm gar next to bio, rimshot	37.664	20.897	0.051	0.000	0.016	31.071	0.928	0.936	8.146	31.071	0.000	99.709
	Circle 1 same as above, core	37.572	21.070	0.020	0.000	0.040	30.384	0.828	1.130	8.696	30.384	0.000	99.740
	Circle 2 leuco matrix sm gar, core	37.489	20.758	0.053	0.000	0.017	30.057	0.809	1.072	9.176	30.057	0.000	99.431
SP-153	Circle 2 same as above, rimshot	37.125	20.936	0.035	0.000	0.042	30.847	0.838	1.036	8.281	30.847	0.000	99.140
	Circle 2 new gar grain, core	37.736	21.284	0.059	0.000	0.059	28.998	0.717	1.079	9.603	28.998	0.000	99.535
	Circle 2 same as above, rimshot	37.553	20.835	0.047	0.000	0.000	30.680	0.876	1.119	8.375	30.680	0.000	99.485
	Gar in leuco, traverse, rimshot	37.623	20.745	0.038	0.000	0.007	28.437	2.058	1.810	9.233	27.882	0.617	100.013
	Same, traverse, inner rim, x axis	37.572	21.204	0.029	0.000	0.000	28.229	1.433	2.200	9.266	27.708	0.579	99.991
	Same, traverse, x axis	37.688	20.934	0.033	0.000	0.009	28.099	1.308	2.135	9.483	27.815	0.315	99.721
	Same, traverse	37.514	21.151	0.044	0.000	0.031	27.815	1.323	2.169	9.606	27.384	0.479	99.701
	Same, traverse	37.819	21.017	0.058	0.000	0.002	28.604	1.257	2.187	9.524	27.901	0.782	100.546
	Same, traverse	37.771	21.158	0.044	0.000	0.009	27.905	1.310	2.137	9.522	27.869	0.040	99.860
	Same, traverse	37.606	21.172	0.092	0.000	0.002	28.256	1.285	2.174	9.237	28.039	0.241	99.848
	Same, traverse, inner rim	37.560	21.009	0.041	0.000	0.059	28.038	1.407	2.162	9.376	27.658	0.422	99.694

Sample	Textural context	Oxides (wt %)													
		SiO ₂	Al ₂ O ₃	TiO ₂	V ₂ O ₃	Cr ₂ O ₃	FeO (measured)			MgO	CaO	FeO (calculated)		Fe ₂ O ₃	Total
SP-153	Same, traverse, rimshot	37.810	21.222	0.031	0.000	0.014	28.448	1.663	2.021	9.022	28.394	0.061	100.237		
DL-33B	Circle 1 gar, rimshot	38.945	21.537	0.017	0.000	0.107	25.849	0.676	4.884	8.593	25.849	0.000	100.608		
	Circle 1 gar, core	38.938	21.342	0.040	0.000	0.000	25.059	0.660	5.145	8.738	25.059	0.000	99.922		
	Circle 1 gar near cpx	38.930	21.442	0.033	0.000	0.000	25.077	0.676	5.116	8.023	25.077	0.000	99.297		
	Circle 2 gar near cpx-plag	38.660	21.431	0.023	0.000	0.015	26.104	0.633	5.323	7.270	26.104	0.000	99.459		
	Circle 2 gar between cpx-plag	38.684	21.341	0.037	0.000	0.040	24.967	0.613	5.062	8.660	24.967	0.000	99.404		
	Circle 3 gar around opaque (ilm)	39.161	21.593	0.050	0.000	0.000	25.945	0.562	5.263	8.360	25.945	0.000	100.934		

GARNET STRUCTURAL FORMULAE

Sample		Site Occupancies (apfu) calculated for 12 oxygens													
		Fe ²⁺ X-site	Mn ²⁺ X-site	Mg X-site	Ca X-site	Total X-site	Ti Y-site	V ³⁺ Y-site	Cr ³⁺ Y-site	Fe ³⁺ Y-site	Total Y-site	Si Z-site	Fe ³⁺ Z-site	Al Z-site	Total Z-site
SP-12		2.070	0.291	0.473	0.115	2.948	0.001	0.000	0.000	0.000	2.032	3.019	0.000	0.000	3.019
		2.083	0.284	0.500	0.111	2.978	0.002	0.000	0.005	0.000	2.022	2.991	0.000	0.009	3.000
		2.133	0.292	0.419	0.101	2.945	0.000	0.000	0.002	0.000	2.030	3.025	0.000	0.000	3.025
		2.109	0.288	0.450	0.103	2.951	0.000	0.000	0.012	0.000	2.033	3.015	0.000	0.000	3.015
		2.101	0.300	0.451	0.106	2.959	0.002	0.000	0.004	0.000	2.027	3.015	0.000	0.000	3.015
		2.146	0.295	0.428	0.102	2.971	0.000	0.000	0.003	0.000	2.011	3.019	0.000	0.000	3.019
		2.114	0.301	0.435	0.106	2.956	0.008	0.000	0.000	0.000	2.044	2.997	0.000	0.003	3.000
		2.115	0.298	0.456	0.106	2.976	0.004	0.000	0.006	0.000	2.024	2.998	0.000	0.002	3.000
SP-149		1.841	0.042	0.664	0.441	2.988	0.002	0.000	0.003	0.000	1.987	3.024	0.000	0.000	3.024
		1.747	0.035	0.729	0.479	2.991	0.000	0.000	0.002	0.000	2.000	3.009	0.000	0.000	3.009
		1.736	0.035	0.769	0.453	2.993	0.002	0.000	0.002	0.000	2.000	3.008	0.000	0.000	3.008
		1.767	0.033	0.734	0.449	2.982	0.003	0.000	0.002	0.000	2.002	3.015	0.000	0.000	3.015
		1.690	0.034	0.778	0.482	2.984	0.004	0.000	0.003	0.000	2.001	3.015	0.000	0.000	3.015
		1.712	0.035	0.761	0.481	2.988	0.002	0.000	0.003	0.023	2.012	2.987	0.002	0.012	3.000
		1.789	0.037	0.679	0.469	2.974	0.002	0.000	0.001	0.000	2.007	3.019	0.000	0.000	3.019
		1.867	0.043	0.664	0.403	2.978	0.003	0.000	0.006	0.000	2.020	3.002	0.000	0.000	3.002
		1.701	0.027	0.770	0.484	2.982	0.002	0.000	0.008	0.000	1.997	3.021	0.000	0.000	3.021
		1.875	0.050	0.634	0.415	2.975	0.003	0.000	0.003	0.000	2.007	3.018	0.000	0.000	3.018
		1.743	0.032	0.737	0.458	2.970	0.002	0.000	0.004	0.000	2.003	3.027	0.000	0.000	3.027
		1.717	0.033	0.761	0.457	2.968	0.002	0.000	0.002	0.000	2.011	3.022	0.000	0.000	3.022
		1.782	0.030	0.729	0.423	2.965	0.001	0.000	0.004	0.000	2.011	3.025	0.000	0.000	3.025
		1.817	0.043	0.685	0.422	2.967	0.000	0.000	0.003	0.000	2.001	3.032	0.000	0.000	3.032
		1.887	0.055	0.625	0.381	2.948	0.001	0.000	0.002	0.000	2.021	3.031	0.000	0.000	3.031

Sample	Site Occupancies (apfu) calculated for 12 oxygens													
	Fe ²⁺ X-site	Mn ²⁺ X-site	Mg X-site	Ca X-site	Total X-site	Ti Y-site	V ³⁺ Y-site	Cr ³⁺ Y-site	Fe ³⁺ Y-site	Total Y-site	Si Z-site	Fe ³⁺ Z-site	Al Z-site	Total Z-site
SP-154	2.073	0.064	0.112	0.731	2.980	0.004	0.000	0.002	0.000	1.992	3.028	0.000	0.000	3.028
	2.076	0.061	0.129	0.756	3.022	0.002	0.000	0.001	0.002	1.959	3.020	0.000	0.000	3.020
	2.010	0.061	0.138	0.757	2.966	0.002	0.000	0.000	0.000	1.992	3.043	0.000	0.000	3.043
	2.024	0.057	0.134	0.754	2.969	0.004	0.000	0.003	0.000	1.998	3.033	0.000	0.000	3.033
	2.046	0.059	0.128	0.754	2.987	0.002	0.000	0.000	0.000	1.974	3.039	0.000	0.000	3.039
	2.041	0.063	0.133	0.727	2.964	0.002	0.000	0.004	0.000	2.011	3.025	0.000	0.000	3.025
	2.037	0.062	0.128	0.755	2.982	0.003	0.000	0.000	0.000	2.006	3.013	0.000	0.000	3.013
	2.090	0.064	0.109	0.751	3.014	0.003	0.000	0.001	0.001	1.975	3.011	0.000	0.000	3.011
	2.096	0.060	0.110	0.726	2.992	0.002	0.000	0.003	0.000	1.998	3.010	0.000	0.000	3.010
	2.095	0.063	0.112	0.704	2.974	0.003	0.000	0.001	0.000	1.990	3.036	0.000	0.000	3.036
	2.042	0.056	0.135	0.749	2.982	0.001	0.000	0.003	0.000	1.999	3.019	0.000	0.000	3.019
SP-153	2.026	0.055	0.129	0.792	3.002	0.003	0.000	0.001	0.000	1.976	3.022	0.000	0.000	3.022
	2.089	0.057	0.125	0.719	2.990	0.002	0.000	0.003	0.000	2.003	3.007	0.000	0.000	3.007
	1.947	0.049	0.129	0.826	2.950	0.004	0.000	0.004	0.000	2.021	3.029	0.000	0.000	3.029
	2.069	0.060	0.135	0.724	2.988	0.003	0.000	0.000	0.000	1.983	3.029	0.000	0.000	3.029
	1.861	0.139	0.215	0.790	3.005	0.002	0.000	0.000	0.037	1.991	3.003	0.000	0.000	3.003
	1.843	0.097	0.261	0.789	2.989	0.002	0.000	0.000	0.033	2.011	2.987	0.002	0.011	3.000
	1.855	0.088	0.254	0.810	3.007	0.002	0.000	0.001	0.019	1.988	3.005	0.000	0.000	3.005
	1.825	0.089	0.258	0.820	2.992	0.003	0.000	0.002	0.026	2.008	2.989	0.003	0.008	3.000
	1.847	0.084	0.258	0.808	2.997	0.003	0.000	0.000	0.043	2.003	2.993	0.003	0.003	3.000
	1.854	0.088	0.253	0.811	3.007	0.003	0.000	0.001	0.002	1.989	3.004	0.000	0.000	3.004
	1.867	0.087	0.258	0.788	2.999	0.006	0.000	0.000	0.009	2.001	2.994	0.006	0.001	3.000
1.845	0.095	0.257	0.801	2.998	0.002	0.000	0.004	0.023	2.002	2.996	0.002	0.002	3.000	

Site Occupancies (apfu) calculated for 12 oxygens														
Sample	Fe ²⁺ X-site	Mn ²⁺ X-site	Mg X-site	Ca X-site	Total X-site	Ti Y-site	V ³⁺ Y-site	Cr ³⁺ Y-site	Fe ³⁺ Y-site	Total Y-site	Si Z-site	Fe ³⁺ Z-site	Al Z-site	Total Z-site
SP-153	1.886	0.112	0.239	0.768	3.005	0.002	0.000	0.001	0.004	1.993	3.003	0.000	0.000	3.003
DL-33B	1.677	0.044	0.565	0.714	3.001	0.001	0.000	0.007	0.000	1.977	3.022	0.000	0.000	3.022
	1.633	0.044	0.598	0.730	3.004	0.002	0.000	0.000	0.000	1.962	3.034	0.000	0.000	3.034
	1.645	0.045	0.598	0.674	2.962	0.002	0.000	0.000	0.000	1.984	3.054	0.000	0.000	3.054
	1.712	0.042	0.622	0.611	2.986	0.001	0.000	0.001	0.000	1.983	3.031	0.000	0.000	3.031
	1.636	0.041	0.591	0.727	2.994	0.002	0.000	0.002	0.000	1.975	3.031	0.000	0.000	3.031
	1.675	0.037	0.606	0.692	3.009	0.003	0.000	0.000	0.000	1.968	3.023	0.000	0.000	3.023

GARNET NOMENCLATURE

Sample	Fe ³⁺			ENDMEMBER COMPOSITION (mole %)						
	Fe ^{tot}	Mg (Mg+Fe ^{tot})	Mg (Mg+Fe ²⁺)	Almandine	Pyrope	Spessartine	Grossular	Andradite	Schorlomite	Uvarovite
SP-12	0.00	0.19	0.19	70.20	16.04	9.87	3.85	0.00	0.03	0.02
	0.00	0.19	0.19	69.94	16.79	9.54	3.43	0.00	0.08	0.23
	0.00	0.16	0.16	72.43	14.24	9.91	3.34	0.00	0.00	0.08
	0.00	0.18	0.18	71.47	15.26	9.77	2.90	0.00	0.00	0.60
	0.00	0.18	0.18	71.02	15.26	10.15	3.29	0.00	0.10	0.19
	0.00	0.17	0.17	72.23	14.41	9.93	3.26	0.00	0.00	0.17
	0.00	0.17	0.17	71.52	14.70	10.17	3.22	0.00	0.38	0.00
	0.00	0.18	0.18	71.09	15.33	10.03	3.03	0.00	0.22	0.30
SP-149	0.00	0.27	0.27	61.77	22.28	1.39	14.31	0.00	0.08	0.16
	0.00	0.29	0.29	58.42	24.39	1.17	15.89	0.00	0.01	0.12
	0.00	0.31	0.31	58.02	25.70	1.16	14.96	0.00	0.08	0.08
	0.00	0.29	0.29	59.24	24.61	1.10	14.83	0.00	0.13	0.10
	0.00	0.32	0.32	56.64	26.06	1.15	15.81	0.00	0.19	0.14
	0.00	0.30	0.31	57.28	25.46	1.16	15.86	0.00	0.09	0.15
	0.00	0.28	0.28	60.16	22.83	1.23	15.63	0.00	0.09	0.07
	0.00	0.26	0.26	62.71	22.31	1.46	13.08	0.00	0.16	0.28
	0.00	0.31	0.31	57.04	25.83	0.91	15.75	0.00	0.08	0.40
	0.00	0.25	0.25	63.02	21.33	1.69	13.67	0.00	0.15	0.15
	0.00	0.30	0.30	58.70	24.81	1.07	15.09	0.00	0.12	0.22
	0.00	0.31	0.31	57.85	25.64	1.10	15.21	0.00	0.08	0.11
	0.00	0.29	0.29	60.12	24.59	1.01	14.05	0.00	0.05	0.18
	0.00	0.27	0.27	61.23	23.09	1.46	14.05	0.00	0.02	0.15
	0.00	0.25	0.25	64.03	21.20	1.86	12.78	0.00	0.04	0.10

Sample	ENDMEMBER COMPOSITION (mole %)									
	Fe ³⁺ (Fe ^{tot})	Mg (Mg+Fe ^{tot})	Mg (Mg+Fe ²⁺)	Almandine	Pyrope	Spessartine	Grossular	Andradite	Schorlomite	Uvarovite
SP-154	0.00	0.05	0.05	69.57	3.75	2.16	24.22	0.00	0.19	0.12
	0.00	0.06	0.06	70.65	4.40	2.07	22.62	0.10	0.10	0.07
	0.00	0.06	0.06	67.78	4.64	2.05	25.45	0.00	0.08	0.00
	0.00	0.06	0.06	68.18	4.52	1.91	25.05	0.00	0.20	0.14
	0.00	0.06	0.06	69.10	4.34	1.99	24.45	0.00	0.13	0.01
	0.00	0.06	0.06	68.87	4.48	2.11	24.24	0.00	0.09	0.20
	0.00	0.06	0.06	68.31	4.29	2.06	25.17	0.00	0.15	0.02
	0.00	0.05	0.05	70.58	3.69	2.15	23.37	0.05	0.13	0.04
	0.00	0.05	0.05	70.06	3.68	2.01	24.04	0.00	0.08	0.13
	0.00	0.05	0.05	70.43	3.78	2.13	23.45	0.00	0.16	0.05
	0.00	0.06	0.06	68.47	4.54	1.89	24.92	0.00	0.06	0.13
	0.00	0.06	0.06	68.35	4.35	1.86	25.22	0.00	0.16	0.05
	0.00	0.06	0.06	69.87	4.18	1.92	23.79	0.00	0.11	0.13
	0.00	0.06	0.06	65.98	4.38	1.65	27.62	0.00	0.18	0.19
0.00	0.06	0.06	69.56	4.52	2.01	23.76	0.00	0.14	0.00	
SP-153	0.02	0.10	0.10	62.31	7.21	4.66	23.82	1.86	0.11	0.02
	0.02	0.12	0.12	61.64	8.72	3.23	26.12	0.20	0.09	0.00
	0.01	0.12	0.12	62.18	8.51	2.96	25.27	0.95	0.10	0.03
	0.02	0.12	0.12	60.99	8.61	2.98	27.00	0.18	0.13	0.10
	0.02	0.12	0.12	61.63	8.61	2.81	25.08	1.69	0.17	0.01
	0.00	0.12	0.12	62.13	8.49	2.96	26.13	0.12	0.13	0.03
	0.01	0.12	0.12	62.24	8.60	2.89	25.61	0.37	0.28	0.01
	0.01	0.12	0.12	61.53	8.57	3.17	25.53	0.89	0.12	0.19

Sample	Fe ³⁺ (Fe ^{tot})				Mg (Mg+Fe ^{tot})				ENDMEMBER COMPOSITION (mole %)						
									Almandine	Pyrope	Spessartine	Grossular	Andradite	Schorlomite	Uvarovite
SP-153	0.00	0.11	0.11	0.11					63.09	8.00	3.74	24.84	0.18	0.09	0.04
DL-33B	0.00	0.25	0.25	0.25					56.56	19.05	1.50	22.51	0.00	0.05	0.33
	0.00	0.27	0.27	0.27					55.48	20.30	1.48	22.62	0.00	0.12	0.00
	0.00	0.27	0.27	0.27					55.53	20.19	1.52	22.66	0.00	0.10	0.00
	0.00	0.27	0.27	0.27					57.55	20.92	1.41	20.00	0.00	0.07	0.05
	0.00	0.27	0.27	0.27					55.21	19.95	1.37	23.22	0.00	0.11	0.13
	0.00	0.27	0.27	0.27					56.76	20.52	1.25	21.33	0.00	0.15	0.00

ILMENITE OXIDE DATA

Sample		Oxides (wt %)									
		MgO	Al ₂ O ₃	SiO ₂	TiO ₂	Cr ₂ O ₃	MnO	FeO	ZnO	V ₂ O ₅	Total
SP-149	Matrix ilmenite between garnet and hornblende	0.501	0.000	0.009	51.837	0.061	0.315	45.077	0.128	0.206	98.134
	Matrix ilmenite	0.755	0.000	0.000	52.224	0.044	0.275	44.842	0.000	0.210	98.350
	Matrix Ilmenite	1.174	0.000	0.000	52.149	0.077	0.234	44.476	0.015	0.282	98.407
SP-154	Ilmenite in plagioclase matrix	0.032	0.000	0.013	48.674	0.042	0.345	48.337	0.086	0.118	97.647
	Ilmenite surrounded by garnet	0.000	0.000	0.015	48.623	0.018	0.465	48.201	0.066	0.266	97.654
SP-153	Ilmenite inclusion in hornblende	0.056	0.000	0.000	50.980	0.025	0.979	45.884	0.158	0.215	98.297
	Small matrix ilmenite	0.053	0.000	0.004	51.078	0.016	1.345	45.525	0.128	0.212	98.361
	Ilmenite between hornblende and plagioclase	0.078	0.000	0.000	50.561	0.031	1.079	46.393	0.027	0.254	98.423

ILMENITE STRUCTURAL FORMULAE

Sample	Site Occupancies (apfu) calculated for 4 oxygens										$\frac{\text{Mg}}{(\text{Mg}+\text{Fe}^{2+})}$	$\frac{\text{Fe}^{2+}}{(\text{Fe}^{2+}+\text{Fe}^{3+})}$	$\frac{\text{Al}}{(\text{Al}+\text{Fe}^{3+}+\text{Cr})}$
	Ti	Al	Cr	Fe3+	Fe2+	Mn	Ni	Mg	Zn	Total			
SP-149	1.503	0.000	0.002	-1.007	2.460	0.010	0.000	0.029	0.004	3	0.012	1.693	0.000
	1.507	0.000	0.001	-1.016	2.455	0.009	0.000	0.043	0.000	3	0.017	1.706	0.000
	1.500	0.000	0.002	-1.003	2.425	0.008	0.000	0.067	0.000	3	0.027	1.705	0.000
SP-154	1.418	0.000	0.001	-0.837	2.402	0.011	0.000	0.002	0.002	3	0.001	1.535	0.000
	1.419	0.000	0.001	-0.838	2.402	0.015	0.000	0.000	0.002	3	0.000	1.536	0.000
SP-153	1.479	0.000	0.001	-0.959	2.440	0.032	0.000	0.003	0.004	3	0.001	1.648	0.000
	1.481	0.000	0.000	-0.963	2.431	0.044	0.000	0.003	0.004	3	0.001	1.656	0.000
	1.465	0.000	0.001	-0.930	2.424	0.035	0.000	0.004	0.001	3	0.002	1.622	0.000

ILMENITE NOMENCLATURE

Sample	Endmembers							
	Spinel	Hercynite	Galaxite	Gahnite	Trevorite	Magnetite	Chromite	Ulvöspinel
SP-149	0.029	-0.043	0.010	0.004	0.000	-0.504	0.001	1.503
	0.043	-0.052	0.009	0.000	0.000	-0.508	0.001	1.507
	0.067	-0.075	0.008	0.000	0.000	-0.501	0.001	1.500
SP-154	0.002	-0.016	0.011	0.002	0.000	-0.418	0.001	1.418
	0.000	-0.017	0.015	0.002	0.000	-0.419	0.000	1.419
SP-153	0.003	-0.040	0.032	0.004	0.000	-0.480	0.000	1.479
	0.003	-0.051	0.044	0.004	0.000	-0.481	0.000	1.481
	0.004	-0.040	0.035	0.001	0.000	-0.465	0.000	1.465

APPENDIX B

THERMOBAROMETRIC DATA

[illegible]

TWO-FELDSPAR THERMOMETRY INPUT DATASETS (Putirka, 2008)

SP-141	K-feldspar composition (weight percent oxide)						Plagioclase feldspar composition (weight percent oxide)					
	SiO ₂	Al ₂ O ₃	FeOt*	CaO	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	FeOt*	CaO	Na ₂ O	K ₂ O
1 Kspar + 1 plag next to kspar	64.107	18.741	0.072	0.014	0.433	15.693	63.367	23.079	0.06	4.033	9.722	0.214
1 Kspar next to hbld + 1 plag next to kspar	64.281	18.79	0.079	0.018	0.539	15.849	63.367	23.079	0.06	4.033	9.722	0.214
**1 Kspar + 1 plag rim next to hbld	64.107	18.741	0.072	0.014	0.433	15.693	64.025	22.777	0.184	4.153	9.477	0.243
**1 Kspar + 1 plag core next to hbld	64.107	18.741	0.072	0.014	0.433	15.693	63.861	22.832	0.133	4.159	9.412	0.288
**1 Kspar + 1 plag next to hbld	64.107	18.741	0.072	0.014	0.433	15.693	63.567	22.63	0.103	3.926	9.661	0.227
**1 Kspar next to hbld + 1 plag rim next to hbld	64.281	18.79	0.079	0.018	0.539	15.849	64.025	22.777	0.184	4.153	9.477	0.243
**1 Kspar next to hbld + 1 plag core next to hbld	64.281	18.79	0.079	0.018	0.539	15.849	63.861	22.832	0.133	4.159	9.412	0.288
**1 Kspar next to hbld + 1 plag next to hbld	64.281	18.79	0.079	0.018	0.539	15.849	63.567	22.63	0.103	3.926	9.661	0.227
2 Kspar + 2 plag adjacent	64.588	18.542	0.083	0.043	0.362	15.893	63.993	22.932	0.148	3.939	9.682	0.24
2 Kspar + 2 plag next to Kspar	64.196	18.543	0.066	0.026	0.33	15.845	64.029	22.912	0.09	4.034	9.551	0.247
2 Kspar + 2 plag matrix	64.257	18.853	0.066	0.018	0.486	15.823	64.015	22.802	0.099	3.999	9.461	0.266
**2 Kspar + 2 plag next to Kspar	64.588	18.542	0.083	0.043	0.362	15.893	64.029	22.912	0.09	4.034	9.551	0.247
**2 Kspar + 2 plag matrix	64.588	18.542	0.083	0.043	0.362	15.893	64.015	22.802	0.099	3.999	9.461	0.266
**2 Kspar + 2 plag adjacent	64.196	18.543	0.066	0.026	0.33	15.845	63.993	22.932	0.148	3.939	9.682	0.24
**2 Kspar + 2 plag matrix	64.196	18.543	0.066	0.026	0.33	15.845	64.015	22.802	0.099	3.999	9.461	0.266
**2 Kspar + 2 plag adjacent	64.257	18.853	0.066	0.018	0.486	15.823	63.993	22.932	0.148	3.939	9.682	0.24
**2 Kspar + 2 plag next to Kspar	64.257	18.853	0.066	0.018	0.486	15.823	64.029	22.912	0.09	4.034	9.551	0.247

*FeO total

**Pairing of analyses not directly indicated as measured from adjacent grains

TWO-FELDSPAR THERMOMETRY INPUT DATASETS (Putirka, 2008)

	K-feldspar composition (weight percent oxide)					Plagioclase feldspar composition (weight percent oxide)						
	SiO ₂	Al ₂ O ₃	FeOt*	CaO	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	FeOt*	CaO	Na ₂ O	K ₂ O
SP-148												
2,3? Kspar + 3 plag touching garnet	62.613	18.937	0.126	0.000	0.925	14.603	59.591	24.955	0.068	6.765	8.001	0.182
**2,3? Kspar + 1 Plag touching garnet	62.613	18.937	0.126	0.000	0.925	14.603	59.326	25.636	0.198	7.595	7.543	0.088
**2,3? Kspar + 1 matrix plag not touching garnet	62.613	18.937	0.126	0.000	0.925	14.603	60.685	24.816	0.078	6.471	8.269	0.162
**2,3? Kspar + 1 matrix plag not touching garnet	62.613	18.937	0.126	0.000	0.925	14.603	63.920	22.756	0.097	3.940	9.562	0.071
**2,3? Kspar + 1 plag touching garnet	62.613	18.937	0.126	0.000	0.925	14.603	59.716	25.397	0.108	6.876	8.084	0.072
3 kspar touching above plag + 3 plag next to kspar not garnet	63.263	18.648	0.045	0.000	1.139	14.765	58.748	25.819	0.068	7.626	7.538	0.104
**3 kspar touching above plag + 3 plag touching garnet	63.263	18.648	0.045	0.000	1.139	14.765	59.591	24.955	0.068	6.765	8.001	0.182
**3 kspar touching above plag + 3 matrix plag	63.263	18.648	0.045	0.000	1.139	14.765	58.809	25.917	0.052	7.666	7.388	0.108
**3 kspar touching above plag + 3? matrix plag far from garnet	63.263	18.648	0.045	0.000	1.139	14.765	60.026	24.970	0.021	6.412	8.113	0.172

*FeO total

**Pairing of analyses not directly indicated as measured from adjacent grains

? Indicates uncertainty of assignment to subregion

TWO-FELDSPAR THERMOMETRY RESULTS (Putirka, 2008)

Thermometer results						
SP-141	P (kbar)	T °C	P (kbar)	T °C	P (kbar)	T °C
1 Kspar + 1 plag next to kspar	0	525	5	538	10	553
1 Kspar next to hbl + 1 plag next to kspar	0	526	5	540	10	555
**1 Kspar + 1 plag rim next to hbl	0	530	5	544	10	559
**1 Kspar + 1 plag core next to hbl	0	531	5	545	10	560
**1 Kspar + 1 plag next to hbl	0	525	5	539	10	553
**1 Kspar next to hbl + 1 plag rim next to hbl	0	532	5	546	10	561
**1 Kspar next to hbl + 1 plag core next to hbl	0	533	5	547	10	562
**1 Kspar next to hbl + 1 plag next to hbl	0	527	5	541	10	555
2 Kspar + 2 plag adjacent	0	632	5	652	10	673
2 Kspar + 2 plag next to Kspar	0	600	5	618	10	637
2 Kspar + 2 plag matrix	0	539	5	553	10	569
**2 Kspar + 2 plag next to Kspar	0	635	5	655	10	677
**2 Kspar + 2 plag matrix	0	637	5	657	10	679
**2 Kspar + 2 plag adjacent	0	597	5	614	10	633
**2 Kspar + 2 plag matrix	0	601	5	620	10	639
**2 Kspar + 2 plag adjacent	0	535	5	549	10	564
**2 Kspar + 2 plag next to Kspar	0	537	5	552	10	567

**Pairing of analyses not directly indicated as measured from adjacent grains

GARNET-BIOTITE THERMOMETRY INPUT DATASETS (Holdaway, 2000)

	Fe^{3+} ($\text{Fe}^{2+}+\text{Fe}^{3+}$)	Compositional Data (weight fraction oxide)									
SP-12 Garnet		SiO_2	TiO_2	Al_2O_3	FeO total	MnO	MgO	CaO	Na_2O	K_2O	
1 (rim)	0.000	0.377	0.000	0.215	0.309	0.043	0.040	0.013	0.000	0.000	
1 (core)	0.000	0.373	0.000	0.215	0.311	0.042	0.042	0.013	0.000	0.000	
3 (rimshot)	0.000	0.372	0.000	0.212	0.314	0.042	0.035	0.012	0.000	0.000	
3 (inner rim)	0.000	0.375	0.000	0.213	0.314	0.042	0.038	0.012	0.000	0.000	
3 (inner rim)	0.000	0.374	0.000	0.213	0.312	0.044	0.038	0.012	0.000	0.000	
3 (inner rim)	0.000	0.379	0.000	0.214	0.322	0.044	0.036	0.012	0.000	0.000	
3 (rim)	0.000	0.371	0.001	0.215	0.313	0.044	0.036	0.012	0.000	0.000	
3 (inner rim)	0.000	0.373	0.001	0.213	0.315	0.044	0.038	0.012	0.000	0.000	

	Fe^{3+} ($\text{Fe}^{2+}+\text{Fe}^{3+}$)	Compositional Data (weight fraction oxide)									
SP-12 Biotite		SiO_2	TiO_2	Al_2O_3	FeO total	MnO	MgO	CaO	Na_2O	K_2O	
1 Matrix	0.000	0.350	0.036	0.197	0.192	0.000	0.102	0.000	0.002	0.098	
1 Adjacent to gar	0.000	0.385	0.021	0.202	0.152	0.000	0.075	0.008	0.022	0.070	
3 Inclusion in gar	0.000	0.353	0.025	0.203	0.186	0.000	0.107	0.000	0.002	0.098	
3 Adjacent to gar	0.000	0.367	0.021	0.189	0.197	0.000	0.084	0.001	0.002	0.067	
3 Matrix	0.000	0.353	0.033	0.195	0.192	0.000	0.103	0.000	0.002	0.095	

GARNET-BIOTITE THERMOMETRY INPUT DATASETS (Holdaway, 2000)

SP-153 Garnet	Compositional Data (weight fraction oxide)									
	Fe ³⁺ (Fe ²⁺ +Fe ³⁺)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO total	MnO	MgO	CaO	Na ₂ O	K ₂ O
Garnet in leuco, rimshot on traverse	0.020	0.376	0.000	0.207	0.284	0.021	0.018	0.092	0.000	0.000
Traverse, inner rim, along x axis	0.018	0.376	0.000	0.212	0.282	0.014	0.022	0.093	0.000	0.000
Traverse, x axis	0.010	0.377	0.000	0.209	0.281	0.013	0.021	0.095	0.000	0.000
Traverse	0.016	0.375	0.000	0.212	0.278	0.013	0.022	0.096	0.000	0.000
Traverse	0.025	0.378	0.001	0.210	0.286	0.013	0.022	0.095	0.000	0.000
Traverse	0.001	0.378	0.000	0.212	0.279	0.013	0.021	0.095	0.000	0.000
Traverse	0.008	0.376	0.001	0.212	0.283	0.013	0.022	0.092	0.000	0.000
Traverse, inner rim	0.014	0.376	0.000	0.210	0.280	0.014	0.022	0.094	0.000	0.000
Traverse rimshot	0.002	0.378	0.000	0.212	0.284	0.017	0.020	0.090	0.000	0.000

SP-153 Biotite	Compositional Data (weight fraction oxide)									
	Fe^{3+} ($\text{Fe}^{2+}+\text{Fe}^{3+}$)	SiO_2	TiO_2	Al_2O_3	FeO total	MnO	MgO	CaO	Na_2O	K_2O
	0.000	0.350	0.042	0.147	0.258	0.001	0.072	0.000	0.001	0.091
	0.000	0.348	0.041	0.152	0.251	0.001	0.070	0.000	0.001	0.091
	0.000	0.349	0.041	0.150	0.242	0.001	0.073	0.000	0.001	0.093
	0.000	0.350	0.041	0.150	0.243	0.001	0.072	0.001	0.001	0.090
	0.000	0.350	0.044	0.152	0.245	0.001	0.074	0.000	0.001	0.090
	0.000	0.348	0.043	0.151	0.246	0.001	0.073	0.000	0.001	0.089
	0.000	0.349	0.042	0.152	0.240	0.000	0.073	0.000	0.001	0.090
	0.000	0.349	0.039	0.148	0.250	0.001	0.073	0.000	0.002	0.090

GARNET-BIOTITE THERMOMETRY RESULTS (Holdaway, 2000)

Sample	Garnet-biotite analysis pairing	T (°C)	Sample	Garnet-biotite analysis pairing	T (°C)
SP-12	1 (rim) gar + 1 (adj) bio	663	SP-153	Traverse rimshot + 8	698
	3 (rimshot) gar + 3 (adj) bio	672		Traverse, same grain, inner rim, along x axis + 1	743
	3 (rim) gar + 3 (adj) bio	682		Traverse, same grain, inner rim, along x axis + 2	739
	1 (core) gar + 1 (matrix) bio	664		Traverse, same grain, inner rim, along x axis + 3	715
	3 (inner rim) gar + 3 (matrix) bio	639		Traverse, same grain, inner rim, along x axis + 4	720
	3 (inner rim) gar + 3 (matrix) bio	641		Traverse, same grain, inner rim, along x axis + 5	715
	3 (inner rim) gar + 3 (matrix) bio	625		Traverse, same grain, inner rim, along x axis + 6	720
	3 (inner rim) gar + 3 (matrix) bio	642		Traverse, same grain, inner rim, along x axis + 7	712
	3 (inner rim) gar + 3 (inclusion in gar) bio	625		Traverse, same grain, inner rim, along x axis + 8	730
	3 (inner rim) gar + 3 (inclusion in gar) bio	627		Traverse, x axis + 1	733
	3 (inner rim) gar + 3 (inclusion in gar) bio	611		Traverse, x axis + 2	729
	3 (inner rim) gar + 3 (inclusion in gar) bio	627		Traverse, x axis + 3	706
SP-153	Garnet in leuco, rimshot on traverse + 1	686		Traverse, x axis + 4	711
	Garnet in leuco, rimshot on traverse + 2	685		Traverse, x axis + 5	706
	Garnet in leuco, rimshot on traverse + 3	664		Traverse, x axis + 6	711
	Garnet in leuco, rimshot on traverse + 4	669		Traverse, x axis + 7	703
	Garnet in leuco, rimshot on traverse + 5	664		Traverse, x axis + 8	721
	Garnet in leuco, rimshot on traverse + 6	668		Traverse + 1	743
	Garnet in leuco, rimshot on traverse + 7	662		Traverse + 2	739
	Garnet in leuco, rimshot on traverse + 8	676		Traverse + 3	715
	Traverse rimshot + 1	710		Traverse + 4	720
	Traverse rimshot + 2	707		Traverse + 5	715
	Traverse rimshot + 3	685		Traverse + 6	720
	Traverse rimshot + 4	690		Traverse + 7	712
	Traverse rimshot + 5	685		Traverse + 8	730
	Traverse rimshot + 6	690		Traverse + 1	739
	Traverse rimshot + 7	683		Traverse + 2	735
				Traverse + 3	712

GARNET-BIOTITE THERMOMETRY RESULTS (Holdaway, 2000) cont.					
Sample	Garnet-biotite analysis pairing	T (°C)	Sample	Garnet-biotite analysis pairing	T (°C)
SP-153 cont.	Traverse + 4	717	SP-153	Traverse, inner rim + 8	726
	Traverse + 5	711			
	Traverse + 6	716			
	Traverse + 7	708			
	Traverse + 8	727			
	Traverse + 1	733			
	Traverse + 2	729			
	Traverse + 3	706			
	Traverse + 4	711			
	Traverse + 5	705			
	Traverse + 6	710			
	Traverse + 7	702			
	Traverse + 8	720			
	Traverse + 1	735			
	Traverse + 2	731			
	Traverse + 3	708			
	Traverse + 4	713			
	Traverse + 5	708			
	Traverse + 6	713			
	Traverse + 7	705			
	Traverse + 8	723			
	Traverse, inner rim + 1	739			
	Traverse, inner rim + 2	735			
	Traverse, inner rim + 3	711			
	Traverse, inner rim + 4	716			
	Traverse, inner rim + 5	711			
	Traverse, inner rim + 6	716			
	Traverse, inner rim + 7	708			

HORNBLende-PLAGIOCLASE THERMOMETRY INPUT DATASETS (Holland and Blundy, 1994)

Amphibole Compositional Data (weight percent oxide)										
Sample	Point	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
SP-149	1	42.55	0.95	15.01	14.01	0.09	11.83	11.09	1.26	0.36
	2	41.82	0.86	14.93	14.08	0.08	11.77	10.98	1.2	0.34
	3	42.97	0.86	14.72	13.04	0.07	11.73	11.19	1.18	0.33
	4	42.66	0.79	15.05	14.26	0.03	11.68	11.09	1.28	0.26
	5	42.25	0.89	15.36	14.21	0.05	11.54	11.03	1.31	0.36
	6	42.59	0.98	15.51	14	0.1	11.54	11.08	1.31	0.39
SP-153	1	39.28	1.16	13.25	22.93	0.19	5.93	10.93	1.67	1.09
	2	39.07	1.37	13.11	24.01	0.21	6.08	11.34	1.6	1.13
	3	38.8	1.46	13.09	22.72	0.19	5.97	11.38	1.77	1.16
	4	38.97	1.36	12.9	23.34	0.21	6.13	11.34	1.69	1.1
	5	39.34	1.17	13.18	23.05	0.19	5.93	11.39	1.68	1.11
	6	39.28	1.32	13.09	23.27	0.2	6.05	11.38	1.74	1.08

Plagioclase Compositional Data			Plagioclase Compositional Data	
Sample	Textural notes	Mole fraction albite	Sample	Textural notes
SP-149	Circle 1 plag touching garnet	0.41	SP-153	Circle 1 plag away from gar
	Circle 1 same plag in corner, core	0.42		Circle 1 new grain in matrix not touching gar
	Circle 1 matrix plag not touching gar	0.51		Circle 1 plag rimshot next to small gar
	Circle 2 (blue) plag touching gar	0.49		Circle 1 same, mm along strike, core
	Circle 2 (blue) same, core	0.46		Circle 2 plag in contact with gar
	Circle 2 (blue) matrix plag	0.41		Circle 3 matrix plag
	Circle 3 plag touching gar	0.39		Circle 2 matrix plag not touching gar
	Circle 3 matrix plag not touching gar	0.4		
	Circle 4 plag not touching gar	0.37		
	Circle 4 matrix plag	0.39		

HORNBLende-PLAGIOCLASE THERMOMETRY RESULTS

Thermometers A and B of Holland and Blundy (1994)

Amphibole analysis		Xab	Edenite-Tremolite				Edenite-Richterite			
↓	Plagioclase analysis		0 kbar	5 kbar	10 kbar	15 kbar	0 kbar	5 kbar	10 kbar	15 kbar
SP-149	1 Circle 1 plag touching garnet	0.41	723	750	778	806	672	729	786	844
	1 Circle 1 same plag in corner, core	0.42	721	749	777	804	671	728	785	842
	1 Circle 1 matrix plag not touching gar	0.51	711	738	764	791	661	717	772	827
	1 Circle 2 (blue) plag touching gar	0.49	715	742	769	796	665	721	777	833
	1 Circle 2 (blue) same, core	0.46	717	745	772	799	668	724	780	837
	1 Circle 2 (blue) matrix plag	0.41	723	750	778	806	672	729	786	844
	1 Circle 3 plag touching gar	0.39	725	753	781	809	674	731	789	847
	1 Circle 3 matrix plag not touching gar	0.40	724	752	780	807	673	730	788	845
	1 Circle 4 plag not touching gar	0.37	728	756	784	813	676	734	792	850
	1 Circle 4 matrix plag	0.39	725	753	781	809	674	731	789	847
	2 Circle 1 plag touching garnet	0.41	739	763	788	813	679	734	789	844
	2 Circle 1 same plag in corner, core	0.42	737	762	787	811	678	733	788	842
	2 Circle 1 matrix plag not touching gar	0.51	726	750	774	798	668	721	775	828
	2 Circle 2 (blue) plag touching gar	0.49	730	754	778	802	672	726	779	833
	2 Circle 2 (blue) same, core	0.46	733	757	782	806	675	729	783	837
	2 Circle 2 (blue) matrix plag	0.41	739	763	788	813	679	734	789	844
	2 Circle 3 plag touching gar	0.39	741	766	791	816	681	736	791	847
	2 Circle 3 matrix plag not touching gar	0.40	740	765	790	815	680	735	790	845
	2 Circle 4 plag not touching gar	0.37	744	769	795	820	683	739	794	850
	2 Circle 4 matrix plag	0.39	741	766	791	815	681	736	791	847
	3 Circle 1 plag touching garnet	0.41	667	704	741	778	628	692	756	821

Thermometers A and B of Holland and Blundy (1994)

Amphibole analysis			Edenite-Tremolite				Edenite-Richterite				
	↓	Plagioclase analysis	Xab	0 kbar	5 kbar	10 kbar	15 kbar	0 kbar	5 kbar	10 kbar	15 kbar
SP-149 cont.	3	Circle 1 same plag in corner, core	0.42	666	703	740	777	627	691	755	819
	3	Circle 1 matrix plag not touching gar	0.51	657	693	729	765	619	681	743	805
	3	Circle 2 (blue) plag touching gar	0.49	661	697	733	769	622	685	747	810
	3	Circle 2 (blue) same, core	0.46	663	699	736	772	624	687	751	814
	3	Circle 2 (blue) matrix plag	0.41	667	704	741	778	628	692	756	821
	3	Circle 3 plag touching gar	0.39	669	706	744	781	629	694	759	824
	3	Circle 3 matrix plag not touching gar	0.40	668	705	742	780	628	693	758	822
	3	Circle 4 plag not touching gar	0.37	671	709	746	784	631	696	762	827
	3	Circle 4 matrix plag	0.39	669	706	744	781	629	694	759	824
	4	Circle 1 plag touching garnet	0.41	715	746	778	810	660	719	779	838
	4	Circle 1 same plag in corner, core	0.42	714	745	777	808	659	718	777	837
	4	Circle 1 matrix plag not touching gar	0.51	703	734	764	795	650	707	765	822
	4	Circle 2 (blue) plag touching gar	0.49	707	738	769	799	654	711	769	827
	4	Circle 2 (blue) same, core	0.46	710	741	772	803	656	714	773	831
	4	Circle 2 (blue) matrix plag	0.41	715	746	778	810	660	719	779	838
	4	Circle 3 plag touching gar	0.39	717	749	781	813	662	721	781	841
	4	Circle 3 matrix plag not touching gar	0.40	716	748	779	811	661	720	780	840
	4	Circle 4 plag not touching gar	0.37	720	752	784	816	663	724	784	844
	4	Circle 4 matrix plag	0.39	717	749	781	813	662	721	781	841
	5	Circle 1 plag touching garnet	0.41	713	748	782	817	660	721	781	842
	5	Circle 1 same plag in corner, core	0.42	712	746	781	816	659	720	780	840
	5	Circle 1 matrix plag not touching gar	0.51	701	735	768	802	650	709	767	825

Thermometers A and B of Holland and Blundy (1994)

Amphibole analysis			Edenite-Tremolite				Edenite-Richterite				
	↓	Plagioclase analysis	Xab	0 kbar	5 kbar	10 kbar	15 kbar	0 kbar	5 kbar	10 kbar	15 kbar
SP-149 cont.	5	Circle 2 (blue) plag touching gar	0.49	705	739	773	806	654	713	772	830
	5	Circle 2 (blue) same, core	0.46	708	742	776	810	656	716	775	834
	5	Circle 2 (blue) matrix plag	0.41	713	748	782	817	660	721	781	842
	5	Circle 3 plag touching gar	0.39	715	750	785	820	66	723	784	845
	5	Circle 3 matrix plag not touching gar	0.40	714	749	784	819	661	722	782	843
	5	Circle 4 plag not touching gar	0.37	718	754	789	824	664	725	787	848
	5	Circle 4 matrix plag	0.39	715	750	785	820	662	723	784	845
	6	Circle 1 plag touching garnet	0.41	696	734	773	811	650	713	776	839
	6	Circle 1 same plag in corner, core	0.42	695	733	771	810	649	712	774	837
	6	Circle 1 matrix plag not touching gar	0.51	685	722	759	796	640	701	762	822
	6	Circle 2 (blue) plag touching gar	0.49	689	726	763	801	644	705	766	827
	6	Circle 2 (blue) same, core	0.46	691	729	766	804	646	708	770	831
	6	Circle 2 (blue) matrix plag	0.41	696	734	773	811	650	713	776	839
	6	Circle 3 plag touching gar	0.39	698	737	776	814	651	715	778	842
	6	Circle 3 matrix plag not touching gar	0.40	697	736	774	813	651	714	777	840
	6	Circle 4 plag not touching gar	0.37	701	740	779	818	653	717	781	845
	6	Circle 4 matrix plag	0.39	698	737	776	814	651	715	778	842
SP-153	1	Circle 1 plag in contact with gar	0.56	805	801	797	793	736	774	811	849
	1	Circle 1 plag away from gar	0.57	801	797	793	789	733	770	808	845
	1	Circle 1 new grain in matrix not touching gar	0.57	801	797	793	789	733	770	808	845
	1	Circle 1 plag rimshot next to small gar	0.56	805	801	797	793	736	774	811	849

		Thermometers A and B of Holland and Blundy (1994)									
Amphibole analysis		Edenite-Tremolite				Edenite-Richterite					
	↓	Plagioclase analysis	Xab	0 kbar	5 kbar	10 kbar	15 kbar	0 kbar	5 kbar	10 kbar	15 kbar
SP-153 cont.	1	Circle 1 same, mm along strike, core	0.59	794	790	786	782	726	763	801	838
	1	Circle 2 plag in contact with gar	0.58	797	793	790	786	729	767	804	842
	1	Circle 3 matrix plag	0.60	791	787	783	779	723	760	797	834
	1	Circle 2 matrix plag not touching gar	0.58	797	793	790	786	729	767	804	842
	*	2	Circle 1 plag in contact with gar	0.56	905	874	842	811	788	814	839
	*	2	Circle 1 plag away from gar	0.57	901	870	838	807	785	810	835
	*	2	Circle 1 new grain in matrix not touching gar	0.57	901	870	838	807	785	810	835
	*	2	Circle 1 plag rimshot next to small gar	0.56	905	874	842	811	788	814	839
	*	2	Circle 1 same, mm along strike, core	0.59	894	862	831	800	778	803	828
	*	2	Circle 2 plag in contact with gar	0.58	897	866	835	803	781	806	832
	*	2	Circle 3 matrix plag	0.60	890	859	828	796	775	799	824
	*	2	Circle 2 matrix plag not touching gar	0.58	897	866	835	803	781	806	832
	3	Circle 1 plag in contact with gar	0.56	867	850	835	815	748	779	810	842
	3	Circle 1 plag away from gar	0.57	863	846	828	811	744	776	807	838
	3	Circle 1 new grain in matrix not touching gar	0.57	863	846	828	811	744	776	807	838
	3	Circle 1 plag rimshot next to small gar	0.56	867	850	832	815	748	779	810	842
	3	Circle 1 same, mm along strike, core	0.59	855	838	820	803	738	769	800	831
	3	Circle 2 plag in contact with gar	0.58	859	842	824	807	741	772	803	834
	3	Circle 3 matrix plag	0.60	851	834	817	799	734	765	796	827
	3	Circle 2 matrix plag not touching gar	0.58	859	842	824	807	741	772	803	834
	4	Circle 1 plag in contact with gar	0.56	894	866	838	809	774	801	828	855
	4	Circle 1 plag away from gar	0.57	890	862	834	805	771	798	824	851

* analyses have low Si content in amphibole phase (^{IV}Si = 6.02 apfu)

Thermometers A and B of Holland and Blundy (1994)

Amphibole analysis			Edenite-Tremolite					Edenite-Richterite			
↓	Plagioclase analysis	Xab	0 kbar	5 kbar	10 kbar	15 kbar	0 kbar	5 kbar	10 kbar	15 kbar	
4	Circle 1 plag rimshot next to small gar	0.56	894	866	838	809	774	801	828	855	
4	Circle 1 same, mm along strike, core	0.59	882	854	826	798	764	791	817	844	
4	Circle 2 plag in contact with gar	0.58	886	858	830	802	767	794	821	847	
4	Circle 3 matrix plag	0.60	878	850	823	895	761	787	814	840	
4	Circle 2 matrix plag not touching gar	0.58	886	858	830	802	767	794	821	847	
5	Circle 1 plag in contact with gar	0.56	830	820	810	800	732	766	800	835	
5	Circle 1 plag away from gar	0.57	826	816	806	796	728	763	797	831	
5	Circle 1 new grain in matrix not touching gar	0.57	826	816	806	796	728	763	797	831	
5	Circle 1 plag rimshot next to small gar	0.56	830	820	810	800	732	766	800	835	
5	Circle 1 same, mm along strike, core	0.59	818	809	799	789	722	756	790	824	
5	Circle 2 plag in contact with gar	0.58	822	812	802	793	725	759	793	828	
5	Circle 3 matrix plag	0.60	815	805	795	785	719	753	786	820	
5	Circle 2 matrix plag not touching gar	0.58	822	812	802	793	725	759	793	828	
6	Circle 1 plag in contact with gar	0.56	866	846	826	807	756	787	817	848	
6	Circle 1 plag away from gar	0.57	862	842	823	803	753	784	814	844	
6	Circle 1 new grain in matrix not touching gar	0.57	862	842	823	803	753	784	814	844	
6	Circle 1 plag rimshot next to small gar	0.56	866	846	826	807	756	787	817	848	
6	Circle 1 same, mm along strike, core	0.59	854	835	815	796	746	777	807	837	
6	Circle 2 plag in contact with gar	0.58	858	838	819	799	750	780	810	841	
6	Circle 3 matrix plag	0.60	850	831	811	792	743	773	803	833	
6	Circle 2 matrix plag not touching gar	0.58	858	838	819	799	750	780	810	841	

AL-IN-AMPHIBOLE BAROMETRY RESULTS (kbar)

	Al total content (apfu)	Hammarstrom & Zen (1986)	Hollister et al. (1987)	Johnson & Rutherford (1989)	Schmidt (1992)
SP-143	2.22	7.23	7.74	5.92	7.54
	2.24	7.37	7.89	6.03	7.67
	2.19	7.08	7.58	5.79	7.40
	2.22	7.24	7.76	5.93	7.55
	2.25	7.41	7.94	6.07	7.71
SP-149	2.57	8.99	9.72	7.40	9.21
	2.58	9.06	9.80	7.46	9.28
	2.54	8.85	9.56	7.28	9.08
	2.57	9.03	9.76	7.43	9.24
	2.63	9.32	10.09	7.68	9.52
	2.65	9.43	10.21	7.76	9.62
SP-153	2.43	8.32	8.96	6.83	8.57
	2.38	8.07	8.68	6.62	8.33
	2.42	8.23	8.86	6.76	8.49
	2.37	7.98	8.58	6.55	8.25
	2.41	8.23	8.86	6.75	8.48
	2.39	8.10	8.72	6.65	8.37

TWQ THERMOBAROMETRY INPUT DATASETS

SP-12	Gar 1 core Bio 1 adj to gar Plag 1 core (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12*	37.342	0.026	21.455	0.072	31.101	4.187	4.189	1.296	0.000	0.000
	bSP12	34.983	3.642	19.747	0.000	19.179	0.000	10.182	0.028	0.196	9.815
	pSP12	61.852	0.000	25.163	0.000	0.003	0.000	0.000	5.922	8.243	0.119
	Gar 1 rim Bio 1 adj to gar Plag 1 core (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12	37.652	0.009	21.497	0.005	30.864	4.283	3.957	1.337	0.000	0.000
	bSP12	38.483	2.126	20.188	0.000	15.245	0.000	7.475	0.846	2.223	7.049
	pSP12	61.852	0.000	25.163	0.000	0.003	0.000	0.000	5.922	8.243	0.119
	Gar 3 rim Bio 3 adj to gar Plag 2 near bio-gar (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12	37.245	0.000	21.187	0.024	31.397	4.242	3.462	1.157	0.000	0.000
	bSP12	36.686	2.112	18.938	0.000	19.656	0.000	8.370	0.106	0.172	6.734
	pSP12	62.724	0.076	23.741	0.000	0.000	0.000	0.000	4.515	8.989	0.068
	Gar 3 inner rim Bio 3 matrix Plag 2 adj to gar-bio (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12	37.505	0.000	21.338	0.185	31.374	4.236	3.758	1.199	0.000	0.000
	bSP12	35.345	3.280	19.544	0.000	19.224	0.000	10.289	0.000	0.234	9.492
	pSP12	62.724	0.076	23.741	0.000	0.000	0.000	0.000	4.515	8.989	0.068
	Gar 3 inner rim Bio 3 inclusion Plag 2 adj to gar-bio (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12	37.505	0.000	21.338	0.185	31.374	4.236	3.758	1.199	0.000	0.000
	bSP12	35.256	2.538	20.328	0.000	18.582	0.000	10.741	0.000	0.207	9.838
	pSP12	62.724	0.076	23.741	0.000	0.000	0.000	0.000	4.515	8.989	0.068
	Gar 3 rim Bio 3 adj to gar Plag 1 core (oxide weight percent)										
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
	gSP12	37.245	0.000	21.187	0.024	31.397	4.242	3.462	1.157	0.000	0.000
	bSP12	36.686	2.112	18.938	0.000	19.656	0.000	8.370	0.106	0.172	6.734
	pSP12	61.852	0.000	25.163	0.000	0.003	0.000	0.000	5.922	8.243	0.119

TWQ THERMOBAROMETRY INPUT DATASETS

SP-12 cont.	Gar 3 inner rim Bio 3 matrix Plag 1 core (oxide weight percent)													
	Phase	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O			
	gSP12	37.505	0.000	21.338	0.185	31.374	4.236	3.758	1.199	0.000	0.000			
	bSP12	35.345	3.280	19.544	0.000	19.224	0.000	10.289	0.000	0.234	9.492			
	pSP12	61.852	0.000	25.163	0.000	0.003	0.000	0.000	5.922	8.243	0.119			

* g = garnet, b =biotite, p = plagioclase analyses

*g = garnet, b = biotite, p = plagioclase analyses

Metapelite sample SP-12

TWQ results plotting metastable reactions for all equilibria in the KCFMASH system, considering 10 phases: almandine, annite, anorthite, eastonite, grossular, phlogopite, pyrope, alpha-quartz, sillimanite, and siderophyllite. Points selected for individual analysis were taken from three subregions and recombined for possible peak and reequilibration conditions.

Thermodynamic dataset:
v 2.02

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

in = inclusion

a = adjacent to garnet

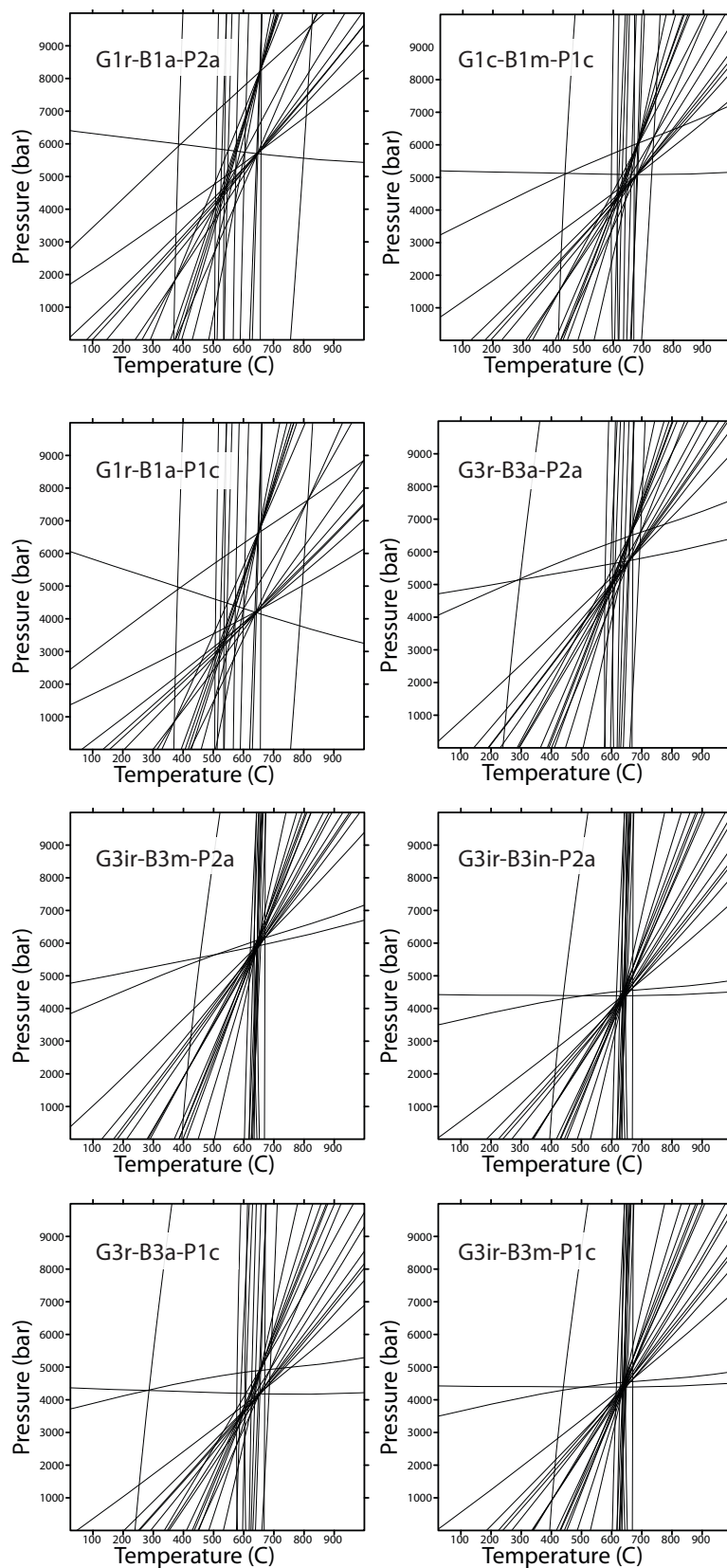
m = matrix occurrence

Peak assemblage:

G3ir-B3m-P2a

Reequilibration assemblage:

G3r-B3a-P1c



Metapelite sample SP-12

TWQ results plotting metastable reactions for all equilibria in the TiKCFMASH system, considering 10 phases: almandine, annite, anorthite, grossular, ilmenite, phlogopite, pyrope, alpha-quartz, rutile, and sillimanite. Points selected for individual analysis were taken from three subregions and recombined for possible peak and reequilibration conditions.

Thermodynamic Dataset:
v 1.02

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

a = adjacent to garnet

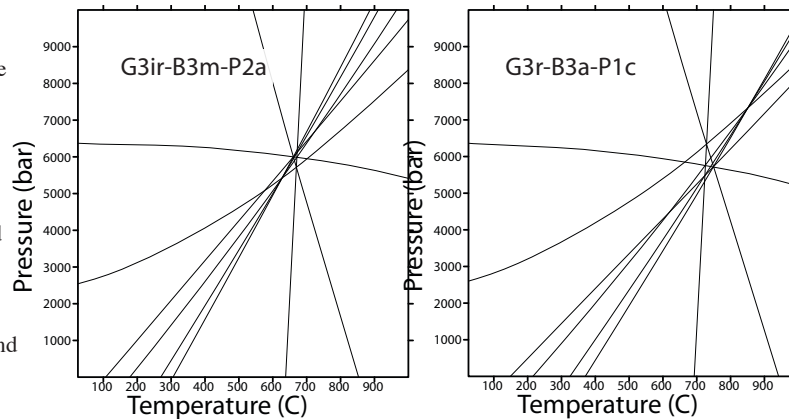
m = matrix occurrence

Peak assemblage:

G3ir-B3m-P2a

Reequilibration assemblage:

G3r-B3a-P1c



Metapelite sample SP-12

TWQ results plotting metastable reactions for selected equilibria in the KCFMASH system, considering 10 phases: almandine, annite, anorthite, eastonite, grossular, phlogopite, pyrope, alpha-quartz, sillimanite, and siderophyllite. Points selected for individual analysis were taken from three subregions and recombined for possible peak and reequilibration conditions.

Thermodynamic dataset:
v 2.02

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

in = inclusion

a = adjacent to garnet

m = matrix occurrence

Reaction curves:

1) GASP

2) GBPQ-Mg

3) GBPQ-Fe

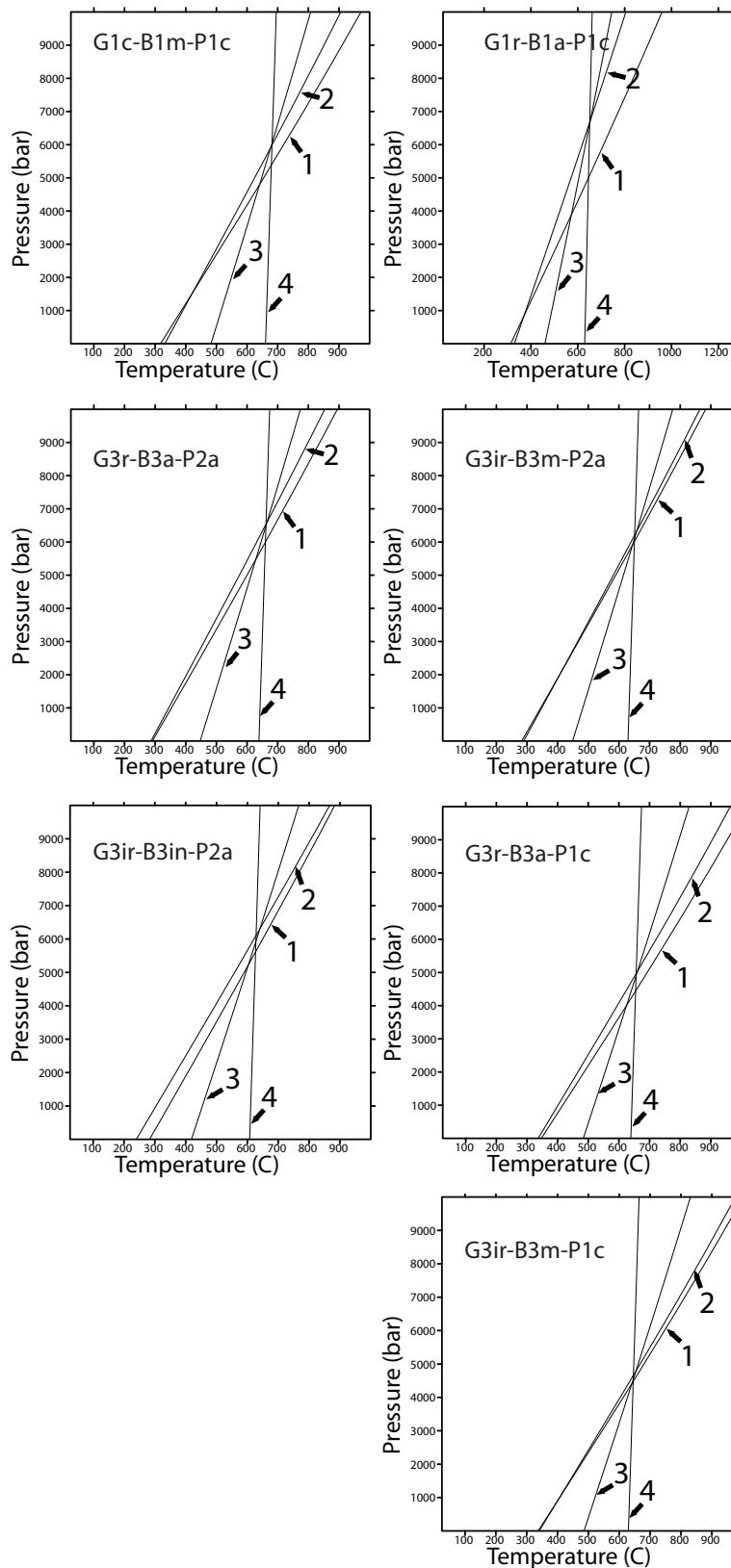
4) Gar-bio

Peak assemblage:

G3ir-B3m-P2a

Reequilibration assemblage:

G3r-B3a-P2c



Metapelite sample SP-12

TWQ results plotting metastable reactions for selected equilibria in the TiKCFMASH system, considering 10 phases: almandine, annite, anorthite, grossular, ilmenite, phlogopite, pyrope, alpha-quartz, rutile, and sillimanite. Points selected for individual analysis were taken from three subregions and recombined for possible peak and reequilibration conditions.

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

a = adjacent to garnet

m = matrix occurrence

Reaction curves:

1) GASP

2) GRAIL

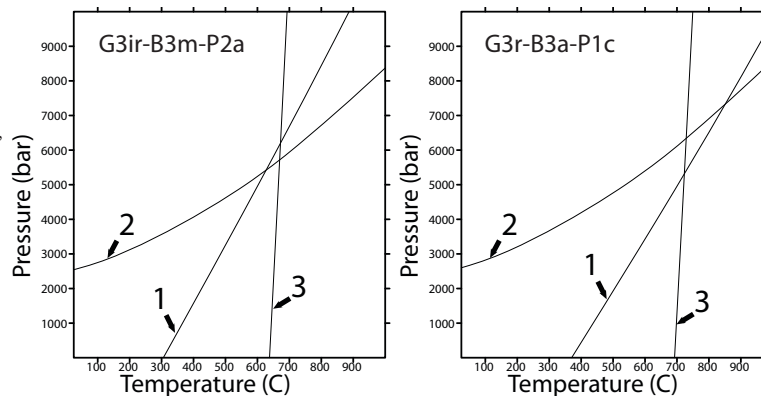
3) Gar-bio

Peak assemblage:

G3ir-B3m-P2a

Reequilibration assemblage:

G3r-B3a-P1c



TWQ THERMOBAROMETRY RESULTS: Garnet-sillimanite schist SP-12

Thermodynamic dataset v2.02: KCFMASH system with garnet-biotite-plagioclase and pure phases α -quartz and sillimanite

Intersections											
Garnet	Biotite	Plagioclase	used	P avg	T avg	GASP	Gar-Bio	GBPQ-Mg	Gar-Bio	GBPQ-Fe	Gar-Bio
1 core	1 matrix	1 core	124/218	4.831 ± 0.265 kbar	650 ± 24 °C	5.383 kbar	679 °C	5.988 kbar	681 °C	6.117 kbar	681 °C
1 rim	1 adj to gar	1 core	90/197	4.075 ± 0.350 kbar	612 ± 43 °C	5.001 kbar	646 °C	6.764 kbar	651 °C	6.693 kbar	651 °C
3 rim	3 adj to gar	2 adj to gar	107/195	5.631 ± 0.300 kbar	644 ± 23 °C	5.998 kbar	660 °C	6.567 kbar	661 °C	6.553 kbar	661 °C
3 inner rim	3 matrix	2 adj to gar	186/204	5.922 ± 0.242 kbar	646 ± 12 °C	6.017 kbar	651 °C	6.207 kbar	651 °C	6.199 kbar	651 °C
3 inner rim	3 inclusion	2 adj to gar	70/194	5.316 ± 0.198 kbar	616 ± 10 °C	5.613 kbar	626 °C	6.108 kbar	628 °C	5.988 kbar	627 °C
3 rim	3 adj to gar	1 core	132/209	4.077 ± 0.298 kbar	636 ± 25 °C	4.442 kbar	654 °C	4.969 kbar	656 °C	5.016 kbar	657 °C
3 inner rim	3 matrix	1 core	210/224	4.384 ± 0.217 kbar	640 ± 13 °C	4.480 kbar	645 °C	4.663 kbar	646 °C	4.631 kbar	646 °C

Thermodynamic dataset v1.02: TiKCFMASH system with pure phases ilmenite, α -quartz, rutile

Intersections									
Garnet	Biotite	Plagioclase	used	P avg	T avg	GASP	Gar-Bio	GRAIL	Gar-Bio
3 inner rim	3 matrix	2 adj to gar	17 / 20	5.996 ± 0.137 kbar	664 ± 5 °C	6.200 kbar	672 °C	5.717 kbar	670 °C
3 rim	3 adj to gar	1 core	14 / 18	5.727 ± 0.159 kbar	741 ± 12 °C	5.316 kbar	723 °C	6.341 kbar	723 °C

TWO THERMOBAROMETRY INPUT DATASETS

SP-149	Gar 1 rim + plag 1 rim adj to bio + amphibole rep + ilmenite rep (oxide weight percent)											
	Phase	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149*	38.955	21.912	0.051	28.935	0.767	5.493	5.003	0.000	0.000	0.000	0.000
	pSP149	53.004	29.457	0.000	0.125	0.000	0.000	12.499	4.713	0.016	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	Gar 1 rim + plag 1 rim adj to bio + amphibole rep + ilmenite rep (oxide weight percent)											
	Phase	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.201	22.088	0.028	26.628	0.501	6.622	5.535	0.000	0.000	0.000	0.000
	pSP149	53.212	29.538	0.000	0.087	0.000	0.000	12.100	4.922	0.018	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	SP-149 Gar 1 core + plag 1 matrix + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.201	22.088	0.028	26.628	0.501	6.622	5.535	0.000	0.000	0.000	0.000
	pSP149	55.226	28.068	0.000	0.078	0.000	0.000	10.330	5.987	0.027	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	SP-149 Gar 2 rim adj to bio + plag 2 rim adj to gar + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	38.654	21.970	0.054	28.745	0.659	5.736	4.839	0.000	0.000	0.000	0.000
	pSP149	54.493	28.531	0.000	0.103	0.000	0.000	10.838	5.692	0.018	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210

TWQ THERMOBAROMETRY INPUT DATASETS

SP-149 cont.	SP-149 Gar 2 core adj to bio + plag 2 core adj to gar + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.508	22.045	0.029	26.593	0.418	6.755	5.906	0.000	0.000	0.000	0.000
	pSP149	54.559	28.740	0.000	0.057	0.000	0.000	11.310	5.330	0.035	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	SP-149 Gar 2 core + plag 2 matrix + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.508	22.045	0.029	26.593	0.418	6.755	5.906	0.000	0.000	0.000	0.000
	pSP149	55.226	28.068	0.000	0.078	0.000	0.000	10.330	5.987	0.027	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	SP-149 Gar 3 rim + plag 3 adj to gar + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.118	21.758	0.029	28.478	0.635	5.763	5.329	0.000	0.000	0.000	0.000
	pSP149	52.451	29.698	0.000	0.148	0.000	0.000	12.610	4.519	0.015	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210
	SP-149 Gar 3 core + plag 3 matrix + amphibole rep + ilmenite rep (oxide weight percent)											
	Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃
	gSP149	39.118	21.758	0.029	28.478	0.635	5.763	5.329	0.000	0.000	0.000	0.000
	pSP149	52.451	29.698	0.000	0.148	0.000	0.000	12.610	4.519	0.015	0.000	0.000
	aSP149	42.250	15.360	0.890	13.290	0.050	11.540	11.030	1.310	0.360	3.880	0.000
	iSP149	0.000	0.000	52.224	44.842	0.275	0.755	0.000	0.000	0.000	0.000	0.210

*g = garnet, p = plagioclase, a = amphibole, l = ilmenite analyses

Garnet-hornblende leucogneiss sample SP-149

TWQ results plotting metastable reactions for all equilibria in the TiNaKCFMASH system, considering 14 phases: albite, almandine, anorthite, grossular, pyrope, alpha-quartz, rutile, ilmenite, tremolite, Fe-tremolite, pargasite, Fe-pargasite, tschermakite, and Fe-tschermakite. Points selected for individual analysis were taken from three subregions and recombined for possible peak and reequilibration conditions.

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
ar = rim of grain adjacent to garnet
ac = core of grain adjacent to garnet
m = matrix occurrence

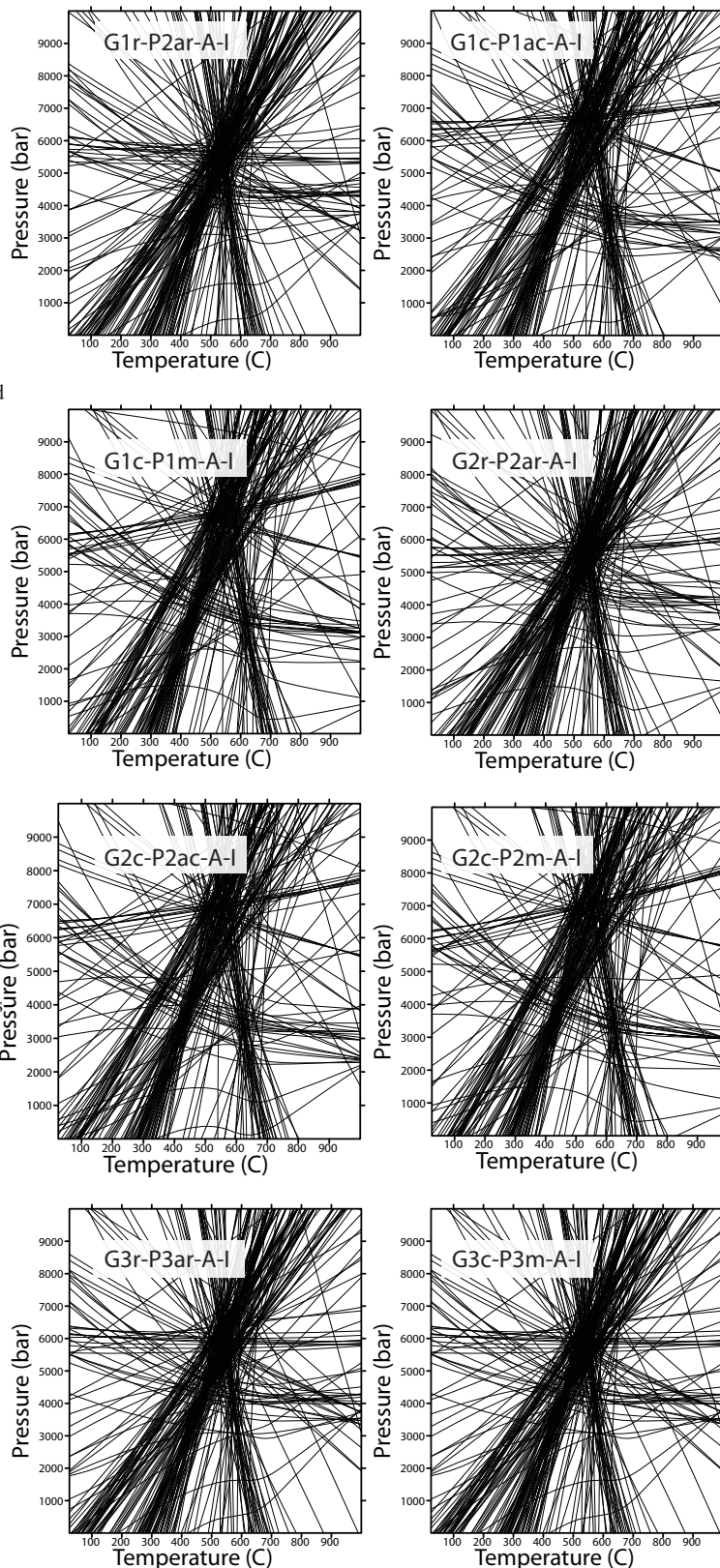
Note that a single composition is used for amphibole and ilmenite analyses. Very little variation was observed between analyses. Amphibole analyses contained a single slightly Fe, Si-enriched outlier, which was found to not shift the positions of equilibria.

Peak assemblage:

G1c-P1ac-A-I

Reequilibration assemblage:

G1r-P1ar-A-I



Garnet hornblende leucogneiss SP-149

TWQ results plotting metastable reactions for all equilibria in the TiNaKCFMASH system, considering the eight phases almandine, annite, anorthite, grossular, pyrope, alpha-quartz, rutile, ilmenite, and two of three amphibole series at a time: tremolite / Fe-tremolite (Tr), pargasite / Fe-pargasite (Prg), and tschermakite / Fe-tschermakite (Tsch).

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core

ar = rim of grain adjacent to garnet
ac = core of grain adjacent to garnet

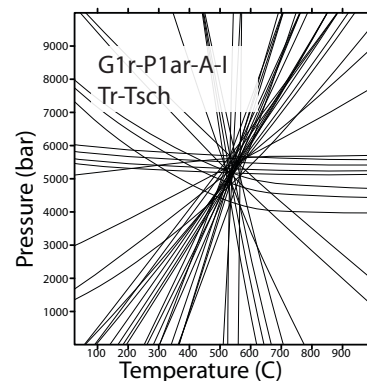
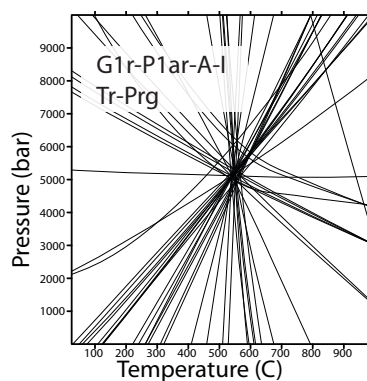
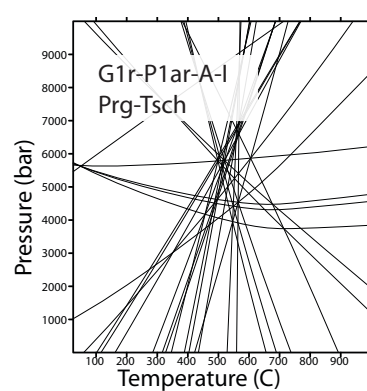
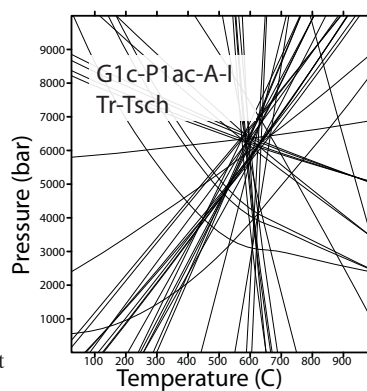
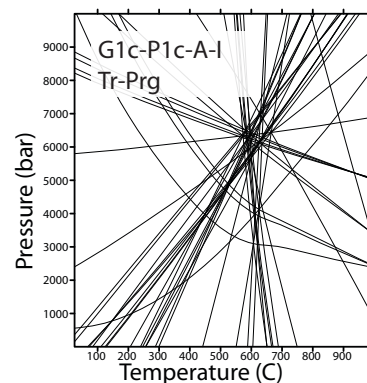
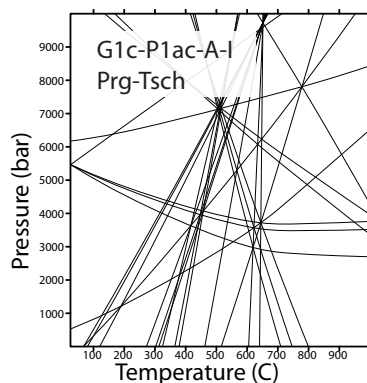
Note that a single composition is used for amphibole and ilmenite analyses. Very little variation was observed between analyses. Amphibole analyses contained a single slightly Fe, Si-enriched outlier, which was found to not shift the positions of equilibria.

Core (peak) assemblage:

G1c-P1ac-A-I

Rim (reequilibration) assemblage:

G1r-P1ar-A-I



**Garnet hornblende leucogneiss
SP-149**

TWQ results plotting metastable reactions for selected equilibria in the TiNaKCFMASH system, considering the eight phases almandine, annite, anorthite, grossular, pyrope, alpha-quartz, rutile, ilmenite, tremolite / Fe-tremolite (Tr), pargasite / Fe-pargasite (Prg), and tschermakite / Fe-tschermakite (Tsch).

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
ar = rim of grain adjacent to garnet
ac = core of grain adjacent to garnet

Note that a single composition is used for amphibole and ilmenite analyses. Very little variation was observed between analyses. Amphibole analyses contained a single slightly Fe, Si-enriched outlier, which was found to not shift the positions of equilibria.

Reaction curves:

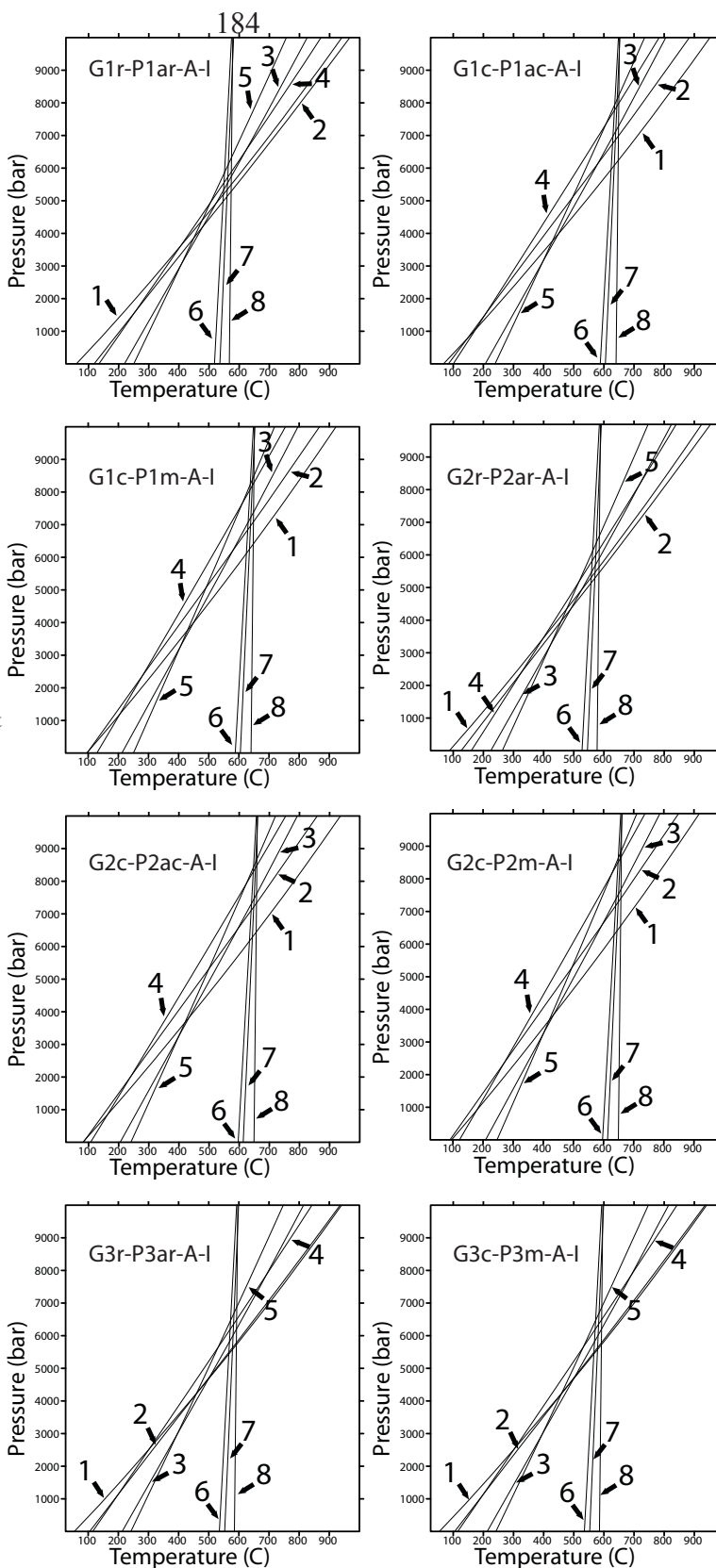
- 1) GRIPS
- 2) GAPQ-Mg '89
- 3) GAPQ-Fe '89
- 4) GAPQ-Mg '90
- 5) GAPQ-Fe '90
- 6) Gar-Tr
- 7) Gar-Prg
- 8) Gar-Tsch

Peak assemblage:

G1c-P1ac-A-I

Reequilibration assemblage:

G1r-P1ar-A-I



TWQ THERMOBAROMETRY RESULTS: Garnet-hornblende leucogneiss SP-149

Thermodynamic dataset v 1.02: NaTiKCFMASH system with garnet-plagioclase-amphibole input and pure phases ilmenite, α -quartz, and rutile

		GAPQ-Mg (Kohn and Spear, 1989)				GAPQ-Fe (Kohn and Spear, 1989)			
Garnet Plagioclase		Gar-Tr	Gar-Prg	Gar-Tsch	Gar-Tr	Gar-Prg	Gar-Tsch	Gar-Tr	Gar-Tsch
1 rim	1 adj to gar rim	4.974 kbar	546 °C	5.125 kbar	559 °C	5.284 kbar	573 °C	5.328 kbar	548 °C
1 core	1 adj to gar core	6.744 kbar	629 °C	6.860 kbar	638 °C	6.987 kbar	648 °C	6.979 kbar	630 °C
1 core	1 matrix	6.842 kbar	629 °C	6.961 kbar	639 °C	7.088 kbar	648 °C	7.075 kbar	631 °C
2 rim	2 adj to gar rim	5.134 kbar	557 °C	5.285 kbar	570 °C	5.478 kbar	584 °C	5.475 kbar	559 °C
2 core	2 adj to gar core	7.103 kbar	640 °C	7.213 kbar	648 °C	7.330 kbar	657 °C	7.319 kbar	641 °C
2 core	2 matrix	7.175 kbar	640 °C	7.287 kbar	649 °C	7.403 kbar	657 °C	7.390 kbar	641 °C
3 rim	3 adj to gar rim	5.134 kbar	557 °C	5.285 kbar	570 °C	5.448 kbar	584 °C	5.475 kbar	559 °C
3 core	3 matrix	5.491 kbar	567 °C	5.634 kbar	579 °C	5.784 kbar	592 °C	5.814 kbar	569 °C

		GAPQ-Mg (Kohn and Spear, 1990)				GAPQ-Fe (Kohn and Spear, 1990)			
Garnet Plagioclase		Gar-Tr	Gar-Prg	Gar-Tsch	Gar-Tr	Gar-Prg	Gar-Tsch	Gar-Tr	Gar-Tsch
1 rim	1 adj to gar rim	5.553 kbar	550 °C	5.723 kbar	562 °C	5.883 kbar	574 °C	5.864 kbar	551 °C
1 core	1 adj to gar core	7.769 kbar	635 °C	7.891 kbar	643 °C	7.986 kbar	649 °C	7.946 kbar	636 °C
1 core	1 matrix	8.066 kbar	637 °C	8.194 kbar	644 °C	8.279 kbar	650 °C	8.226 kbar	638 °C
2 rim	2 adj to gar rim	5.821 kbar	561 °C	6.001 kbar	573 °C	6.167 kbar	584 °C	6.119 kbar	563 °C
2 core	2 adj to gar core	8.291 kbar	647 °C	8.405 kbar	654 °C	8.749 kbar	659 °C	8.436 kbar	648 °C
2 core	2 matrix	7.175 kbar	640 °C	7.287 kbar	649 °C	7.403 kbar	657 °C	7.503 kbar	648 °C
3 rim	3 adj to gar rim	5.821 kbar	561 °C	6.001 kbar	573 °C	6.167 kbar	584 °C	6.119 kbar	563 °C
3 core	3 matrix	6.193 kbar	571 °C	6.351 kbar	582 °C	6.695 kbar	584 °C	6.467 kbar	572 °C

TWQ THERMOBAROMETRY RESULTS: Garnet-hornblende leucogneiss SP-149

GRIPS

Garnet Plagioclase		Gar-Tr		Gar-Prg		Gar-Tsch	
1 rim	1 adj to gar rim	5.195 kbar	547 °C	5.343 kbar	560 °C	5.494 kbar	573 °C
1 core	1 adj to gar core	5.958 kbar	624 °C	6.079 kbar	634 °C	6.233 kbar	647 °C
1 core	1 matrix	6.119 kbar	625 °C	6.247 kbar	635 °C	6.405 kbar	648 °C
2 rim	2 adj to gar rim	5.314 kbar	558 °C	5.466 kbar	571 °C	5.625 kbar	584 °C
2 core	2 adj to gar core	6.166 kbar	634 °C	6.286 kbar	644 °C	6.441 kbar	656 °C
2 core	2 matrix	6.280 kbar	635 °C	6.402 kbar	644 °C	6.557 kbar	657 °C
3 rim	3 adj to gar rim	5.314 kbar	558 °C	5.466 kbar	571 °C	5.625 kbar	584 °C
3 core	3 matrix	5.435 kbar	567 °C	5.574 kbar	579 °C	5.722 kbar	592 °C

TWQ THERMOBAROMETRY INPUT DATASETS

SP-153	Gar core + biotite rep + plag 1 core + ilmenite in matrix + amphibole rep (oxide weight percent)														
	Phase	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃	Cr ₂ O ₃	ZnO	BaO
	gSP153*	37.514	21.151	0.044	27.815	1.323	2.169	9.606	0.000	0.000	0.000	0.000	0.031	0.000	0.000
	bSP153	34.956	15.013	4.078	24.250	0.102	7.189	0.055	0.136	8.994	0.000	0.000	0.105	0.000	0.435
	pSP153	57.412	27.267	0.066	0.000	0.000	0.000	8.605	6.788	0.043	0.000	0.000	0.000	0.000	0.000
	iSP153	0.004	0.000	51.078	45.525	1.345	0.053	0.000	0.000	0.000	0.000	0.000	0.212	0.016	0.000
	aSP153	39.280	13.090	1.320	22.740	0.200	6.050	11.380	1.740	1.080	3.050	0.000	0.000	0.000	0.000
	Gar rim + biotite rep + plag 1 rim + ilmenite adjacent to amphibole + amphibole rep (oxide weight percent)														
	Phase	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	V ₂ O ₃	Cr ₂ O ₃	ZnO	BaO
	gSP153	37.514	21.151	0.044	27.815	1.323	2.169	9.606	0.000	0.000	0.000	0.000	0.031	0.000	0.000
	bSP153	34.956	15.013	4.078	24.250	0.102	7.189	0.055	0.136	8.994	0.000	0.000	0.105	0.000	0.435
	pSP153	57.412	27.267	0.066	0.000	0.000	0.000	8.605	6.788	0.043	0.000	0.000	0.000	0.000	0.000
	iSP153	0.000	0.000	50.561	46.393	1.079	0.078	0.000	0.000	0.000	0.000	0.254	0.031	0.027	0.000
	aSP153	39.280	13.090	1.320	22.740	0.200	6.050	11.380	1.740	1.080	3.050	0.000	0.000	0.000	0.000

* g = garnet, b = biotite, p = plagioclase, i = ilmenite, a = amphibole analyses

Garnet amphibolite SP-153

TWQ results plotting metastable reactions for all equilibria in the TiNaKCFMASH system, considering 14 phases: albite, almandine, anorthite, grossular, pyrope, alpha-quartz, rutile, ilmenite, tremolite, Fe-tremolite, pargasite, Fe-pargasite, tschermakite, and Fe-tschermakite. Representative points were selected from individual analyses and combined to estimate a core (peak) and rim (reequilibration) assemblage.

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
m = matrix occurrence

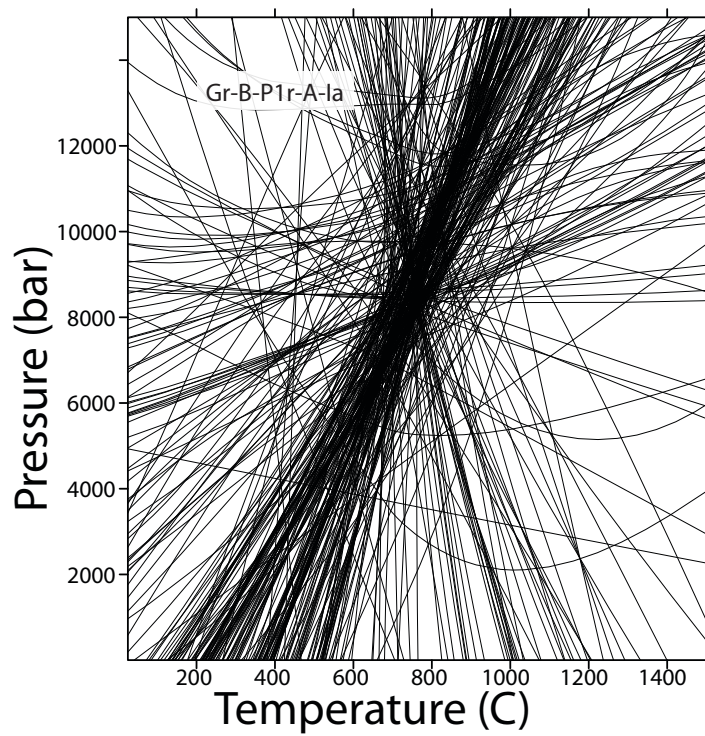
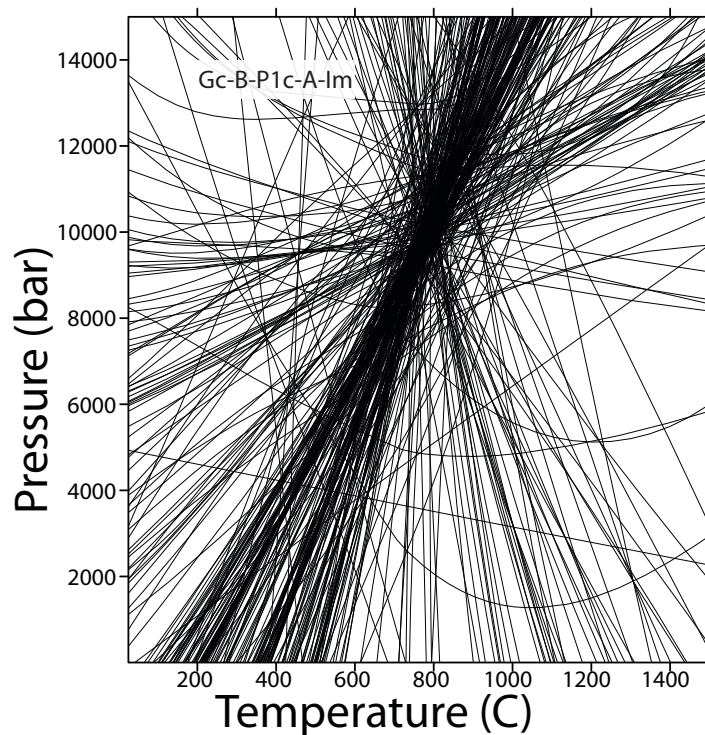
Note that a single composition is used for biotite, amphibole, and ilmenite analyses. Very little compositional variation was observed in analyses of each phase.

Peak assemblage:

Gc-B-P1c-A-Im

Reequilibration assemblage:

Gr-B-P1r-A-Ia



Garnet amphibolite SP-153

TWQ results plotting metastable reactions for all equilibria in the MnTiNaKCFMASH system, considering 14 phases: albite, almandine, annite, anorthite, eastonite, grossular, ilmenite, phlogopite, pyrope, pyrophanite, alpha-quartz, rutile, siderophyllite, spessartine, and tremolite. Representative points were selected from individual analyses and combined to estimate a core (peak) and rim (reequilibration) assemblage.

Thermodynamic dataset:
v 2.02

Mineral abbreviations:

G = garnet
B = biotite
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
a = adjacent to garnet
m = matrix occurrence

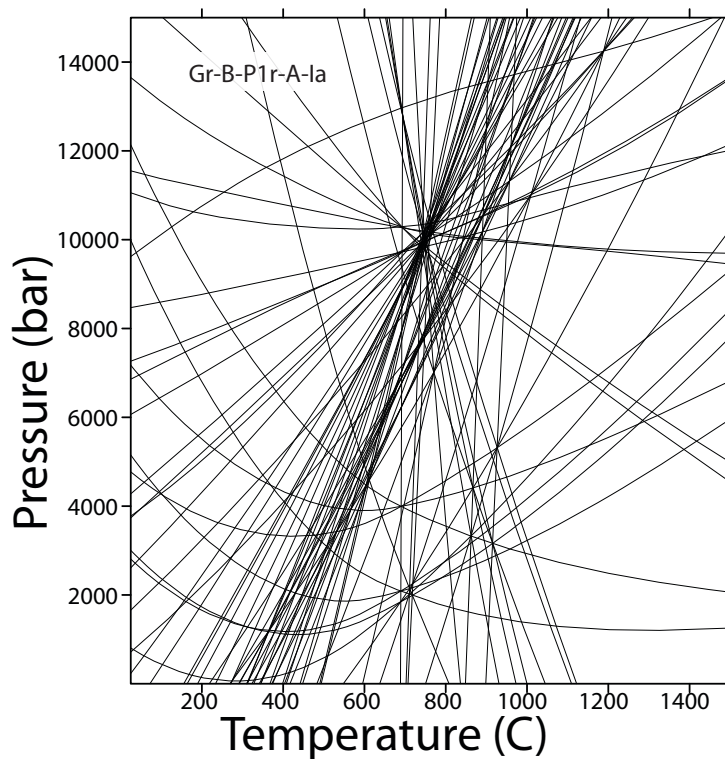
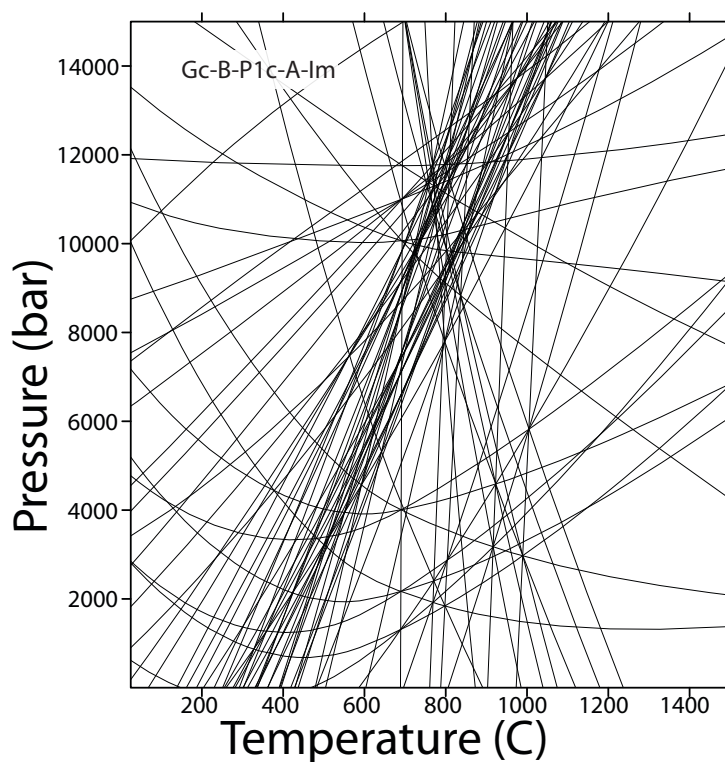
Note that a single composition is used for biotite, and amphibole analyses. Very little compositional variation was observed in analyses of each phase.

Peak assemblage:

Gc-B-P1c-A-Im

Reequilibration assemblage:

Gr-B-P1r-A-Ia



Garnet amphibolite SP-153

TWQ results plotting metastable reactions for all equilibria in the TiNaKCFMASH system, considering the ten phases albite, almandine, annite, anorthite, grossular, ilmenite, phlogopite, pyrope, alpha-quartz, rutile, and two of three amphibole series at a time: tremolite / Fe-tremolite (Tr), pargasite / Fe-pargasite (Prg), and tschermakite / Fe-tschermakite (Tsch).

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
B = biotite
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
a = adjacent to garnet
m = matrix

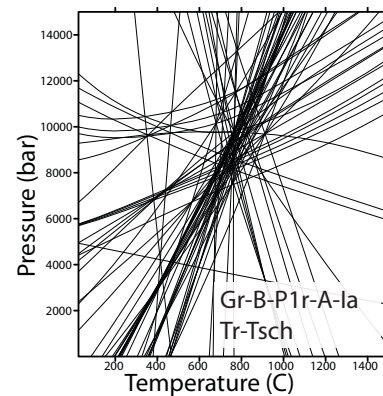
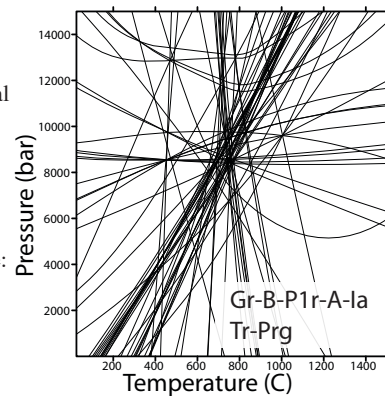
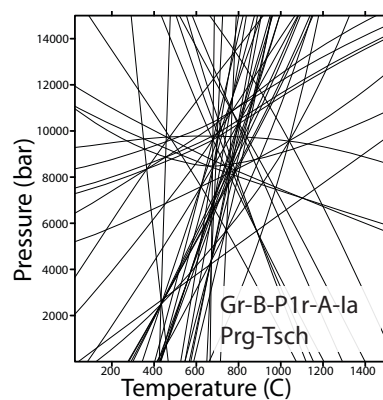
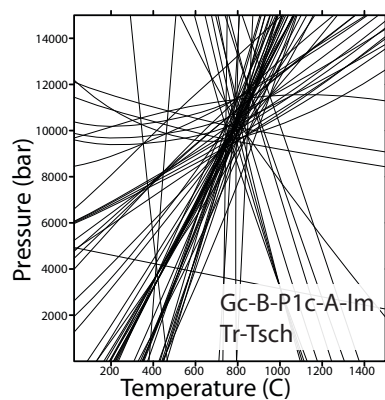
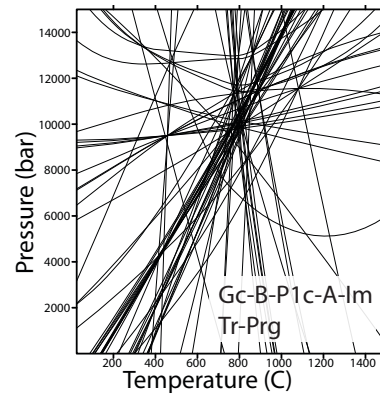
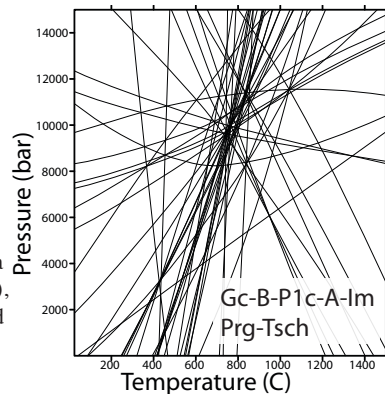
Note that a single composition is used for biotite and amphibole analyses. Very little compositional variation was observed between individual analyses.

Core (peak) assemblage:

Gc-B-P1c-A-Im

Rim (reequilibration) assemblage:

Gr-B-P1r-A-Ia



Garnet amphibolite SP-153

TWQ results plotting metastable reactions for selected equilibria in the TiNaKCFMASH system, considering 14 phases: albite, almandine, anorthite, grossular, pyrope, alpha-quartz, rutile, ilmenite, tremolite, Fe-tremolite, pargasite, Fe-pargasite, tschermakite, and Fe-tschermakite. Representative points were selected from individual analyses and combined to estimate a core (peak) and rim (reequilibration) assemblage.

Thermodynamic dataset:
v 1.02

Mineral abbreviations:

G = garnet
B = biotite
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
a = adjacent to garnet
m = matrix occurrence

Note that a single composition is used for biotite, and amphibole analyses. Very little compositional variation was observed in analyses of each phase.

Reaction curves:

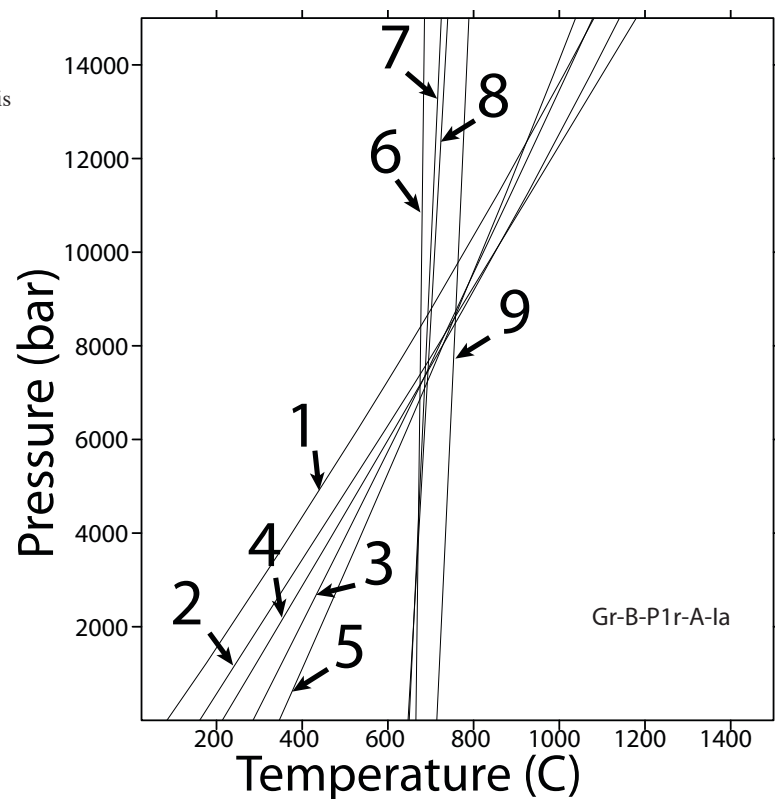
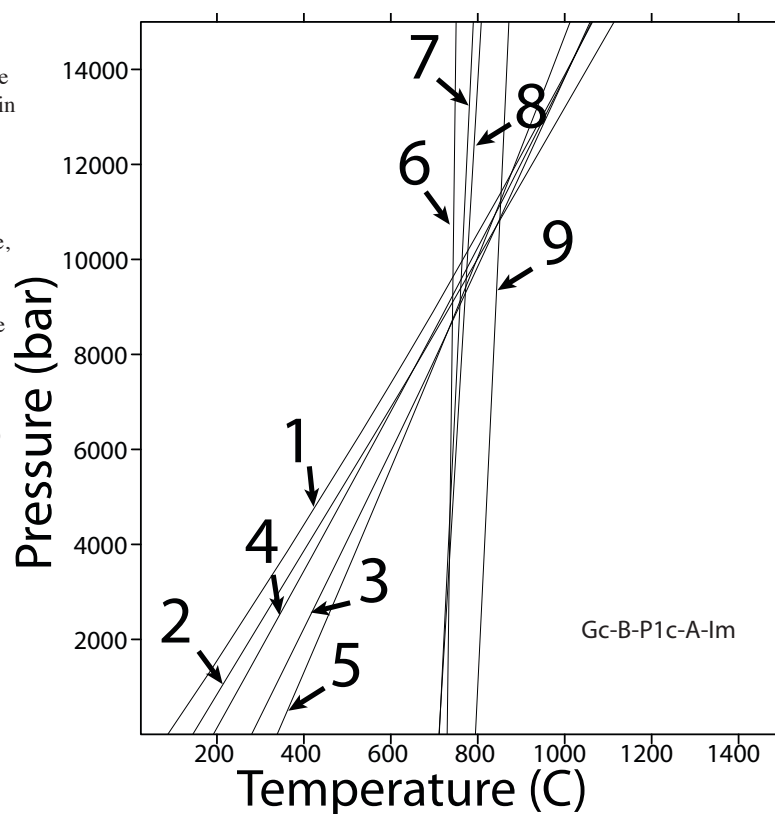
- 1) GRIPS
- 2) GAPQ-Mg '89
- 3) GAPQ-Fe '89
- 4) GAPQ-Mg '90
- 5) GAPQ-Fe '90
- 6) Gar-Tr
- 7) Gar-Prg
- 8) Gar-Tsch
- 9) Gar-bio

Peak assemblage:

Gc-B-P1c-A-Im

Reequilibration assemblage:

Gr-B-P1r-A-Ia



TWQ RESULTS: GARNET AMPHIBOLITE SAMPLE SP-153

Thermodynamic dataset v 1.02 with garnet-biotite-plagioclase-amphibole-ilmenite input

GAPQ-Mg (Kohn and Spear, 1989)									
Garnet	Plagioclase	Gar-Bio		Gar-Tr		Gar-Prg		Gar-Tsch	
core	1 core	10.825 kbar	851 °C	9.599 kbar	774 °C	9.398 kbar	761 °C	9.103 kbar	742 °C
rim	1 rim	8.630 kbar	758 °C	7.683 kbar	695 °C	7.577 kbar	688 °C	7.393 kbar	675 °C
GAPQ-Fe (Kohn and Spear, 1989)									
		Gar-Bio		Gar-Tr		Gar-Prg		Gar-Tsch	
core	1 core	10.859 kbar	851 °C	9.287 kbar	772 °C	9.040 kbar	759 °C	8.698 kbar	742 °C
rim	1 rim	8.749 kbar	758 °C	7.499 kbar	694 °C	7.366 kbar	687 °C	7.143 kbar	675 °C
GAPQ-Mg (Kohn and Spear, 1990)									
		Gar-Bio		Gar-Tr		Gar-Prg		Gar-Tsch	
core	1 core	11.168 kbar	853 °C	9.810 kbar	775 °C	9.852 kbar	762 °C	9.243 kbar	742 °C
rim	1 rim	8.481 kbar	757 °C	7.463 kbar	694 °C	7.355 kbar	687 °C	7.170 kbar	675 °C
GAPQ-Fe (Kohn and Spear, 1990)									
		Gar-Bio		Gar-Tr		Gar-Prg		Gar-Tsch	
core	1 core	11.244 kbar	853 °C	9.419 kbar	772 °C	9.126 kbar	759 °C	8.725 kbar	742 °C
rim	1 rim	8.661 kbar	758 °C	7.235 kbar	695 °C	7.091 kbar	685 °C	6.861 kbar	675 °C
GRIPS									
		Gar-Bio		Gar-Tr		Gar-Prg		Gar-Tsch	
core	1 core	11.419 kbar	854 °C	10.186 kbar	777 °C	9.969 kbar	764 °C	9.633 kbar	743 °C
rim	1 rim	9.775 kbar	764 °C	8.800 kbar	702 °C	8.670 kbar	693 °C	8.418 kbar	677 °C

Garnet amphibolite SP-153

TWQ results plotting metastable reactions for selected equilibria in the TiNaKCFMASH system, considering 12 phases: albite, almandine, annite, anorthite, eastonite, grossular, ilmenite, phlogopite, pyrope, pyrophanite, alpha-quartz, rutile, and siderophyllite. Representative points were selected from individual analyses and combined to estimate a core (peak) and rim (reequilibration) assemblage.

Thermodynamic dataset:
v 2.02

Mineral abbreviations:

G = garnet
B = biotite
P = plagioclase
A = amphibole
I = ilmenite

Textural indicators:

r = rim
c = core
a = adjacent to garnet
m = matrix occurrence

Note that a single composition is used for biotite, and amphibole analyses. Very little compositional variation was observed in analyses of each phase.

Reaction curves:

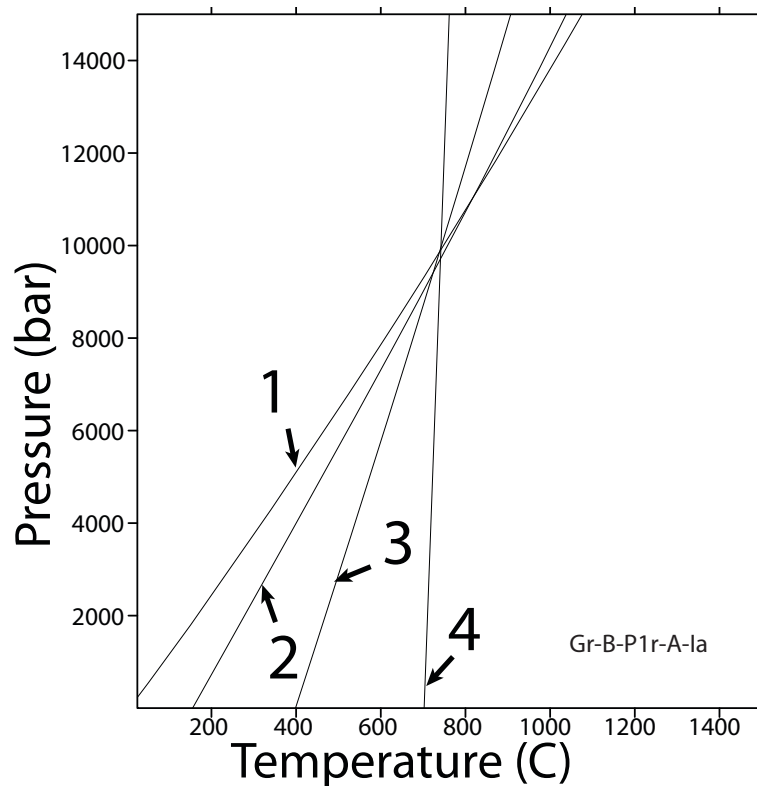
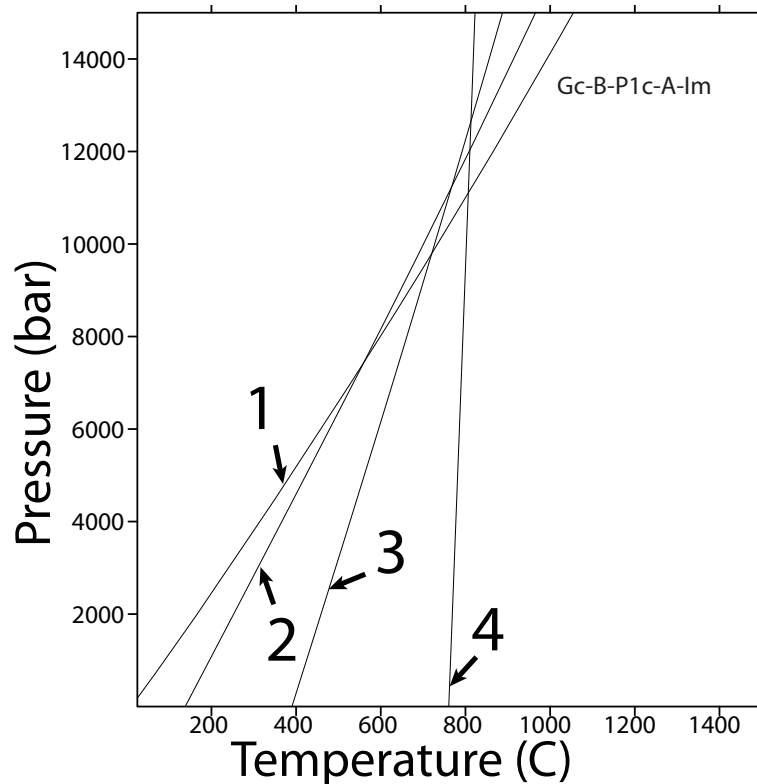
- 1) GRIPS
- 2) GBPQ-Mg
- 3) GBPQ-Fe
- 4) Gar-bio

Peak assemblage:

Gc-B-P1c-A-Im

Reequilibration assemblage:

Gr-B-P1r-A-Ia



TWQ RESULTS: GARNET AMPHIBOLITE SAMPLE SP-153

Thermodynamic dataset v 2.02 with garnet-biotite-plagioclase-amphibole-ilmenite input

		GRIPS		GBPQ-Mg		GBPQ-Fe	
Garnet	Plagioclase	Gar-Bio		Gar-Bio		Gar-Bio	
1 rim	1 adj to gar rim	9.908 kbar	742 °C	9.712 kbar	741 °C	10.147 kbar	743 °C
1 core	1 adj to gar core	11.104 kbar	807 °C	12.035 kbar	811 °C	12.765 kbar	813 °C

GTB THERMOBAROMETRY INPUT DATASETS

SP-12

Gar 1 core-Bio 1 matrix-Plag 1 core (cations)

Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12*	2.99	2.02	0.00	0.00	0.00	2.08	0.28	0.50	0.11	0.00	0.00	0.00	0.00	0.00	0.00	99.668
bSP12	5.20	3.46	0.41	0.00	0.00	2.38	0.00	2.26	0.00	0.00	0.06	1.86	2.00	0.00	0.00	97.772
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302

Gar 3 inner rim (1)-Bio 3 inclusion-Plag 1 core

Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.02	0.00	0.01	0.00	2.11	0.29	0.45	0.10	0.00	0.00	0.00	0.00	0.00	0.00	99.595
bSP12	5.23	3.55	0.28	0.00	0.00	2.31	0.00	2.38	0.00	0.00	0.06	1.86	1.99	0.02	0.00	97.525
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302

Gar 3 inner rim (2)-Bio 3 inclusion-Plag 1 core

Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.01	2.02	0.00	0.00	0.00	2.10	0.30	0.45	0.11	0.00	0.00	0.00	0.00	0.00	0.00	99.384
bSP12	5.23	3.55	0.28	0.00	0.00	2.31	0.00	2.38	0.00	0.00	0.06	1.86	1.99	0.02	0.00	97.525
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302

Gar 3 inner rim (3)-Bio 3 inclusion-Plag 1 core

Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.01	0.00	0.00	0.00	2.15	0.29	0.43	0.10	0.00	0.00	0.00	0.00	0.00	0.00	100.774
bSP12	5.23	3.55	0.28	0.00	0.00	2.31	0.00	2.38	0.00	0.00	0.06	1.86	1.99	0.02	0.00	97.525
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302

Gar 3 inner rim (1)-Bio 3 matrix-Plag 1 core (PEAK)

Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.02	0.00	0.01	0.00	2.11	0.29	0.45	0.10	0.00	0.00	0.00	0.00	0.00	0.00	99.595
bSP12	5.26	3.43	0.37	0.00	0.00	2.39	0.00	2.28	0.00	0.00	0.07	1.80	1.83	0.33	0.00	98.111
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302

*g = garnet, b = biotite, p = plagioclase analyses

SP-12
cont.

Gar 3 inner rim (2)-Bio 3 inclusion-Plag 1 core (cations)																
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.01	2.02	0.00	0.00	0.00	2.10	0.30	0.45	0.11	0.00	0.00	0.00	0.00	0.00	0.00	99.384
bSP12	5.26	3.43	0.37	0.00	0.00	2.39	0.00	2.28	0.00	0.00	0.07	1.80	1.83	0.33	0.00	98.111
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302
Gar 3 inner rim (3)-Bio 3 inclusion-Plag 1 core																
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.01	0.00	0.00	0.00	2.15	0.29	0.43	0.10	0.00	0.00	0.00	0.00	0.00	0.00	100.774
bSP12	5.26	3.43	0.37	0.00	0.00	2.39	0.00	2.28	0.00	0.00	0.07	1.80	1.83	0.33	0.00	98.111
pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00	101.302
Gar 3 inner rim (1)-Bio 3 matrix-Plag 2 adj to gar																
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.02	0.00	0.01	0.00	2.11	0.29	0.45	0.10	0.00	0.00	0.00	0.00	0.00	0.00	99.595
bSP12	5.26	3.43	0.37	0.00	0.00	2.39	0.00	2.28	0.00	0.00	0.07	1.80	1.83	0.33	0.00	98.111
pSP12	2.77	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.77	0.00	0.00	0.00	0.00	100.113
Gar 1 rim-Bio 1 adj to gar-Plag 2 adj to gar																
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.02	2.03	0.00	0.00	0.00	2.07	0.29	0.47	0.11	0.00	0.00	0.00	0.00	0.00	0.00	99.604
bSP12	5.20	3.46	0.41	0.00	0.00	2.38	0.00	2.26	0.00	0.00	0.06	1.86	2.00	0.00	0.00	93.816
pSP12	2.77	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.77	0.00	0.00	0.00	0.00	100.113
Gar 3 rim (1)-Bio 3 adj to gar-Plag 2 adj to gar (REEQ)																
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total
gSP12	3.03	2.03	0.00	0.00	0.00	2.13	0.29	0.42	0.10	0.00	0.00	0.00	0.00	0.00	0.00	98.714
bSP12	5.62	3.42	0.24	0.00	0.00	2.52	0.00	1.91	0.02	0.00	0.05	1.32	1.85	0.30	0.00	93.397
pSP12	2.77	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.77	0.00	0.00	0.00	0.00	100.113

SP-12 cont.	Gar 3 rim (2)-Bio 3 adj to gar-Plag 2 adj to gar (cations)														Weight percent oxide total	
	Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl
	gSP12	3.00	2.04	0.01	0.00	0.00	2.11	0.30	0.43	0.11	0.00	0.00	0.00	0.00	0.00	0.00
	bSP12	5.62	3.42	0.24	0.00	0.00	2.52	0.00	1.91	0.02	0.00	0.05	1.32	1.85	0.30	0.00
	pSP12	2.77	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.77	0.00	0.00	0.00	0.00
	Gar 3 rim (3)-Bio 3 adj to gar-Plag 2 adj to gar														Weight percent oxide total	
	Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl
	gSP12	3.03	2.03	0.00	0.00	0.00	2.13	0.29	0.42	0.10	0.00	0.00	0.00	0.00	0.00	0.00
	bSP12	5.62	3.42	0.24	0.00	0.00	2.52	0.00	1.91	0.02	0.00	0.05	1.32	1.85	0.30	0.00
	pSP12	2.77	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.77	0.00	0.00	0.00	0.00
	Gar 3 rim (1)-Bio 3 adj to gar-Plag 1 core														Weight percent oxide total	
	Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl
	gSP12	3.03	2.03	0.00	0.00	0.00	2.13	0.29	0.42	0.10	0.00	0.00	0.00	0.00	0.00	0.00
	bSP12	5.62	3.42	0.24	0.00	0.00	2.52	0.00	1.91	0.02	0.00	0.05	1.32	1.85	0.30	0.00
	pSP12	2.71	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.70	0.01	0.00	0.00	0.00

Metapelite sample SP-12

GTB results for peak assemblages. Preferred peak assemblage G3ir¹-B3in-P1c discussed previously in results chapter.

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

in = inclusion

a = adjacent to garnet

m = matrix occurrence

Reaction curves:

GARB

Garnet-biotite

GRAIL

Garnet-rutile-aluminosilicate-ilmenite

GRIPS

Garnet-rutile-ilmenite-plagioclase-quartz

GBPQ-Mg

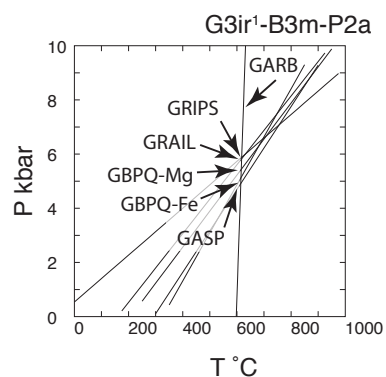
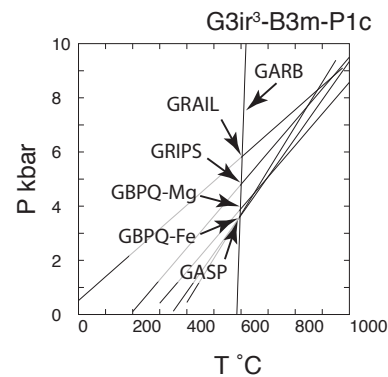
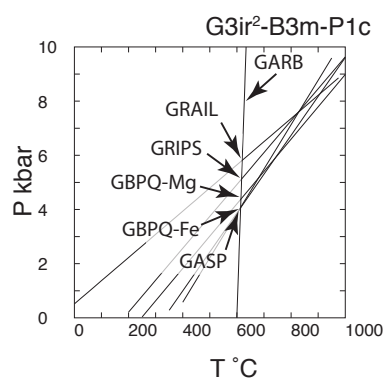
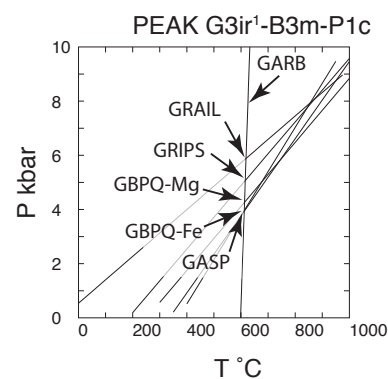
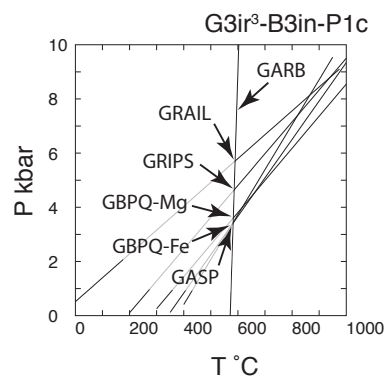
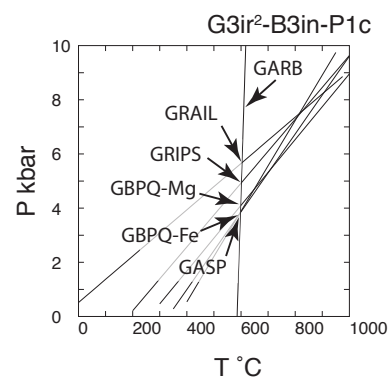
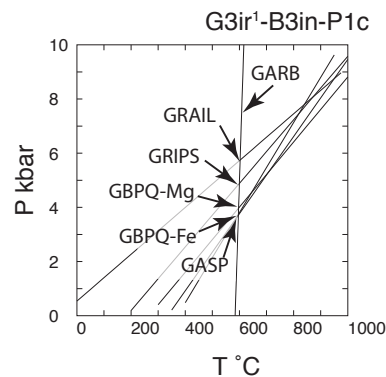
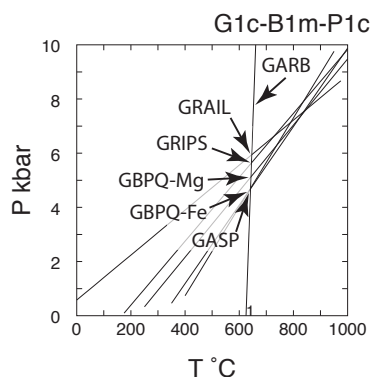
Garnet-biotite-plagioclase-quartz

GBPQ-Fe

Garnet-biotite-plagioclase-quartz

GASP

Garnet-aluminosilicate-quartz-plagioclase



Metapelite sample SP-12

GTB results for reequilibration assemblages. Preferred assemblage G3r¹-B3a-P2a is discussed previously in results chapter.

Mineral abbreviations:

G = garnet

B = biotite

P = plagioclase

Textural indicators:

r = rim

ir = inner rim

c = core

a = adjacent to garnet

Reaction curves:

GARB

Garnet-biotite

GRAIL

Garnet-rutile-aluminosilicate-ilmenite

GRIPS

Garnet-rutile-ilmenite-plagioclase-quartz

GBPQ-Mg

Garnet-biotite-plagioclase-quartz

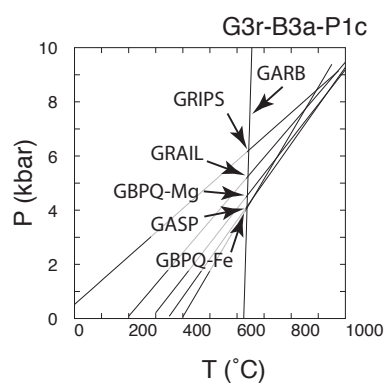
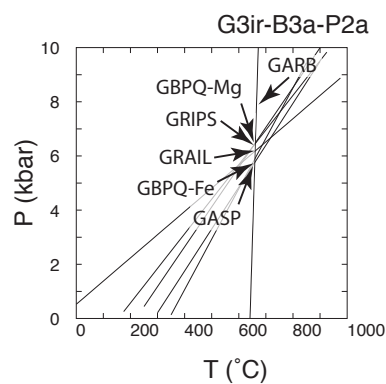
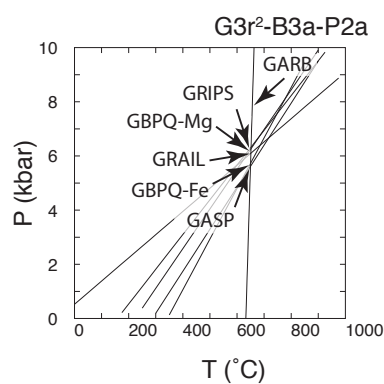
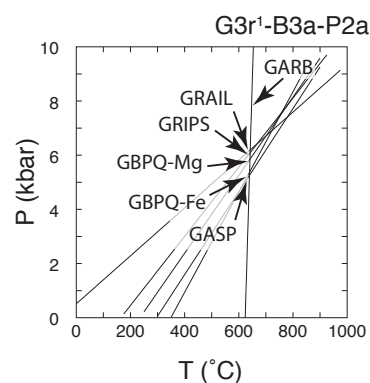
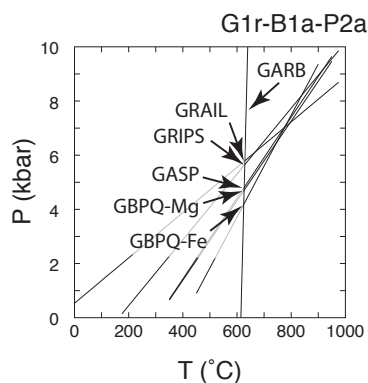
GBPQ-Fe

Garnet-biotite-plagioclase-quartz

GASP

Garnet-aluminosilicate-quartz-plagioclase

^{1,2}Superscript differentiates between mineral analyses from same subregion and textural occurrence.



GTB THERMOBAROMETRY RESULTS: Garnet-sillimanite schist SP-12

Garnet	Biotite	Plagioclase	GASP	Gar-Bio	GBPQ-Mg	Gar-Bio	GBPQ-Fe	Gar-Bio	GRIPS	Gar-Bio	GRAIL	Gar-Bio
1 core	1 matrix	1 core	4,690 kbar	642 °C	5,130 kbar	643 °C	4,707 kbar	642 °C	5,645 kbar	645 °C	5,945 kbar	646 °C
3 inner rim (1)	3 inclusion	1 core	3,709 kbar	596 °C	3,970 kbar	597 °C	3,740 kbar	596 °C	4,882 kbar	600 °C	5,746 kbar	602 °C
3 inner rim (2)	3 inclusion	1 core	3,842 kbar	598 °C	4,095 kbar	599 °C	3,861 kbar	598 °C	4,944 kbar	602 °C	5,684 kbar	604 °C
3 inner rim (3)	3 inclusion	1 core	3,421 kbar	583 °C	3,609 kbar	583 °C	3,444 kbar	583 °C	4,644 kbar	586 °C	5,709 kbar	509 °C
3 inner rim (1)	3 matrix	1 core	3,936 kbar	612 °C	4,266 kbar	613 °C	3,966 kbar	612 °C	5,071 kbar	616 °C	5,866 kbar	619 °C
3 inner rim (2)	3 matrix	1 core	4,066 kbar	614 °C	4,388 kbar	615 °C	4,082 kbar	614 °C	5,128 kbar	617 °C	5,818 kbar	620 °C
3 inner rim (3)	3 matrix	1 core	3,625 kbar	597 °C	3,887 kbar	598 °C	3,649 kbar	597 °C	4,815 kbar	601 °C	5,837 kbar	604 °C
3 inner rim (1)	3 matrix	2 adj to gar	4,920 kbar	615 °C	5,455 kbar	617 °C	5,138 kbar	615 °C	5,832 kbar	618 °C	5,887 kbar	618 °C
1 rim	1 adj to gar	2 adj to gar	4,814 kbar	627 °C	4,708 kbar	626 °C	4,187 kbar	625 °C	5,654 kbar	629 °C	5,798 kbar	629 °C
3 rim (1)	3 adj to gar	2 adj to gar	5,266 kbar	640 °C	5,859 kbar	642 °C	5,384 kbar	640 °C	6,097 kbar	642 °C	6,199 kbar	643 °C
3 inner rim	3 adj to gar	2 adj to gar	5,622 kbar	650 °C	6,270 kbar	652 °C	5,736 KBAR	650 °C	6,331 kbar	652 °C	6,103 kbar	651 °C
3 rim (2)	3 adj to gar	2 adj to gar	5,759 kbar	659 °C	6,483 kbar	661 °C	5,893 kbar	659 °C	6,461 kbar	661 °C	6,179 kbar	660 °C
3 rim (1)	3 adj to gar	1 core	4,149 kbar	637 °C	4,553 kbar	639 °C	4,087 kbar	637 °C	5,254 kbar	641 °C	6,215 kbar	644 °C

Bold indicates preferred peak and reequilibration assemblages.

GTB THERMOBAROMETRY INPUT DATASETS

SP-149

Gar 1 core-Plag 1 adjacent core-Amphibole-Ilmenite (cations)																	
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total	
gSP149*	3.02	2.00	0.00	0.00	0.00	1.87	0.05	0.63	0.42	0.00	0.00	0.00	0.00	0.00	0.00	101.163	
pSP149	2.41	1.58			0.00	0.00	0.00	0.00	0.61	0.00	0.41	0.00	0.00	0.00	0.00	99.814	
aSP149	6.14	2.63	0.10	0.00	1.01	0.61	0.01	2.50	1.72	0.00	0.37	0.07	0.98	0.04	0.00	100.040	
iSP149	0.00	0.00	1.01	0.00	0.00	0.96	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.350	
Gar 1 rim-Plag 1 adjacent rim-Amphibole-Ilmenite																	
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total	
gSP149	3.02	2.00	0.00	0.00	0.00	1.72	0.03	0.76	0.46	0.00	0.00	0.00	0.00	0.00	0.00	100.639	
pSP149	2.41	1.58			0.00	0.00	0.00	0.00	0.59	0.00	0.43	0.00	0.00	0.00	0.00	99.877	
aSP149	6.14	2.63	0.10	0.00	1.01	0.61	0.01	2.50	1.72	0.00	0.37	0.07	0.98	0.04	0.00	100.040	
iSP149	2.41	1.58			0.00	0.00	0.00	0.00	0.59	0.00	0.43	0.00	0.00	0.00	0.00	98.350	

*g = garnet, p = plagioclase, a = amphibole, i = ilmenite analyses

GTB THERMOBAROMETRY INPUT DATASETS

SP-149

Gar core-Bio-Plag 1 core-Amphibole-Ilmenite matrix (cations)																	
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total	
gSP153*	3.02	2.00	0.00	0.00	0.00	1.87	0.05	0.63	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.701
bSP153	5.50	2.78	0.48	0.01	0.00	3.19	0.01	1.69	0.01	0.03	0.04	1.80	2.00	0.01	0.00	0.00	95.327
pSP153	2.50	1.48	0.00	0.00	0.02	0.00	0.00	0.00	0.44	0.00	0.56	0.00	0.00	0.00	0.00	0.00	98.424
aSP153	6.09	2.39	0.15	0.00	0.62	2.33	0.03	1.40	1.89	0.00	0.52	0.21	1.95	0.04	0.01	0.00	100.040
iSP153	0.00	0.00	1.98	0.00	0.00	1.96	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.361

Gar rim-Bio-Plag 1 rim-Amphibole-Ilmenite adjacent																	
Phase	Si	Al ^{tot}	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Ba	Na	K	H ₂ O	F	Cl	Weight percent oxide total	
gSP153	3.02	2.00	0.00	0.00	0.00	1.72	0.03	0.76	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.237
bSP153	5.50	2.78	0.48	0.01	0.00	3.19	0.01	1.69	0.01	0.03	0.04	1.80	2.00	0.01	0.00	0.00	95.327
pSP153	2.57	1.44	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.59	0.00	0.00	0.00	0.00	0.00	100.181
aSP153	6.09	2.39	0.15	0.00	0.62	2.33	0.03	1.40	1.89	0.00	0.52	0.21	1.95	0.04	0.01	0.00	100.040
iSP153	0.00	0.00	1.95	0.00	0.00	1.99	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.423

*g = garnet, b = biotite, p = plagioclase, a = amphibole, i = ilmenite analyses