EXPLAINING DISCONTINUOUS GARNET ZONING USING REACTION HISTORY P-T MODELS: AN EXAMPLE FROM THE SALMON RIVER SUTURE ZONE, WEST-CENTRAL IDAHO

by

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A THESIS

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ABSTRACT

Discontinuously zoned or two-stage garnet has been observed in numerous locations and geologic settings worldwide. These garnets are characterized by sharp breaks in inclusion density and compositional zoning, and often, these sharp breaks are interpreted as a hiatus in growth, change in growth rate, change in bulk rock composition, chemical diffusion, or absorption and new growth of garnet. During accretion of terranes and microplates, thermal pulses and thrust fault movements occur, which drive metamorphism and therefore the growth of garnet. Multiple garnet growth events could produce a discontinuously zoned garnet and each growth stage could be interpreted to represent a separate metamorphic event.

Two-stage garnet is common in the Salmon River suture zone (SRSZ) and multiple tectonic models have been proposed based on the two-stage garnet. Getty et al. (1993) and Selverstone et al. (1992) proposed multiple accretion and metamorphic events based on the estimates for pressure, temperature, and age of these garnets. Recently, McKay (2011) proposed that heating after several major fault displacements caused the growth of two-stage garnet. This study uses compositions of garnet cores and rims on isochemical phase diagrams to construct new garnet growth P-T paths. Core and rim P-T estimates combined with observed mineral assemblages indicate an initial garnet growth reaction, followed by a reaction consuming and then growing garnet, e.g., chlorite + garnet = amphibole + H₂O and amphibole = garnet + Al₂SiO₅ (kyanite) + H₂O. Isochemical P-T modeling of garnet modal percentages, mineral compositions, and petrologic observations supports the occurrence of these reactions in the SRSZ garnet. The proposed reaction history would produce two-stage garnet along a single
prograde path, which does not require multiple thermal and tectonic events. This interpretation supports the single terrane accretion hypothesis proposed by McKay (2011).
DEDICATION

I would like to dedicate this thesis to my husband Rob for his ability to keep me mostly sane over the entirety of this project, my undergraduate advisor Dr. Hollabaugh for providing me with my first taste of research and opening the door to so many other possibilities, and my parents for their support of my interest in geology.
LIST OF ABBREVIATIONS AND SYMBOLS

Geologic Unit Abbreviations:

PMp  Pollock Mountain plate
RRp  Rapid River plate
PMF  Pollock Mountain fault
RRF  Rapid River fault
SCF  Slate Creek fault
HGF  Heavens Gate fault

Mineral Abbreviations after Kretz (1983):

Grt  Garnet
St  Staurolite
Ky  Kyanite
Camp  Clinoamphibole
Oamp  Orthoamphibole
Cpx  Clinopyroxene
Opx  Orthopyroxene
Bt  Biotite
Chl  Chlorite
Czo  Clinozoisite
Sill  Sillimanite
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Mineral Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt</td>
<td>Rutile</td>
</tr>
<tr>
<td>Ilm</td>
<td>Ilmenite</td>
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<tr>
<td>PI</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>Ab</td>
<td>Albite</td>
</tr>
<tr>
<td>Qtz</td>
<td>Quartz</td>
</tr>
<tr>
<td>Sph</td>
<td>Sphene (Titanite)</td>
</tr>
</tbody>
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**Garnet Endmembers:**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Endmember Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alm</td>
<td>Almandine (Fe)</td>
</tr>
<tr>
<td>Pyr</td>
<td>Pyrope (Mg)</td>
</tr>
<tr>
<td>Gr</td>
<td>Grossular (Ca)</td>
</tr>
<tr>
<td>Spss</td>
<td>Spessartine (Mn)</td>
</tr>
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</table>
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This research would not have been possible without the feedback and wisdom from the University of Alabama Department of Geological Sciences faculty and staff, namely Dr. Harold Stowell, Dr. Kimberly Genareau, Dr. Delores Robinson, Dr. Fred Andrus, and Karen Parker. I would also like to thank my external committee member Dr. Joshua Schwartz and fellow research group member Rebecca Norton for providing feedback, comments, and conversation on anything and everything.
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CHAPTER 1

INTRODUCTION

Metamorphic garnet records the duration and timing of metamorphism, changes in bulk rock composition, changes in effective bulk rock composition, and the pressure and temperature (P-T) conditions during equilibration (Spear et al., 1984; Spear, 1993; Evans, 2004; Baxter and Scherer, 2013). This information can be extracted from isotopic data, compositional zoning, thermobarometry, and pressure-temperature thermodynamic forward models (isochemical pseudosections). Garnet that grows along a typical P-T path for regional metamorphism is often complexly zoned in both chemical composition and inclusion density. Garnet zoning could reflect a single prograde P-T path, a change in P-T trajectory related to tectonics, a hiatus in growth, changes in the effective bulk composition, or modification by diffusion (Spear et al., 1984; Florence and Spear, 1995; Stowell and Goldberg, 1997; Evans, 2004; Gaidies et al, 2008; Caddick et al, 2010). Effective bulk compositional changes may result from extraction or addition of melt, metasomatic fluid fluxes, and/or change in minerals that participate in equilibrium (Spear, 1995). Garnet with complex zoning patterns and a distinct change in inclusion density between core and rim are referred to here as two-staged garnets. At the core-rim boundary of two-stage garnet, elemental zoning may change in slope and trend, such as increasing Fe in the core changing to a decrease in Fe for the rim. These changes between core and rim have been attributed to the following: 1) multiple thermal events related to accretion of terranes or microplates (Bestel, et al., 2009; Gaidies et al., 2008; Likhanov and Reverdatto,
2013), 2) plutonism and thermal relaxation related to thrust faulting during a single accretion event (McKay, 2011), and 3) changing mineralogical reactions during growth (Moynihan and Pattison, 2013; Prinz and Abart, 2009; Spear, 1993). The first two explanations require a hiatus between garnet growth stages and could result in a measurable age difference between garnet cores and rims. Changing garnet growth reactants does not require multiple thermal pulses or events; instead changes can occur along a single P-T path during a single event (Spear, 1993).

Pressure-temperature diagrams can be used to identify the P-T path along which garnet grew. This type of model is useful because it allows the composition of the garnet to be plotted in P-T space alongside stable mineral assemblages and can therefore be used to model garnet growth with increasing P and T. P-T paths for garnet growth are constructed by utilizing bulk rock compositions to construct isochemical phase diagram sections or pseudosections (Vance and Holland, 1993; Moynihan and Pattison, 2013). The phase diagrams are generally two-dimensional and can be temperature-composition (T-X), pressure-composition (P-X), or pressure-temperature (P-T). P-T models are the most useful for constructing garnet growth P-T paths because observed and predicted garnet compositions can be incorporated into the phase diagram to predict the pressure and temperature conditions for garnet equilibration. Modal percentages for minerals can also be calculated to determine growth and breakdown of specific phases, such as garnet, along a P-T path (Spear, 1988). Initial garnet growth is inferred from the garnet core composition, and the mineral assemblage is inferred from inclusions in the garnet core. The P-T path is constrained by textural evidence of mineralogical reactions and zoning. Assuming that fractionation of the bulk composition is negligible or accounted for in the phase diagrams, final garnet growth is predicted from the garnet rim composition. Using other mineral modes in conjunction with garnet mode can allow for the identification of reactions involving the
growth of garnet. By identifying garnet growth reactions it is possible to interpret inclusions, inclusion density within grains, and compositional zoning pattern (Spear, 1993).

Garnet Zoning

Compositional zoning in garnet depends on rock composition and conditions reached (temperature and pressure) (Spear et al., 1984; Evans et al., 2004). The garnet zoning is observed as changes in the following end-member compositions: Mn (spessartine), Mg (pyrope), Fe (almandine), and Ca (grossular). Prograde (increasing temperature) garnet growth generally results in a Mn ‘bell curve’, containing highest Mn in the core and lowest in the rim. Mn is preferentially sequestered from the whole rock composition by garnet (Hollister, 1966). During nucleation and initial garnet growth garnet incorporates far more Mn than other minerals stable at these conditions. Mn is a minor element in most rocks with abundances that range from <0.10 to ca. 0.20 weight percent. Fractionation of Mn into garnet depletes the rock, and there is more Mn in the core than in the rim. Conversely, Mg will increase toward the rim during prograde metamorphism due to the Fe-Mg exchange between biotite and chlorite with garnet (Spear, 1993; Florence and Spear, 1995). Ca and Fe zoning depends on the growth of coexisting minerals and the P-T path of garnet growth (Hollister, 1966). Zoning patterns can be relaxed, perturbed, or even completely erased due to diffusion, often a problem for interpreting conditions of growth because the composition no longer represents the equilibrium conditions that originally grew the garnet. Diffusion has a significant effect above 700°C and may completely erase compositional zoning depending on the duration of heating and size of garnet crystal (e.g., Caddick, 2010).
Discontinuous (Two-Stage) Garnet

Two-stage garnets are also known as two-phase, polyphase, and polymetamorphic garnets. Discounting an origin involving diffusion, two-stage garnet must be related to growth and/or consumption. Two-stage garnets have cores and rims that are either texturally or chemically distinct from one another. Textural breaks may be sharp changes in inclusion density or composition zoning patterns (Gaidies et al., 2008; Bestel et al., 2009; Likhanov and Reverdatto, 2013). Two-stage garnet growth zoning can be readily interpreted from the spessartine (Mn) and Fe# (Fe/(Fe+Mg)) zoning patterns. Spessartine and Fe# decrease with prograde garnet growth and each textural break or hiatus in growth zones may result from diffusion and/or garnet consumption, which may alter the profile at the end of each growth stage. The resulting Mn and Fe# profiles decrease from the center of stage one garnet (core), increases slightly before reaching the growth of stage two (rim), decreases again at the start of stage two (rim), and then increases slightly again at the edges of the garnet rim-matrix contact (Figure 1).

Figure 1: Simplified two-stage garnet growth and diffusion profiles for prograde metamorphism. Spessartine (Mn) and Fe# (Fe/(Fe+Mg)) are highest at the start of each growth. Diffusion occurs at the end of each crystallization phase and causes modification of the outermost rim.

Possible causes for two-stage growth are as diverse as their occurrences. Studies have linked two-stage garnets with temporally distinct thermal events, including the Wolz complex of
the Eastern Alps (Gaidies et al., 2008; Bestel et al., 2009) and Yenisey Ridge in Siberia (Likhanov and Reverdatto, 2013). These two studies utilized garnet cation diffusion modeling and P-T-t paths to determine that garnet growth was temporally separate and coincided with known regional-scale metamorphic heating events. Yardley et al. (1996) identified two-stage garnet in western Ireland that they interpreted to result from metamorphic rims grown on detrital garnet.

Sm-Nd and Lu-Hf geochronology can identify separate growth events that produce two-stage garnet (Stowell and Goldberg, 1997; Kohn, 2009; Baxter and Scherer, 2013; Skora et al., 2009). In this method, the core and rim of garnet are analyzed separately to attempt to date separate growth events. These ages can then be interpreted to represent either two distinct growth events or the duration of a single event. Garnet growth duration can last <1 m.y. or tens of millions of years. For example, garnet from Garnet Ledge, southeastern Alaska grew over a short interval of <2.3 m.y. (Stowell et al., 2001). Kohn (2009) utilized Lu-Hf geochronology on two stage garnet in the Himalaya and found a 40 m.y. age difference between core and rim. Due to the large expanse of time between growth periods the sample was interpreted to result from separate metamorphic events (Kohn, 2009). Stowell et al (1997) identified polyphase garnet in the western metamorphic belt of the Coast Plutonic Complex, Alaska with a ~20 my age difference between core and rim. Depending on the age separation and associated errors, the timing of two-stage growth can be interpreted as duration of a single event or ages for two events. Important for age interpretations is a pre-existing knowledge of thermal events that were likely related to accretion/collision/thrust faulting and/or pluton emplacement (see Figure 2 for crustal thickening and heating explanation).
This thesis focuses on abundant and varied two-stage garnet from the Salmon River suture zone (SRSZ) of west-central Idaho. The goal for this thesis is to establish a detailed understanding of two-stage garnet formation mechanisms by evaluating reaction histories concurrent with garnet growth. Results will be used to evaluate potential tectonic causes for two-stage garnet formation (i.e. pluton emplacement, multiple accretions). This goal is achieved by careful analyses of garnet compositional zoning integrated into isochemical P-T modeling. Through these methods garnet growth is interpreted along a derived P-T path. This type of detailed approach has been lacking for the Salmon River two-stage garnets. The results suggest that two-stage garnets in the SRSZ form from mineralogical reactions involving the growth and consumption of garnet.
The Salmon River Suture Zone (SRSZ)

The Salmon River suture zone (SRSZ) trends approximately N-S and is composed of accreted terranes in west-central Idaho, west of the Mesozoic margin of North America (Figure 3). The SRSZ is bordered on the east by the Western Idaho Shear zone and Idaho Batholith and to the west by the Seven Devils Volcanics of the Wallowa terrane. The rocks of the SRSZ are separated into structural blocks by east-dipping, thrust faults over the Seven Devils Volcanics (Hamilton, 1963). Most notable of the thrust faults are in the areas directly north and south of Riggins, Idaho: the Pollock Mountain, Rapid River, Slate Creek, and Heaven’s Gate thrust faults. The thrust faults divide the area into the following structural blocks: the Pollock Mountain plate, Rapid River plate, Slate Creek plate, and Heaven’s Gate plate (Figure 4) (Hamilton, 1963; McKay, 2011).

Figure 3: Map showing the location of the Wallowa Terrane, Baker Terrane, and Izee Basin Terrane separated by short dashed lines. The north-south long dashed line is the location of the Sr 0.706 line that denotes the boundary between accreted terranes and the craton. Small box denotes location of the SRSZ (map modified from Wicander et al., 2010).
Figure 4: Geologic map of the Riggins, Idaho area of the SRSZ showing all samples discussed in this study (see Appendix for all sample locations) after Lund et al. (2004) and Reed et al. (2014, personal communication). Thrust faults are the Pollock Mountain fault (PMF), Rapid River fault (RRF), Slate Creek fault (SCF), and Heavens Gate fault (HGF).

Getty et al. (1993) used two-stage garnets combined with geochronologic data to infer two separate terrane accretions resulting in two metamorphic events. A more recently proposed tectonic model for the SRSZ infers multiple temporally separate thrust faulting events related to
a single terrane collision (McKay, 2011; Schwartz, 2011). McKay (2011) constrained garnet growth ages for garnet core at 144-135 Ma and rim at 135-124 m.y. (Getty et al., 1993; McKay, 2011). Two-stage garnets are common east of the Pollock Mountain fault (Pollock Mountain plate); however, some are found west of the fault in the Rapid River plate (Selverstone et al., 1992; Getty et al., 1993, McKay et al., 2011). In this thesis I present detailed models for growth of two-stage garnet in both plates to ascertain any possible connection of two-stage garnet with the tectonic history of the SRSZ.
CHAPTER 2: METHODOLOGY

Petrography

Samples were collected during 2010 and 2014, cut into rectangular rock tabs in the Rock Preparation Laboratory at the University of Alabama. National Petrographic Service, Inc. and Spectrum Petrographic produced thin sections from these tabs. Minerals and textures were identified and described using a petrographic microscope.

X-ray Fluorescence Spectrometry

Bulk rock compositions were determined using X-Ray Fluorescence Spectrometry (XRF) for use in P-T isochemical pseudosection modeling. Representative portions of each rock were cut, weathered portions removed, and then cleaned with isopropanol. The prepared samples were then crushed and powdered using a low carbon steel ring and puck mill in a SPEX shatterbox. Resulting powders were then weighed and dried in an oven at 110°C for at least 6 hours to drive off any unbound water. The samples were then weighed and dried in an oven at 900°C for no more than 6 hours to remove structurally bound water, carbon, sulfur, and other volatiles. Loss on ignition was calculated based on the difference in mass between the 110°C and 900°C steps. Fused glass disks were then produced by melting 0.5 g of sample and 4.5 g of lithium metaborate and tetraborate (flux) inside a platinum crucible placed over a Bunsen burner. Once completely molten, each mixture was poured into a Pt-Au alloy mold to solidify and cool. Each disk was then analyzed five times using the University of Alabama Geological Sciences Phillips PW2400
X-ray Fluorescence Spectrometer. A set of USGS standards were used for calibration (see Stowell et al., 2010). The USGS standard AGV-1, analyzed with each batch of unknowns, was used as an internal standard.

**Electron Microprobe Analyses**

Electron microprobe analysis was conducted at the University of Alabama’s Central Analytical Facility. Backscatter and X-ray images, and quantitative mineral compositions were obtained using the JEOL 8600 with energy dispersive spectrometer (EDS) and wavelength dispersive spectrometer (WDS) techniques, respectively. Rock tabs containing two-stage garnet were polished and carbon coated prior to analyses. The instrument was calibrated with multiple silicate mineral standards using two different calibrated routines. The first routine used a 15 keV accelerating voltage and 20 nA beam current to obtain major element line scans and spot analyses for minerals for Fe, Mg, Ca, Mn, Ti, Si, Al, Cr, Na, Ca, and K. This technique was applied to amphibole, plagioclase, and only one sample of garnet for comparison with the second routine. The second routine used a 15 keV accelerating voltage and 200 nA beam current to obtain major element line scans for the elements Si, Fe, Mg, Mn, Ca, and Al (Al calculated based on stoichiometry). The 200 nA routine greatly reduces the analyses time required and is only used for garnet line scans (technique from Gatewood et al., 2015). The resulting wt. % oxide compositions from each routine were used to calculate mineral structural formulas and mole fractions of solid solution end members. These observed compositions were then compared to solid solution compositions predicted for P-T diagrams in order to define P-T paths. Garnet mole fractions used for P-T path constructions are plotted with ±0.01 (±1%) to account for fluctuations.
in garnet compositions in both core and rim. Compositional variations related to zoning discussed in the text are reported as absolute values with no associated error.

*Phase Diagram Sections: Pseudosections*

Pressure-temperature paths were determined from isochemical phase diagram sections (pseudosections) constructed with the program THERIAK-DOMINO (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) using the system SiO$_2$-Na$_2$O-CaO-K$_2$O-FeO-MgO-MnO-TiO$_2$-Al$_2$O$_3$-H$_2$O. Doug Tinkham compiled the program from source code, assembled the data file with the Holland and Powell (1998) internally consistent dataset (v. 5.5), and coded the activity models. The following activity models were used for modeling rocks: plagioclase (Holland and Powell, 2003), garnet and biotite (White et al., 2007; garnet compiled by Doug Tinkham to include Mn), clinoamphibole and orthoamphibole (Diener and Powell, 2012), staurolite and chlorite (Holland and Powell, 1998).

Whole rock compositions obtained by XRF analysis (Table 1) were converted to mole proportions of major elements for use in THERIAK-DOMINO. Water contents during metamorphism were estimated from T-X$_{H2O}$ diagrams. The minimum water content required for saturation was used for all samples discussed. The saturation point is determined on each diagram by finding the water-in line, above which all assemblages contain water as a free phase at all temperatures (and pressures). The water contents estimated from T-X$_{H2O}$ phase diagrams are all greater than 10 mole proportions (see individual model figures for amount used). Such high water content was selected because basaltic compositions hydrate along prograde P-T paths and dehydrate along retrograde paths.
The estimated maximum water content was used with the whole rock composition to calculate a P-T pseudosection. Modal percentages of key phases such as garnet, titanite, staurolite, and amphibole were then used to determine when each phase was growing or breaking down. Isopleths of the mole fractions of end-member compositions for plagioclase and garnet were then calculated and plotted to determine the equilibration P-T during metamorphism.
CHAPTER 3: SAMPLE DESCRIPTIONS

10IDMM48

Sample 10IDMM48 is a garnet-biotite-amphibole-staurolite-kyanite schist from the edge of the Pollock Mountain fault zone. The sample is from the Ruby Rapids schist and was collected along the Salmon River at a spot favored by locals because of the red euhedral garnet found there. The rock contains 35% biotite, 30% plagioclase, 12% clinoamphibole, 10% quartz, 8% garnet, <2% staurolite, <2% kyanite, and <2% chlorite. Schistosity is well defined by biotite. Amphibole occurs as large, late porphyroblasts growing over biotite and riddled with numerous inclusions (Figure 5A-B). Staurolite occurs as small anhedral remnants in the matrix and as inclusions within the garnet core and is not inferred to be part of the peak assemblage (Figure 5C-D, 6A, 6C). Figure 6 shows EDS spectra for staurolite, which shows kα peaks for Ti and Zn. Small blades of kyanite are found throughout the rock and as inclusions in garnet rims (Figure 5E-F). The garnet in this sample is two-staged, characterized by an inclusion free core and inclusion rich rim (Figure 7A). Inclusions in the core include: staurolite, clinoamphibole, biotite, chlorite, plagioclase, quartz, and rutile. Inclusions in the rim include: kyanite, biotite, clinoamphibole, plagioclase, quartz, and rutile.
Figure 5: Thin section images of sample 10IDMM48. A) Plane polarized light and B) crossed polarized light image showing clinoamphibole and biotite within the matrix. Clinoamphibole has numerous large inclusions (apatite, quartz, and plagioclase). C) plane polarized light and D) crossed polarized light images of remnant staurolite and clinoamphibole. E) Plane polarized light and F) crossed polarized light images of kyanite, biotite, and chlorite in close proximity to two garnet porphyroblasts.
Figure 6: A) Backscatter electron image showing staurolite (highlighted in yellow) and locations for EDS x-ray intensity spectra analyses (green cross). B) EDS x-ray intensity spectra analysis for location on A. C) Backscatter electron image showing staurolite (highlighted in yellow) and locations for EDS x-ray intensity spectra analyses (green cross). D) EDS x-ray intensity spectra analysis for location on C.

The compositional zoning pattern in this garnet displays a subtle change at the core-rim boundary (Figure 6A-B). Within the core, grossular decreases from 0.10 to 0.70 mole fractions, pyrope increases from 0.24 to 0.26, and spessartine decreases from 0.07 to 0.06. Almandine remains nearly constant in the core, however it does increase slightly toward the rim boundary from 0.58 to 0.59. Within the rim, grossular increases and then plateaus from 0.70 to 0.80. Almandine decreases from 0.59 to 0.57 where it remains constant. Pyrope increases steadily from 0.26 to 0.30. Spessartine decreases from 0.06 to 0.03. The garnet rim shows evidence of diffusion: pyrope decreases sharply and almandine and spessartine increase sharply.
Figure 7: A) 10IDMM48 garnet showing distinct core and rim indicated by white dashed line. A-A’ line is location of line scan analyses. B) WDS 159 point line-scan. Core and rim segments are labeled.

Sample 14ID24c

Sample 14ID24c is part of the Squaw Creek unit of the Rapid River plate and contains garnet, clinoamphibole, biotite, clinozoisite, titanite, plagioclase, quartz, and ilmenite. This sample was collected from a hillside along the Lake Creek trail south of the Salmon River and
contains <1 cm to 6 cm granitic intrusions. Modal abundances are 15% biotite, 5% garnet, 35% amphibole, 2% clinozoisite, 30% plagioclase, 10% quartz, 1% titanite, and 2% ilmenite.

Schistosity, defined by aligned amphibole and biotite, is parallel to poorly defined compositional layering which is evident from the modal variation in biotite and amphibole (Figure 8). Both biotite and amphibole are found as inclusions in garnet. Clinozoisite appears to be earlier than amphibole, titanite, biotite, and garnet based on amphibole, titanite, and biotite overgrowths on clinozoisite crystals. Titanite is an earlier phase than amphibole based on overgrowths of amphibole around titanite and partially resorbed titanite (Figure 9C-F). The garnet is anhedral, approximately 2.5 mm, and is two-staged with a small inclusion-rich core and larger inclusion-rich rim (Figure 9A-B). Inclusions in the core are as follows: biotite, plagioclase, quartz, and ilmenite. Inclusions in the rim are clinoamphibole, biotite, plagioclase, quartz, and ilmenite.

Figure 8: 14ID24c cut and polished sample tab showing small two stage garnet and compositional layering. A small granitic intrusion cross-cuts the foliation.

The transition between garnet core and rim is sharp and includes changes in inclusion density and composition (Figure 9A-B, 10, 11). Due to the large number and size of inclusions in the rim, a single continuous line of analyses is difficult. Figure 11 shows two distinct line scans, chosen to avoid large inclusions. Each garnet end-member component zoning profile changes slope at the core-rim boundary. Spessartine is highest in the core (0.15) and decreases toward the
rim (0.05), changing slope at the core-rim boundary. Pyrope is lowest in the core at 0.02 and increases to 0.09 at the core-rim boundary. In the rim, pyrope remains fairly constant. The amount of grossular stays a constant 0.29 in the core and shows a slight decrease at the boundary before increasing to 0.32, then decreasing to 0.25, followed by an abrupt increase to 0.35, and ultimately decreasing to 0.27 at the rim. The almandine component is lowest in the core (0.52) and increases at the core-rim boundary. Almandine then sharply increases to 0.62 after the boundary, decreases to 0.55, and then increases again to 0.63 at the rim edge.
Figure 10: Mosaic maps showing major element zoning of 14ID24c garnet. 
A) Mn Kα x-ray intensity map, B) Fe Kα x-ray intensity map, C) Mg Kα x-ray intensity map, 
D) Ca Kα x-ray intensity map, E) Na Kα x-ray intensity map, F) K Kα x-ray intensity map, 
G) Al Kα x-ray intensity map, H) Si Kα x-ray intensity map.
Figure 11: A) Backscattered electron image of garnet in 14ID24c showing location of line scan analyses through garnet core and one of the inclusion-rich rims from A-A'. B) Quantitative 135 point line scan showing garnet mole fractions along A-A'. The core-rim boundaries are indicated.
Sample 14ID40b is part of the Pollock Mountain amphibolite of the Pollock Mountain plate and consists of garnet, staurolite, kyanite, orthoamphibole, clinoamphibole, chlorite, clinozoisite, rutile, plagioclase, quartz, and ± biotite (Figure 12). The sample was collected from an outcrop of amphibolite directly above the mapped Pollock Mountain fault along Denny Creek road. The outcrop was vegetated and weathered making field relationships difficult to determine. The foliation in this rock is well defined by chlorite and amphibole. Portions of the rock contain small leucocratic slivers, which can be observed along the foliation. Larger leucocratic veins cross-cut the foliation (Figure 13). Modal abundances are as follows: 10% garnet, 20% orthoamphibole, 25% clinoamphibole, 4% staurolite, 5% kyanite, 5% chlorite, 2% clinozoisite, 3% rutile, 12% plagioclase, and 14% quartz. Kyanite is altered to plagioclase and quartz but can still be observed as skeletal textures throughout the rock (Figure 14D, F). Staurolite is found in the matrix and as inclusions in kyanite and garnet cores. Matrix staurolite is subhedral to anhedral, and is not stable with the peak assemblage (Figure 14C-D, 15). The EDS X-ray spectrum of staurolite indicates the presence of Zn and Ti (Figure 14). Around garnet, there is a lower abundance of orthoamphibole. The 1 cm sized euhedral garnet in this rock is two staged with very few inclusions in the core and large inclusions in the rim. The boundary between core and rim is extremely sharp and may indicate a hiatus in garnet growth. Inclusions in garnet core are staurolite, clinoamphibole, quartz, plagioclase, chlorite, and rutile. Inclusions in garnet rim are kyanite, orthoamphibole, clinoamphibole, quartz, plagioclase, and rutile.
Figure 12: Cut surface through 14ID40b showing two-stage garnets.

Figure 13: A cut surface through 14ID40b showing a cross cutting vein leucocratic material.
Figure 14: Photomicrographs (A-E) and EDS x-ray intensity map (F) showing various minerals in 14ID40b. A) Clinoamphibole and orthoamphibole in the matrix. B) Kyanite altered to quartz surrounded by clinoamphibole. C) and D) Anhedral staurolite crystals in a matrix of rutile, kyanite, clinoamphibole, and chlorite. E) Inclusions of staurolite in kyanite porphyroblast. F) Backscatter electron image overlain with false color Kα x-ray Al intensity map (indicates kyanite, yellow) and Si intensity map (indicates quartz, blue) reaction habit.
Figure 15: A) Backscatter electron image of staurolite, green cross indicates location of EDS spectra analysis location. B) Resulting X-ray spectra showing presence of Zn and Ti and other major elements in staurolite. C) Map of Al Kα X-ray intensity, D) Map of Si Kα X-ray intensity, E) Map of Fe Kα X-ray intensity, F) Map of Mg Kα X-ray intensity, G) Map of Ti Kα X-ray intensity, H) Map of Zn Kα X-ray intensity.
Garnets in sample 14ID40b are ≤ 1cm in diameter with sizes that range down to 0.25 cm. Most of the garnet are 0.5 cm-1 cm. Small garnets do not show obvious core-rim breaks like their larger counterparts (small garnets not analyzed). The two 1 cm garnets analyzed in this rock show a very abrupt transition between core and rim. Cores are nearly inclusion free and the rims are inclusion rich. The large gaps in data in the line scan (Figure 16 and 17) are due to inclusions. The shape of the garnet core outlined in Figure 16 is anhedral and appears to have been resorbed. Subsequent growth of the rim resulted in a euhedral shape for the garnet. The compositional line scans show different profile trends for core versus rim growth. Spessartine decreases from 0.015 in the core to 0.01 in the rim. Pyrope is lowest in the core (0.27) and increases steadily toward the core-rim boundary (0.28). In the rim pyrope content continues to increase at a different rate with a shallower slope, reaching 0.32 at the maximum, before decreasing at the rim edge to 0.28. Grossular increases from 0.12 to 0.13 in the core. At the core-rim boundary, grossular begins to decrease to a final value of 0.09 at the rim edge. Almandine decreases from 0.60 to 0.59 in the core. In the rim, almandine increases slightly to from 0.58 to 0.59 before decreasing back to 0.58 and then increasing again to 0.60 at the rim edge. Figure 16C shows a short line scan across the core-rim boundary. There is very little composition change between garnet core and rim, possibly revealing that diffusion did not alter the profile between core and rim growth.
Figure 16: A) High-resolution photograph of 14ID40b garnet showing two stage growth. Core-rim boundary is indicated by the white dashed line. Location of A-A’ traverse is shown. B) Garnet mole fractions from the 177 point A-A’ line scan analyses using the 20 nA routine from rim to rim. Core and rim are denoted. C) Short 200 point traverse across the core-rim boundary using the 200 nA routine. Note lack of major composition change. Core and rim are denoted.
Figure 17: A) 14ID40b garnet showing distinct core and rim indicated by white dashed line. A-A’ line is location of line scan analyses. B) 155 point line-scan analyses using the 200 nA routine. Core and rim segments are labeled.
CHAPTER 4: ROCK COMPOSITIONS

The whole rock and matrix compositions obtained from XRF analyses are described for samples 10IDMM48, 14ID24c, and 14ID40b. Compositions are given for each rock in Table 1.

Table 1

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<tr>
<th>Rock Compositions</th>
<th>10IDMM48</th>
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<th>14ID40b fMtx</th>
<th>14ID40b (1) bulk</th>
<th>14ID24c</th>
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<td><strong>99.48</strong></td>
<td><strong>101.55</strong></td>
<td><strong>100.16</strong></td>
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Table 1: Rock compositions (whole rock and matrix) obtained from XRF analyses for all rocks discussed. Values listed are in weight percent (wt.%).

10IDMM48

Due to problems with modeling the bulk rock composition of this sample (McKay, 2011), a new XRF disk was prepared using a larger portion of the rock. The new XRF sample includes all observed portions of the rock, including textures and phases, and yields a better P-T modeling results. Figure 18 shows a polished tab cut from the same piece used for XRF analyses. The
composition of this sample reflects the dominance of mafic minerals. The presence of amphibole, chlorite, biotite, and garnet results in high Fe$_2$O$_3$ (11.57 wt. %), high MgO (9.50 wt. %), and relatively low SiO$_2$ (50.86 wt. %). The Al$_2$O$_3$ content of this rock is ~5% higher when compared to the average MORB composition recorded in Gale et al. (2013). The high Al is reflected in the presence of kyanite and staurolite, which are more often found in pelitic rocks. This is the only sample with an appreciable mode of biotite (K$_2$O 3.24 wt. %).

Figure 18: 10IDMM48 polished tab high-resolution image. The tab is from the portion of the rock used to make the XRF disk for this sample.

14ID24c

The XRF disk was prepared from a bulk rock portion, and differs significantly in all components, particularly SiO$_2$, from 14ID40b and 10IDMM48. Figure 19 shows a polished tab from the sample piece used for XRF analyses (see Table 1 for results). SiO$_2$ is at most ~9 wt. % higher and Al$_2$O$_3$ is ~2 wt. % lower. Fe$_2$O$_3$ and MgO components are lower, 9.06 wt. % and 3.14 wt. % respectively. Despite these differences, this sample is mafic in composition. The lower Al
content reflects the absence of kyanite and staurolite. The 3.30 wt % Na₂O and 8.48 wt. % CaO indicate that plagioclase is the principle consumer of Al in this rock.

Figure 19: 14ID24c polished tab high-resolution image. The tab is from the same portion of rock used to make the XRF disk. The dashed line indicates slight compositional layering. The granitic vein shown cross-cutting the foliation and layering was not included in the whole rock composition.

14ID40b

Three compositions were prepared for sample 14ID40b (Figure 20). Table 1 presents these analyses. Bulk and fine matrix were extracted from a more foliated portion of the rock with less leucocratic material (plagioclase and feldspar along the foliation) and contains two-stage garnet as well as single stage garnet. The bulk composition is the most representative of the rock as a whole as it contains all relevant textures and components. The coarse matrix was extracted from below a small crack and is less foliated, contains more leucocratic material (relatively high amount of Al₂O₃, Na₂O, and CaO) and has a higher mode of staurolite and orthoamphibole (relatively low amount of MgO and Fe₂O₃). Unlike the coarse matrix, the fine matrix contains less staurolite and less leucocratic material. However, it contains ~2% more MgO than the coarse matrix, which could be due to less leucocratic material resulting in a higher mode of
orthoamphibole in the fine matrix. The bulk composition has relatively higher SiO$_2$ and an intermediate MgO content (between coarse and fine matrix).

Despite the differences discussed above, 14ID40b bulk, coarse matrix, and fine matrix are all mafic based on the composition characteristics of 10 wt. % Fe$_2$O$_3$, 7 wt. % MgO, and 6 wt. % CaO. SiO$_2$ is lower for the compositions of this sample compared to 14ID24c (49.29 wt. % average). Similarly to 14IDMM48, the Al$_2$O$_3$ content for 14ID40b is higher than expected for a mafic rock. Al$_2$O$_3$ ranges between 19.74 and 21.01 wt. %, which is observed as the presence of kyanite and staurolite.

Figure 20: Cut surface of 14ID40b showing representative locations of coarse matrix (cMtx, dashed line), fine matrix (fMtx, solid line), and whole rock (bulk, solid line). The actual material used for the XRF analyses was sampled from the adjacent slab (not shown).
A P-T pseudosection was constructed from 400-800°C and 4-11 kbar. Due to problems with over-prediction, this was constructed without orthoamphibole. This sample was previously modeled by McKay (2011), which did not predict staurolite. In addition, an updated clinoamphibole activity model was used. The new model predicts staurolite at 5-8.15 kbar and 575-650°C (Figure 21, green field). Staurolite occurs as inclusions within garnet cores and therefore the predicted stability region for staurolite indicates part of the prograde P-T path. The observed peak assemblage is garnet, kyanite, clinoamphibole, biotite, rutile, plagioclase, quartz, and ± chlorite. This assemblage occurs at 625-700°C and 7.2-11 kbar (shown as red on Figure 21).

Garnets in this sample contain texturally distinct core and rims with more inclusions in the rim than in the core. The garnet rim composition used for isopleth intersections are 0.03±0.01 spessartine, 0.30±0.01 pyrope, 0.08±0.01 grossular, and 0.57±0.01 almandine. The rim produces an intersection at 9.25-10.2 kbar 630-700°C (rim intersection). The rim intersection is shown by a yellow circle on the P-T diagram (Figure 21). Garnet core was not included on this plot due to near vertical (T dependent) isopleths. Garnet mode increases with T and P until ~8 kbar ~650°C (between the core and rim equilibration assemblages), where it decreases for 10°C before increasing again.
Figure 23 shows a more detailed view of the reactions taking place between 7.6-8.1 kbar and 590-669°C. The up temperature mode observations are interpreted as follows: 1) staurolite does not affect the growth of garnet, 2) decreasing chlorite mode with the introduction of clinoamphibole results in the decrease in garnet mode (resorption of garnet core), and 3) chlorite-out facilitates the growth of garnet rim over the resorbed core. Therefore, the introduction of clinoamphibole and decrease in chlorite, not staurolite, causes the sudden decrease and then increase in garnet mode. This indicates absorption and growth between the observed prograde and peak assemblages due to clinoamphibole stability (Figure 23).
Figure 21: P-T pseudosection for sample 10IDMM48 modeled without the orthoamphibole activity model. Green field indicates region of staurolite stability. The P-T path for this rock must have passed through the staurolite region based on inclusions in garnet core and staurolite remnants in the matrix. Red indicates peak assemblage field: garnet, clinoamphibole, biotite, kyanite, plagioclase, quartz, and rutile. Garnet compositional isopleths for rim are shown as a yellow circle overlain with isopleth lines used for intersections: almandine (red), pyrope (purple), spessartine (orange), and grossular (green). Gray box is region modeled in Figure 23.
Figure 22: Predicted garnet mode for sample 10IDMM48. Colors denote volume % (or mode) of garnet present in the rock at a given pressure and temperature. Note the presence of a small region of decreasing garnet mode going up pressure and temperature at 8 kbar 650°C. This decrease in garnet mode is caused by the introduction of clinoamphibole. Garnet mode increases following the chlorite-out line.
Figure 23: Detail of P-T pseudosection showing the area above the T of staurolite stability where garnet mode decreases then increases on an isobaric path. A) Phase diagram section. B) Garnet mode. C) Chlorite mode. D) clinoamphibole mode. Note that the presence of staurolite does not account for the garnet mode changes at 665°C.
A P-T pseudosection was constructed from 400-800°C and 4-11 kbar (Figure 24). The peak assemblage is garnet, biotite, clinopyroxene, ilmenite, plagioclase, and quartz. Titanite is included inside garnet cores and is also found in the matrix as small, retrogressed subhedral crystals. The peak mineral assemblage field (field 5 on Figure 24) does not overlap with the garnet rim composition; however, the peak minerals + pyroxene are predicted at 570-710°C and 4-9.5 kbar (field 8 on Figure 24). Mineralogical observations suggest that pyroxene is over-predicted based on the absence of pyroxene in this rock, including outcrop scale, and a large (500-800°C 4-11 kbar) stability region. The over-prediction of clinopyroxene is somewhat problematic because the observed peak assemblage is not compatible with the garnet rim composition. Not including clinopyroxene results in a large stability region for the observed peak assemblage as well as core and rim isopleth intersections at or above the solidus. Because this rock does not contain melt, equilibration above the solidus is unlikely. Therefore, clinopyroxene was kept in the model because it makes the most sense of petrographic evidence and garnet isopleth intersections. The garnet core intersection overlaps with the garnet core assemblage, observed from inclusions in garnet core. Garnet core isopleths intersect at 5.25-6 kbar and 540-630°C. The garnet core composition used for the intersection is 0.52±0.01 almandine, 0.14±0.01 spessartine, 0.03±0.01 pyrope, and 0.30±0.01 grossular. The rim composition plots in the clinopyroxene stability region at 7-8 kbar and 600-650°C using the composition 0.55±0.01 almandine, 0.06±0.01 spessartine, 0.32±0.01 grossular, and 0.14±0.01 pyrope (see Figure 24).

Figure 25 shows titanite (sphene) mode and potential growth path toward the garnet core equilibration intersection. This confirms that titanite is not a stable phase and thus not part of the peak assemblage. The garnet mode shown in Figure 26 illustrates that garnet grows with
increasing temperature and pressure with no major perturbations. However, the slopes of the lines change from temperature dependent to pressure dependent at 500°C. This change in slope along the inferred P-T path likely resulted in the inclusion size and density changes at the core-rim boundary.
Figure 24: P-T pseudosection for sample 14ID24c. Gray indicates region of sphene stability. Up temperature of gray region is clinopyroxene stability region (not observed). Red field is observed garnet core inclusion assemblage: garnet, sphene (titanite), clinoamphibole, biotite, plagioclase, quartz, and ilmenite. Field 5 is the observed peak assemblage: garnet, biotite, clinoamphibole, ilmenite, plagioclase, and quartz. Yellow boxes overlaying compositional isopleths of garnet show equilibration P-T conditions for core (6 kbar 600°C) and rim (7.5 kbar 625°C).
Figure 25: Titanite (sphene) mode for sample 14ID24c. Arrow indicates potential garnet growth path up temperature toward garnet core inclusion assemblage stability field (red): garnet, biotite, clinoamphibole, ilmenite, plagioclase, and quartz. Arrow indicates that titanite becomes less prevalent up temperature toward the core inclusion assemblage.
Figure 26: 14ID24c garnet mode. Warmer colors indicate higher abundance of garnet and garnet growth. Colder colors indicate lower garnet mode. Lower pressures (4-6 kbar) and temperatures (400-525°C) have mode lines farther apart that the higher P-T space. This indicates that if one assumes a constant rate of P-T increase the garnet will increase less in volume at lower P-T space than at higher.

14ID40b

Three P-T pseudosections were constructed from 300-800°C and 4-14 kbar: 14ID40b bulk, 14ID40b coarse matrix, and 14ID40b fine matrix (Figure 27-29). The matrix compositions were modeled to constrain conditions of garnet rim growth by accounting for fractionation of the bulk rock composition. The following discussion first addresses the three models together before identifying differences between them.
The peak assemblage observed for 14ID40b is garnet, clinoamphibole, orthoamphibole, kyanite, quartz, plagioclase, and rutile. This field is predicted for each of the compositions at approximately 9.5-12 kbar and 625-680°C (shown as blue on P-T diagrams). However, the leucocratic veins could be interpreted as melt, resulting in a possible second peak assemblage at approximately 12.75-10.5 kbar 680-720°C (red field on P-T diagrams). The assemblage with which garnet core equilibrated with is staurolite, clinoamphibole, chlorite, biotite, plagioclase, quartz, and rutile. This assemblage is not predicted in any of the models; however, a similar field (green on P-T diagrams) is predicted. This field is very small, located at ~9 kbar and 620°C, and is likely small because staurolite is not accurately predicted. Staurolite can contain elements not included in the activity models used (Ti and Zn); therefore stability could have been enhanced by these two elements. This could change the phase diagram because staurolite would include Al, Fe, and other elements that would not be available to other minerals. Furthermore, amphibolites have more plagioclase, which lowers the activity of Al, resulting in a decrease in staurolite activity. Therefore, the garnet likely equilibrated between 7-9 kbar and 550-625°C. The assemblage with which garnet equilibrated (green field) is lumped together with the purple field, which contains all minerals except staurolite. I use these two fields under the assumption that staurolite is under predicted due to Zn and Ti and would likely be stable in that P-T space.

All three models (bulk, coarse, or fine matrix) predict very similar assemblage fields with the exception of the fine matrix model, which did not predict staurolite (Figure 29). Conversely, the coarse matrix produced a higher observed mode of staurolite and lower observed mode of orthoamphibole than the bulk composition (Figure 28). The higher mode of staurolite and lower mode of orthoamphibole in the coarse matrix (also described in the Rock Composition section) combined with the lack of two stage garnet suggests one of the following: 1) staurolite and
chlorite did not break down to grow garnet rims and orthoamphibole in this part of the rock, or 2) this portion contains more leucocratic material (melt?) resulting in a staurolite rich residue and less orthoamphibole. Both of the above explanations could account for the higher mode of staurolite in the coarse matrix. Based on the corresponding P-T models for all three 14ID40b compositions the melt(?)-rich hypothesis is most likely because orthoamphibole reacts out with the addition of melt along the observed P-T path.

All models produced garnet compositional isopleth intersections in the observed peak assemblage fields (blue and red fields) at 10.5 kbar and 675°C. The garnet rim composition used for peak conditions are as follows: 0.02±0.01 spessartine, 0.28±0.01 pyrope, 0.12±0.01 grossular, and 0.59±0.01 almandine. The composition of garnet core is similar to the rim and does not plot with the prograde assemblages.

Garnet mode calculated for the bulk composition (Figure 30) shows increasing garnet toward the solidus with increasing temperature and pressure. At approximately 9.5 kbar, there is a change in garnet mode, resulting in an ‘island-like’ shape, which can be seen in all three garnet mode diagrams (Figure 30-32). Increasing in P and T toward the ‘island’ results in increasing garnet mode. Additional increases P and T results in a decrease in garnet mode indicating absorption. After approximately 10°C of T increase, the garnet mode once again increases. This indicates that if garnet grew from P-T conditions near the garnet mode zero line across the ‘island’ to a pressure and temperature near the solidus, there would first be growth, then resorption of garnet, and then a second episode of garnet growth. In this study, this pattern in garnet mode behavior is termed the garnet transition discontinuity.

The minerals responsible for this sudden decrease and then increase in garnet mode are chlorite, orthoamphibole, and staurolite. Figure 33 shows a more detailed view of reactions
occurring across the garnet discontinuity. On closer inspection the up temperature reaction series
is as follows (see Figure 34). 1) Garnet mode increases until the orthoamphibole-in line after
which garnet mode decreases sharply. 2) The staurolite-in line is crossed resulting in a slight
steepening of the decreasing garnet mode lines. 3) The chlorite-out line is then crossed and
orthoamphibole mode becomes less temperature dependent, these last two changes cause garnet
mode to stop decreasing and begin to increase, growing the garnet rim over the resorbed core.
Figure 27: 14ID40b bulk composition P-T pseudosection. Purple and green fields indicate garnet core assemblages inferred from inclusions: garnet, staurolite, clinoamphibole, biotite, plagioclase, quartz, and rutile. Blue indicates the rim assemblage inferred from inclusions in the rim: garnet, kyanite, clinoamphibole, ± orthoamphibole, plagioclase, quartz, and rutile. The red field is the peak assemblage and includes all blue field phases with the exception of kyanite. The yellow circle is an intersection point from the overlain compositional isopleth lines for garnet rim: almandine (red), pyrope (purple), spessartine (orange), and grossular (green).
Figure 28: 14ID40b coarse matrix composition P-T pseudosection. Purple and green fields indicate garnet core assemblages inferred from inclusions: garnet, staurolite, clinoamphibole, biotite, plagioclase, quartz, and rutile. Blue indicates the rim assemblage inferred from inclusions in the rim: garnet, kyanite, clinoamphibole, ± orthoamphibole, plagioclase, quartz, and rutile. The red field is the peak assemblage and includes all blue field phases with the exception of kyanite. The yellow circle is an intersection point from the overlain compositional isopleth lines for garnet rim: almandine (red), pyrope (purple), spessartine (orange), and grossular (green).
Figure 29: 14ID40b fine matrix composition P-T pseudosection. Purple field indicate garnet core assemblages inferred from inclusions: garnet, staurolite, clinoamphibole, biotite, plagioclase, quartz, and rutile. Blue indicates the rim assemblage inferred from inclusions in the rim: garnet, kyanite, clinoamphibole, ± orthoamphibole, plagioclase, quartz, and rutile. The red field is the peak assemblage and includes all blue field phases with the exception of kyanite. The yellow circle is an intersection point from the overlain compositional isopleth lines for garnet rim: almandine (red), pyrope (purple), spessartine (orange), and grossular (green).
Figure 30: Garnet mode (volume %) of sample 14ID40b using the Bulk composition. Warmer colors indicate the presence of more garnet, the cooler colors represent less garnet. Note the presence of the small ‘island’ at ~9.5 kbar and 630°C. Increasing in pressure and temperature toward the ‘island’ results in garnet growth. Once the highest point is crossed the garnet mode decreases and garnet is absorbed. Continuing up temperature and pressure causes garnet to once again start growing. The area of decreasing garnet mode up P and T of the ‘island’ is the result of chlorite, orthoamphibole, and staurolite stability.
Figure 31: 14ID40b fine matrix (fMtx) garnet mode (volume %). Warmer colors indicate more garnet, the cooler colors represent less garnet. Note the ‘island’ in garnet mode contours at 9kbar and 600°C. Increasing in pressure and temperature toward the ‘island’ results in garnet growth. Once the highest point is crossed the garnet mode decreases and garnet is absorbed. Continuing up temperature and pressure causes garnet to once again start growing. The area of decreasing garnet mode up P and T of the ‘island’ is the result of chlorite and orthoamphibole stability.
Figure 32: 14ID40b coarse matrix (cMtx) garnet mode. Warmer colors indicate more garnet, the cooler colors represent less garnet. Note the ‘island’ in garnet mode contours at 9kbar and 600°C. Increasing in pressure and temperature toward the ‘island’ results in garnet growth. Once the highest point is crossed the garnet mode decreases and garnet is absorbed. Continuing up temperature and pressure causes garnet to once again start growing. The area of decreasing garnet mode up P and T of the ‘island’ is the result of chlorite, orthoamphibole, and staurolite stability.
Figure 33: Magnified P-T space for 14ID40b bulk focused on the area between garnet core and rim equilibration. Purple, green, and blue fields are the same previously discussed in the text and prior figures. Gray box is location of fine scale mode plots for the garnet discontinuity transition (garnet mode ‘island’).
Figure 34: 14ID40b garnet discontinuity transition mineral modes from gray box in Figure 32. A) P-T diagram, B) Garnet, C) orthoamphibole, and D) chlorite modes are plotted for this P-T space. Note changes in garnet mode in response to orthoamphibole, chlorite, and, to a lesser extent, staurolite.
CHAPTER 6: DISCUSSION

Two-stage garnet textures observed differ in type of inclusions present, inclusion density, nature of the core-rim boundary, and observed mineral assemblages. Furthermore, the samples are from several different thrust sheets and lithologies within the SRSZ, establishing a location specific cause difficult, especially since two-stage garnet is sporadically located throughout the SRSZ.

Based on compositional zoning (i.e., Fe# and Mn), the garnets all grew along a single prograde path, with the exception of narrow rim zones, which experienced re-equilibration diffusion after peak conditions. The prograde P-T paths are constrained by the prograde mineral assemblages inferred from inclusions in the garnet cores and rims, and textural evidence for reactions in matrix phases.

In the case of sample 14ID24c, inclusions in garnet core include titanite, plagioclase, biotite, clinoamphibole, and quartz. However, titanite is not stable in the matrix and is inferred to have been unstable during the latter part of metamorphism. Closer inspection of titanite mode reveals that along the P-T path proposed in Figure 35, titanite is decreasing in mode. However, garnet mode is increasing along this path. Furthermore, garnet mode lines change slope along the P-T path, caused by clinozoisite becoming unstable. Clinozoisite is an early phase. If garnet grew at a constant rate throughout the entire P-T path, then the inclusion density would change between core and rim upon crossing the slope change in garnet mode. This is the most likely cause for two-stage garnet in sample 14ID24c.
Sample 14ID40b and 10IDMM48 represent a different type of two-stage garnet core-rim boundary formation than 14ID24c. The garnet mode 10IDMM48 increases with P and T as expected (Figure 36). However, garnet mode is perturbed at 8 kbar 670°C for sample 10IDMM48 (Figure 36). The cause of this ‘island’ of garnet growth is not staurolite stability, such as multiple authors (Foster et al., 1986; Karabinos, 1985; and Spear, 1993) have observed in pelitic schists. Spear (1993) described the reaction garnet + chlorite = staurolite + biotite + H₂O for the first appearance of staurolite. The next major garnet controlling reaction staurolite = garnet + biotite + Al₂SiO₅ (kyanite) + H₂O results in garnet resorption followed by additional growth around 600°C (Spear, 1993). However, in amphibolite from the SRSZ (10IDMM48 and 14ID40b) the garnet, chlorite, and clinoamphibole modes shown in Figure 23 indicate that it is ultimately clinoamphibole that causes the resorption of the garnet core and final garnet growth (rim) occurred from consumption of the remaining chlorite. Clinoamphibole is a complex phase to model due to complex solid solutions between Fe, Mg, Ca, Na, and Al-rich end members. Despite this, a possible sequence of reactions is proposed as follows: 1) chlorite + garnet = clinoamphibole + Al₂SiO₅ (kyanite) + biotite(?) (resorption of garnet core) and 2) clinoamphibole + chlorite = garnet + Al₂SiO₅ (kyanite) + H₂O (growth of garnet rim). In each of these reactions, clinoamphibole combined with chlorite is causing the consumption of garnet until the breakdown of chlorite. Therefore, staurolite is not necessary to form the discontinuous two-stage garnet observed. The P-T path for 10IDMM48 is shown in Figure 36 crossing the above reaction lines from staurolite stability to the peak assemblage and garnet rim isopleth intersection.

14ID40b is most similar to 10IDMM48 in minerals present and conditions reached. However, the combined presence of orthoamphibole and staurolite complicates the identification
of the garnet consumption mechanism. Mineral modes show that the decrease in garnet mode is
caused by multiple reactions in a relatively small P-T area. Figure 34 shows with increasing
temperature the introduction of orthoamphibole combined with staurolite causes the resorption of
garnet (see Figure 33 for location of Figure 34). Once the chlorite-out field is crossed, garnet
increases once again and grows over the resorbed core. Each composition (fine matrix, coarse
matrix, and bulk) modeled shows this same perturbation in garnet mode caused by staurolite and
orthoamphibole-in and chlorite-out reactions. The split of sample 14ID40b (fine matrix) that did
not predict staurolite still shows the same pattern at the orthoamphibole-in and chlorite-out lines.
This means that the major controlling factor for discontinuous garnet growth for 14ID40b is
orthoamphibole. Staurolite is not necessary to form the two-staged garnets found in this sample.
However, when staurolite is predicted, the ‘island’ of growth and subsequent mode decrease
followed by increase up temperature is much more pronounced. Similarly to clinoamphibole, the
effect of orthoamphibole on the growth of garnet is not a well-understood relationship due to
complex solid solutions. However, from the mineral modes in Figure 34 two generalized
reactions can be inferred: 1) garnet + chlorite = orthoamphibole + staurolite + biotite(?) and 2)
chlorite + staurolite + orthoamphibole = kyanite + garnet + H₂O biotite(?). These reactions
involving amphibole should result in a Mg-rich orthoamphibole due to the breakdown of Mg-
rich chlorite (Spear, 1993). The orthoamphibole is Mg-rich, supporting the proposed reaction
history. Furthermore, Mg, Fe, and Al uptake in orthoamphibole would have a drastic impact on
garnet mode. The P-T path for 14ID40b is shown in Figure 37 crossing the above reaction lines
from staurolite stability to the peak assemblage and garnet rim isopleth intersection.
Figure 35: 14ID24c garnet mode with P-T path based on observed mineral assemblages and garnet compositions.
Figure 36: 10IDMM48 garnet mode with P-T path based on observed mineral assemblages and garnet compositions.
Figure 37: 14ID40b garnet mode with P-T path based on observed mineral assemblages and garnet compositions.

The P-T paths discussed above indicate isothermic pressure increases similar to those reported by McKay (2011). There is no evidence of two accretionary events or two thermal
pulses. The two samples from the Pollock Mountain plate (14ID40b and 10IDMM48) and the Rapid River plate sample (14ID24c) show different P-T paths due to their structural position in relation to the Pollock Mountain fault. Figure 38 shows the thermal perturbations related to thrust faulting. 14ID40b and 10IDMM48 are from the upper plate on this diagram and 14ID24c is from the lower plate. The P-T path of 14ID24c shows a T and P increase caused by the initial faulting (loading, P increase) and then the thermal relaxation (T increase). Samples 14ID40b and 10IDMM48 record a single P increase without an overlying thrust fault. However, there are likely other thrust faults in this area, which are difficult to identify in the field. The loading caused by potentially unknown thrust faults farther east could account the observed P increase in 10IDMM48 and 14ID40b.

Figure 38: Pollock Mountain thrust faulting schematic showing relative positions of samples 14ID40b, 10IDMM48, and 14ID24c in the Pollock Mountain plate (PMP) and Rapid River plate (RRP) respectively. Depth and distance axis are not scaled to reflect the SRSZ but instead provide a conceptual view. Figure modified after Shi and Wang (1987).
CHAPTER 7: CONCLUSION

The simplest interpretation for two-stage garnet growth in the SRSZ is that garnet grew along a single prograde sequence of mineralogical reactions. The core-rim discontinuities likely result from growth, then consumption, of staurolite and/or orthoamphibole in some rocks and stability of clinzoisite in others. All of the two-stage garnet likely grew during a single thermal event, which may have resulted from terrane accretion. In sample 14ID24c, a sample of more pelitic affinity yet still under the amphibolite classification, clinzoisite stability appears to be the cause of two stage garnet, increasing the mode of garnet dramatically, forming an abrupt inclusion-rich rim.

In pelitic rocks, the reaction garnet + chlorite = staurolite + biotite + H₂O, produce staurolite, initiates the breakdown of chlorite, and resorption of garnet ca. 620°C. With increased temperature to ca. 630°C the staurolite then breaks down in the reaction staurolite = garnet + biotite + Al₂SiO₅ (kyanite) + H₂O. These two staurolite reactions are primarily evident in pelites, but they can also occur in more mafic rocks. However, the cause for garnet resorption and growth in 10IDMM48 and 14ID40b is due to the interaction between chlorite and amphibole (clinoamphibole and orthoamphibole) instead of staurolite. For sample 10IDMM48 the following reactions took place: 1) chlorite + garnet = clinoamphibole + H₂O (resorption of garnet core) and 2) clinoamphibole + chlorite = garnet + H₂O (growth of garnet rim). In sample 14ID40b there is a second set of garnet consuming and growing reactions observed from mineral modes: 1) garnet + chlorite = orthoamphibole + H₂O and 2) chlorite + orthoamphibole = garnet + H₂O. These four
reactions proposed for garnet resorption and growth in amphibolite are very generalized and based solely on mineral mode diagrams, more compositional data for minerals involved is required to confirm these reactions. However, it is evident in this study that amphibole (combined with chlorite), not necessarily staurolite, plays a significant role in two-stage (discontinuous) garnet growth.

The samples containing two-stage garnet utilized in this study do not indicate multiple tectonic events such as pluton emplacement and accretions. Instead the mineralogical reactions involving garnet described above could occur along a single P-T path during a single thermal event. The P and T increases observed in 14ID24c could be a result of loading and thermal relaxation along the Pollock Mountain fault, which was found to be active during the growth of garnets (McKay et al., 2011; and in press). The P increase recorded by 14ID40b and 10IDMM48 could be due to loading (?) of the Western Idaho Shear Zone. Regardless of the cause for the observed loading P-T path the results of this study conclude that two-stage discontinuous garnet growth in the SRSZ occurs as a result of mineralogical reactions along a single P-T path and not as a result of multiple accretion/thermal events.
REFERENCES


Pb zircon geochronology and P-T paths from the Salmon River suture zone, west-central Idaho, *Tectonics*, in press


Figure 39: Geologic Map of the Salmon River suture zone showing locations of all samples collected in this study during 2009, 2010, and 2014.
Table 2: 2014 Sample List

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<th>Easting</th>
<th>Strike/Dip</th>
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### APPENDIX B

#### Table 3: Whole Rock Major Element XRF Analyses Data

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<th>Al₂O₃</th>
<th>Fe₂O₃</th>
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<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
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Table 1: All rock compositions obtained during the course of this thesis from XRF analyses.
Table 4: Mineral Compositions
14ID40b

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**09IDMM03a**

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Table 2: Mineral compositions (except garnet) are shown for 09IDMM03a and 14ID40b. Abbreviations are mtx=matrix and inc.=inclusion. Mineral abbreviations are the same as previously used.
Figure 40: T-XH2O diagram with varying water (mole proportions) versus temperature constructed to choose water content. The water contents indicated on the diagram (arrows and dotted lines) are the maximum (chosen) and minimum water content. The values are based on the chlorite-out reaction, which marks the transition from greenschist to amphibolite facies. Water contents can be chosen at any point along this line (i.e. water content 2.5-15) without any major changes to assemblage and mineral stability. Colored fields are same as shown in P-T models.
Figure 2: T-XH2O diagram with varying water (mole proportions) versus temperature constructed to choose water content. The water contents indicated on the diagram (arrows and dotted lines) are the maximum (chosen) and minimum water content. The values are based on the chlorite-out reaction, which marks the transition from greenschist to amphibolite facies. Water contents can be chosen at any point along this line (i.e. water content 4-20) without any major changes to assemblage and mineral stability. Colored fields are same as shown in P-T models.
Figure 41: T-XH2O diagram with varying water (mole proportions) versus temperature constructed to choose water content. The water contents indicated on the diagram (arrows and dotted lines) are the maximum (chosen) and minimum water content. The values are based on the chlorite-out reaction, which marks the transition from greenschist to amphibolite facies. Water contents can be chosen at any point along this line (i.e. water content 4.5-20) without any major changes to assemblage and mineral stability. Colored fields are same as shown in P-T models.
Figure 42: T-XH2O diagram with varying water (mole proportions) versus temperature constructed to choose water content. The water contents indicated on the diagram (arrows and dotted lines) are the maximum (chosen) and minimum water content. The values are based on the chlorite-out reaction, which marks the transition from greenschist to amphibolite facies. Water contents can be chosen at any point along this line (i.e. water content 4-20) without any major changes to assemblage and mineral stability. Colored fields are same as shown in P-T models.
APPENDIX C

The data provided below is included to show all products derived from this thesis research. The samples and data briefly discussed here either did not fit with the theme of two-stage garnet growth or data collection was not completed. This data is for reference.

Sample 14ID37a

This sample is from the Lightning Creek Schist unit of the Rapid River plate. Two garnets were analyzed using EDS and one garnet was analyzed using WDS analyses using the electron microprobe. Garnet in this sample are extremely small (~300 um in diameter). Figure 1 and Figure 3 show garnet G1 and G2 EDS maps of Kα x-ray intensity for major elements. The garnets are strongly zoned and indicate prograde growth. The G2 line scan is shown in Figure 2.

This sample was not modeled due to problems with estimated Fe3+. Epidote and clinozoisite are both present in this rock which required any modeling to include to the Fe3+ content in order to accurately predict stability of those phases.
Figure 43: 14ID37a garnet EDS mosaic maps. A) Mn Kα x-ray intensity map, B) Mg Kα x-ray intensity map, C) Fe Kα x-ray intensity map, D) Ca Kα x-ray intensity map, E) Ti Kα x-ray intensity map, F) Al c Kα x-ray intensity map, G) Na Kα x-ray intensity map, H) K Kα x-ray intensity map, I) Si Kα x-ray intensity map.
Figure 44: 14ID37a garnet 1 line scan across same garnet as in Figure 1. A) EDS map showing location of A-A’ line scan traverse. B) Quantitative results of A-A’ line scan showing mole fractions of garnet end member composition. Zoning profile is characteristic of prograde growth (spessartine bell curve). At approximately 175 and 325 um changes in the pyrope, almandine, and spessartine compositions suddenly occur. This change also coincides with the slight inclusion density break between core and rim observed in this sample. This indicates that this garnet may also be two-staged. No P-T model for this sample has been produced.
Figure 45: 14ID37a garnet 2 EDS maps. A) Mn Kα x-ray intensity map, B) Mg Kα x-ray intensity map, C) Fe Kα x-ray intensity map, D) Ca Kα x-ray intensity map, E) Ti Kα x-ray intensity map, F) Al Kα x-ray intensity map, G) K Kα x-ray intensity map, H) Na Kα x-ray intensity map, I) Si Kα x-ray intensity map.

Sample 14ID26

This sample is part of the Squaw Creek Schist and was collected near the edge of garnet stability, west of the Salmon River along the Seven Devils road. One garnet from this sample was analyzed using EDS mosaic x-ray intensity maps and WDS line scan. The garnet is only slightly zoned and is not two-staged.

This sample was modeled using the same methods as previously discussed. Figure 6 shows that the peak assemblage occurs at 600-700°C 7-9.5 kbar. The garnet compositional isopleths plot in the peak assemblage field at 600-700°C 7-8.5 kbar.
Figure 46: Sample 14ID26 garnet EDS maps on nearly unzoned garnet. A) Mn Kα x-ray intensity map, B) Mg Kα x-ray intensity map, C) Fe Kα x-ray intensity map, D) Ca Kα x-ray intensity map, E) Ti Kα x-ray intensity map, F) K Kα x-ray intensity map, G) Na Kα x-ray intensity map, H) Al Kα x-ray intensity map, I) Si Kα x-ray intensity map.
Figure 47: 14ID26 (western most garnet sample?) garnet line scan showing no zoning at all. A) EDS mosaic of garnet from sample 14ID26 showing location of A-A’ line scan traverse. B) Quantitative data from the A-A’ traverse showing very little, if any, zoning. Large spikes in the data are caused by cracks and wholes, values still within the acceptable range. This sample is not two-staged.
Figure 48: 14ID26 P-T model showing peak assemblage field (red) and overlapping garnet isopleth intersections (yellow).
Figure 49: 10IDMM24 EDS Maps for two-staged garnet (note sharp inclusion density break between core and rim. A) Mn Kα x-ray intensity map, B) Mg Kα x-ray intensity map, C) Ca Kα x-ray intensity map, D) Fe Kα x-ray intensity map, E) Na Kα x-ray intensity map, F) K Kα x-ray intensity map, G) Al Kα x-ray intensity map, H) Si Kα x-ray intensity map, I) Ti Kα x-ray intensity map, and J) Zr Kα x-ray intensity map.
Figure 50: 10IDMM24 garnet line scan data. A) EDS mosaic map showing location of A-A’ line scan through the inclusion-rich core and inclusion-free rims. B) Quantitative results of the A-A’ line scan showing a broad ‘plateau’ of similar values for the core, abruptly changing at the core-rim boundary. No P-T model was produced for this sample.
Sample 09IDMM03a

Figure 51: 09IDMM03a garnet line scan. A) EDS mosaic map showing location of A-A’ line scan through the inclusion-rich core and inclusion-free rims. B) Quantitative results of the A-A’ line scan, abruptly changing at the core-rim boundary.
Figure 52: P-T diagram showing peak assemblage (red) and garnet inclusion assemblage. Yellow circle indicates region of garnet isopleth intersections for the core. Path shows a clear isothermic increase from 6 kbar to ~8.5 kbar at 700°C.