PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2015
Union College, Schenectady, NY

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ISSN# 1528-7491

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KECK GEOLOGY CONSORTIUM
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2014-2015 PROJECTS

RESILIENCE OF ENDANGERED ACROPORA SP. CORALS IN BELIZE. WHY IS CORAL GARDENS REEF THRIVING?:
Faculty: LISA GREER, Washington & Lee University, HALARD LESCINSKY, Otterbein University, KARL WIRTH, Macalester College
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TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH CENTRAL ALASKA:
Faculty: CAM DAVIDSON, Carleton College, JOHN GARVER Union College
Students: KAITLYN SUAREZ, Union College, WILLIAM GRIMM, Carleton College, RANIER LEMPERT, Amherst College, ELAINE YOUNG, Ohio Wesleyan University, FRANK MOLINEK, Carleton College, EILEEN ALEJOS, Union College

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SW MONTANA: METASUPRACRUSTAL ROCKS OF THE RUBY RANGE
Faculty: TEKLA HARMS, Amherst College, JULIE BALDWIN, University of Montana
Students: BRIANNA BERG, University of Montana, AMAR MUKUNDA, Amherst College, REBECCA BLAND, Mt. Holyoke College, JACOB HUGHES, Western Kentucky University, LUIS RODRIGUEZ, Universidad de Puerto Rico-Mayaguez , MARIAH ARMENTA, University of Arizona, CLEMENTINE HAMELIN, Smith College

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GEOMORPHOLOGIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA:
Faculty: KELLY MACGREGOR, Macalester College, AMY MYRBO, LabCore, University of Minnesota
Students: ERIC STEPHENS, Macalester College, KARLY CLIPPINGER, Beloit College, ASHLEIGH, COVARRUBIAS, California State University-San Bernardino, GRAYSON CARLILE, Whitman College, MADISON ANDRES, Colorado College, EMILY DIENER, Macalester College

ANTARCTIC PLIOCENE AND LOWER PLEISTOCENE (GELASIAN) PALEOCLIMATE RECONSTRUCTED FROM OCEAN DRILLING PROGRAM WEDDELL SEA CORES:
Faculty: SUZANNE O'CONNELL, Wesleyan University
Students: JAMES HALL, Wesleyan University, CASSANDRE STIRPE, Vassar College, HALI ENGLERT, Macalester College

HOLOCENE CLIMATIC CHANGE AND ACTIVE TECTONICS IN THE PERUVIAN ANDES: IMPACTS ON GLACIERS AND LAKES:
Faculty: DON RODBELL & DAVID GILLIKIN, Union College
Students: NICHOLAS WEIDHAAS, Union College, ALIA PAYNE, Macalester College, JULIE DANIELS, Northern Illinois University

GEOLOGICAL HAZARDS, CLIMATE CHANGE, AND HUMAN/ECOSYSTEMS RESILIENCE IN THE ISLANDS OF THE FOUR MOUNTAINS, ALASKA
Faculty: KIRSTEN NICOLAYSEN, Whitman College
Students: LYDIA LOOPESKO, Whitman College, ANNE FULTON, Pomona College, THOMAS BARTLETT, Colgate University

CALIBRATING NATURAL BASALTIC LAVA FLOWS WITH LARGE-SCALE LAVA EXPERIMENTS:
Faculty: JEFF KARSON, Syracuse University, RICK HAZLETT, Pomona College
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FIRE AND CATASTROPHIC FLOODING, FOURMILE CATCHMENT, FRONT RANGE, COLORADO:
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Keck Geology Consortium: Projects 2014-2015
Short Contributions— Tectonics of the Ruby Range, MT Project

EXPLORING THE PRECAMBRIAN GEOLOGIC EVOLUTION OF THE RUBY RANGE IN SOUTHWEST MONTANA
TEKLA HARMS, Amherst College
JULIE BALDWIN, University of Montana

PETROLOGY, GEOCHEMISTRY, AND THERMOBAROMETRY OF AMPHIBOLITES IN THE RUBY RANGE, SOUTHWEST MONTANA
BRIANNA BERG, University of Montana
Research Advisor: Julie Baldwin

MONAZITE OCCURRENCE IN GARNET BEARING SCHIST AND GNEISS FROM THE RUBY RANGE, SOUTHWEST MONTANA
AMAR MUKUNDA, Amherst College
Research Advisor: Tekla Harms

CALCITE-GRAPHITE STABLE ISOTOPE THERMOMETRY IN MARBLES OF THE RUBY RANGE, SW MONTANA
REBECCA BLAND, Mount Holyoke College
Research Advisor: Steven R. Dunn

GEOTHERMOBAROMETRY AND PETROGRAPHIC INTERPRETATIONS OF CHRISTENSEN RANCH METAMORPHOSED BANDED IRON FORMATION FROM THE RUBY RANGE, MONTANA
JACOB HUGHES, Western Kentucky University
Research Advisor: Dr. Andrew Wulff

PETROGRAPHY AND MINERALOGY OF ULTRAMAFIC PODS IN THE RUBY RANGE WITH SPECIAL ATTENTION TO IDENTIFYING ACCESSORY MINERAL PHASES, INCLUDING ZIRCON
LUIS G. RODRIGUEZ, University of Puerto Rico-Mayaguez
AARON CAVOSIE, Curtin University Australia, University of Puerto Rico-Mayaguez

INVESTIGATING THE TIMING OF MELT-PRODUCING HIGH GRADE METAMORPHISM IN THE RUBY RANGE, SOUTHWESTERN MONTANA THROUGH ZIRCON U-PB GEOCHRONOLOGY
MARIAH ARMENTA, University of Arizona
Research Advisor: George Gehrels

PETROGRAPHY, GEOTHERMOBAROMETRY, AND METAMORPHIC HISTORY OF METAPELITES FROM THE CENTRAL RUBY RANGE, SOUTHWEST MONTANA
CLÉMENTINE HAMELIN, Smith College
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Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

Learning Science Through Research
Published by Keck Geology Consortium

Short Contributions
28th Annual Symposium Volume
25th April, 2015
ISBN: 1528-7491

PETROLOGY, GEOCHEMISTRY, AND THERMOBAROMETRY OF AMPHIBOLITES IN THE RUBY RANGE, SOUTHWEST MONTANA

BRIANNA BERG, University of Montana
Research Advisor: Julie Baldwin

INTRODUCTION

The Ruby Range provides an exceptional exposure for investigating the tectonic events that affected the northwest margin of the Archean Wyoming province and the crustal evolution and growth of the North American continent. Previous studies in the Ruby Range and adjacent Tobacco Root Mountains have identified two distinct tectono-metamorphic events at 2.55–2.45 Ga and 1.79–1.72 Ga (Cheney et al., 2004; Harms et al., 2004; Alcock and Muller, 2012; Jones, 2008). Previous *P–T* investigations of metamorphic rocks in the Ruby Range have interpreted upper amphibolite facies metamorphism with peak conditions around 4–7.2 kbar and 650–750 °C (Dahl, 1980; Desmarais, 1981; Immega and Klein, 1976).

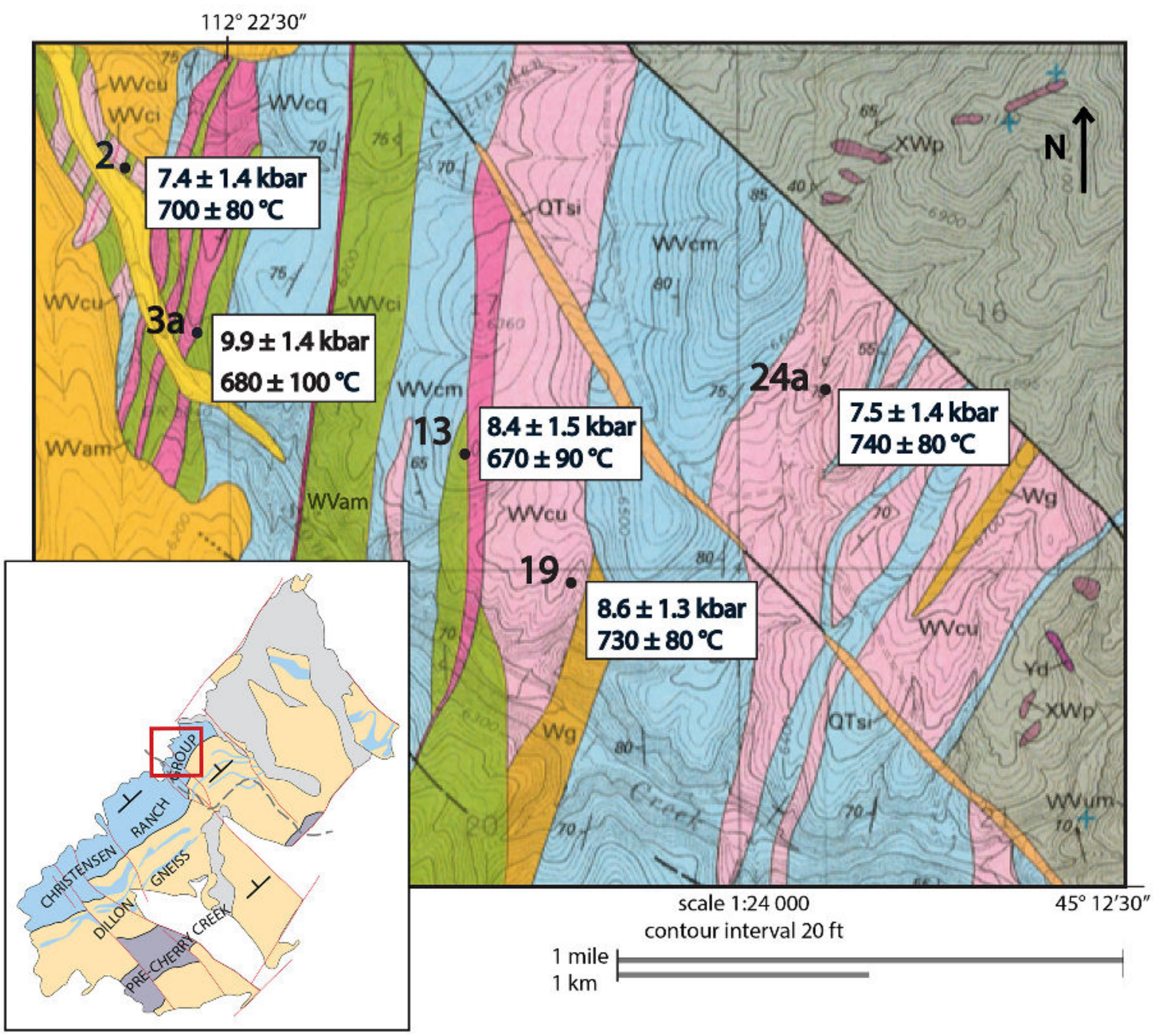

Figure 1. Geologic map of the Stone Creek section of the Christensen Ranch metasedimentary suite showing sample locations and corresponding pressures and temperatures based on Thermocalc. (Geologic map taken from James, 1990) Map units: WVam = amphibolite, WVcu = undifferentiated metasedimentary rocks, WVcm = marble, WVci = iron formation, WVcq = quartzite, QTsi = siliceous fault line deposits, Wg = granite gneiss, XWp = sheets and dikes, Yd = diabase dikes.

Amphibolite layers occur within each of the three major lithologic suites of the Ruby Range. Overall, the amphibolite unit (Fig. 1) can be subdivided into three rock types based on the mineralogy: hornblende-plagioclase amphibolite, garnet-hornblende-plagioclase amphibolite, and calcareous garnet-hornblende-plagioclase-diopside-clinozoisite-calcite amphibolite. The composition and volume of these three rock types vary in each of the three suites in the Ruby Range. All three varieties occur in both the Christensen Ranch metasedimentary suite (CRMS) and Dillon Gneiss, whereas in the Pre-Cherry Creek suite only garnet-hornblende-plagioclase amphibolite has been observed.

The presence and abundance of amphibolite with garnet-bearing assemblages that are amenable for geothermobarometry in all three compositional suites of the range make it an ideal target for placing constraints on regional metamorphic conditions. Preliminary *P–T* results are presented for a transect across the Christensen Ranch metasedimentary suite (CRMS) along Stone Creek Road on the western flank of the Ruby Range (Fig. 1). This study will add to collective data from the SW Montana Keck project by providing new data on the metamorphic conditions across the Ruby Range using a consistent mineral assemblage. The information obtained from these rocks can be integrated with data from other lithologies to better characterize the tectonothermal evolution of this margin of North America in the Precambrian.

METHODS

Polished thin sections were examined with a polarizing microscope, and supported by backscattered electron images and compositional maps obtained with a Tescan Vega-3 LM Scanning Electron Microscope (SEM) housed in the Department of Geosciences, University of Montana. The SEM is equipped with an Oxford Instruments 80mm^2 X-Max SDD energy-dispersive analytical system (EDS), and chemical analyses of minerals were determined by calibrating the instrument to a range of natural mineral standards. For spot analyses, accelerating voltage was 20 kV, beam current 1.4 nA, and live counting time was 120 s.

Elemental X-ray maps were collected for garnet in all samples in order to characterize zoning. Quantitative garnet, hornblende, and plagioclase were then analyzed by SEM-EDS, as well as ilmenite, biotite, epidote, clinopyroxene, and orthopyroxene compositions where present. Additionally, bulk chemistry data for major (XRF) and trace elements (ICP-MS) were collected for 10 samples (both garnet-bearing and garnet-absent) from the CRMS. These analyses were performed by Acme Labs.

Pressure and temperature calculations were performed using the software THERMOCALC v. 3.40 (Holland and Powell, 1998, with upgrades) and the internally consistent data set 6.2 (Holland and Powell, 2011). Average *PT* calculations were performed, which is a method based on the calculation of an independent set of reactions between the phases of an equilibrium mineral assemblage and calculates the av*P*, av*T*, or av*PT* from the intersection of all independent reactions. The method outlined in Holland and Powell (2008) was followed where mineral compositions are input into the activity solution model (*a-x*) data file. This allows the same *a-x* relationships to be used for calculations on individual reactions. THERMOCALC calculates the individual activities from the overall coding of the phase involved.

This study incorporated the calculation of av*P* and av*T* separately for each sample because the statistical fit for the av*PT* calculation was poor. *A-x* models were used for garnet, hornblende, and plagioclase; and quartz and H_2O were treated as pure phases. Calculations were done at a constant $a(H_2O) = 0.75$ because this produced the best statistical fit. Likewise, the glaucophane end member of amphibole was excluded because of the small activity and improved fit of the data when excluding it from the calculations. Estimates of ferric iron in garnet and hornblende were experimented with to determine the effects on the pressure and temperature calculations. An arbitrarily small amount of Fe^{3+} in garnet (3%) and stoichiometry of ferric iron in amphibole based on charge balance from the method of Holland and Blundy (1994) was used since this produced the best fit in the data.

PETROGRAPHY AND MINERAL CHEMISTRY

Within the CRMS, the analyzed amphibolite samples consist of garnet amphibolite and calcareous garnet amphibolite that occur in north-northeast striking ribbed outcrops interlayered with a heterogeneous suite of metasedimentary rocks on the northwestern flank of the Ruby Range. The calcareous amphibolite commonly occurs adjacent to marble layers, but the stratigraphic relationship between the units within the CRMS is uncertain.

	mineral modes							
sample	Grt	Hbl	Plg	Qtz	Cal	Ser	Bt	Opaques
14-BB-2	10%	55%	8%	10%	10%	2%	1%	4%
14-BB-3a	10%	50%	20%	15%	-	-	-	5%
14-BB-13	35%	20%	8%	35%	-	-	-	2%
14-BB-19	6%	55%	25%	10%	-	-	2%	2%
14-BB 24a	15%	60%	15%	8%	-	-	-	2%

Table 1. Table of approximate mineral modes for each of the CRMS samples analyzed in this study.

Calcareous Garnet Amphibolite

Sample 14-BB-2 contains the peak mineral assemblage garnet-amphibole-plagioclase-quartz-ilmenite. Sample BB-2 is the structurally highest garnet amphibolite in the CRMS (Fig. 1). The sample is fine-grained (≤ 1 mm) with garnet porphyroblasts (1–3 mm) that contain small inclusions and resorbed rims in contact with plagioclase, quartz, and amphibole. This sample also contains calcite, epidote, retrograde chlorite and biotite, and the accessory minerals ilmenite, sphene, and apatite. The approximate proportions of minerals are shown in Table 1.

Garnet Amphibolite

Garnet amphibolite samples from the CRMS contain the peak mineral assemblage garnet-hornblende-plagioclase-quartz-ilmenite. Samples 14-BB-3a (Fig. 2), 14-BB-19, and 14-BB-24a are of similar composition. All three samples are fine-grained (≤ 1 mm) with poikilitic garnet porphyroblasts that range from 1 to 5 mm. Garnet contains amphibole, plagioclase, and quartz inclusions, and exhibits thin, discontinuous coronas of plagioclase and resorbed

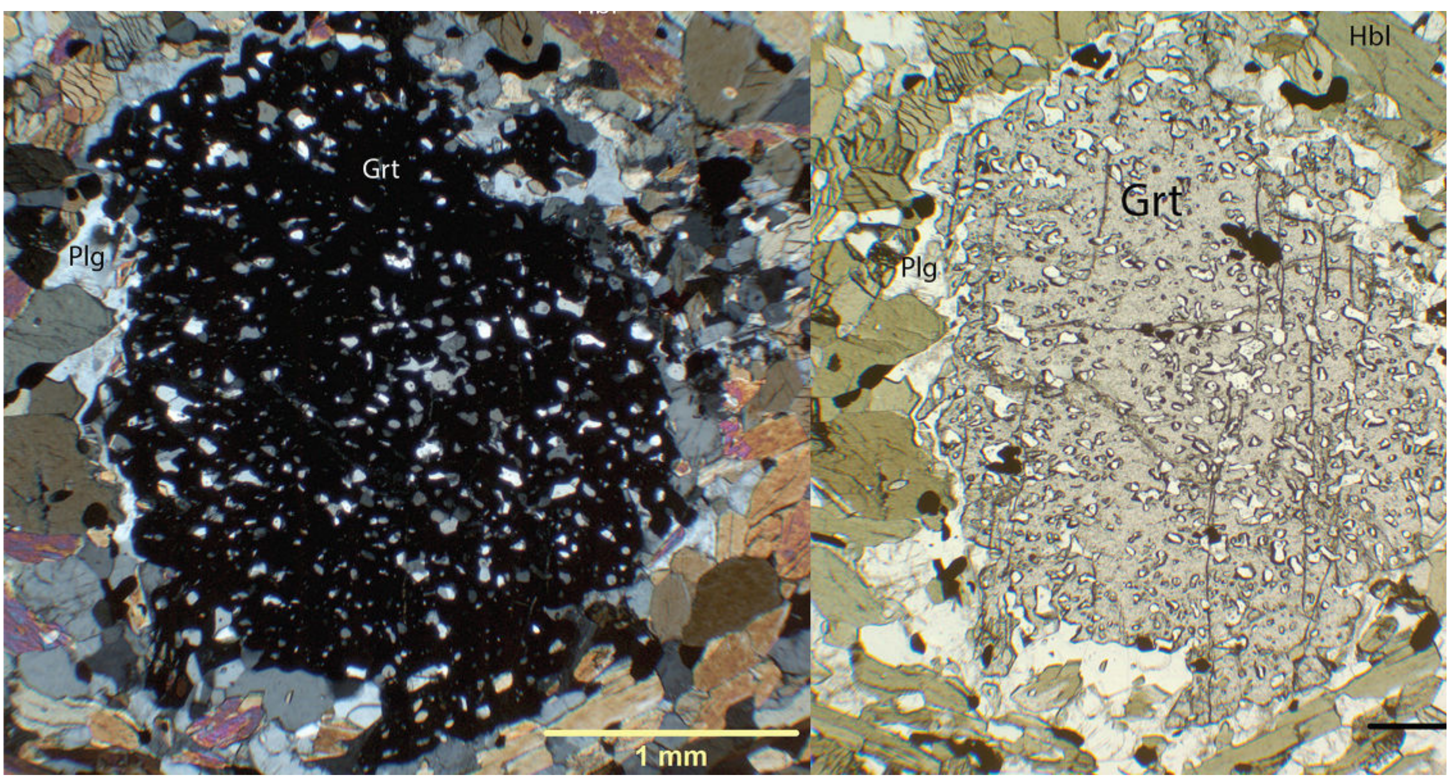

Figure 2. Photomicrograph (crossed polarized light, left; plane polarized light, right) from sample 14-BB-3a of a poikilitic garnet porphyroblast in a matrix of amphibole, plagioclase, quartz, and opaques. Garnet in these images has resorbed rims and a discontinuous corona of plagioclase.

rims. Amphibole is also in contact with garnet. The samples are dominated by amphibole, but are more enriched in plagioclase than the calcareous samples. Accessory minerals are ilmenite and apatite with trace amounts of sphene (Table 1). Sample 14-BB-13 is both garnet- and quartz-rich. It is fine grained (< 1 mm) with elongate garnet porphyroblasts 1–2 mm. Rims of garnet are resorbed and in contact with amphibole, plagioclase, quartz, and ilmenite. Inclusions of all these minerals are also present (Table 1).

Mineral Compositions

Garnet from the CRMS samples ranges from 54-67% almandine, 16-28% grossular, 5-15% pyrope, and 1-5% spessartine. Garnet displays minimal zoning due to retrograde re-equilibration. Although the element maps obtained for the CRMS garnets are predominantly flat, there are localized depletions or enrichments observed in Mn, Fe, and/or Mg in the garnet rims (Fig. 3). Rim zoning is interpreted as retrograde modification during cooling. Amphibole, plagioclase, quartz, and ilmenite are present as inclusions, but there is a noticeable range in poikilitic vs. non-poikilitic garnet from sample to sample.

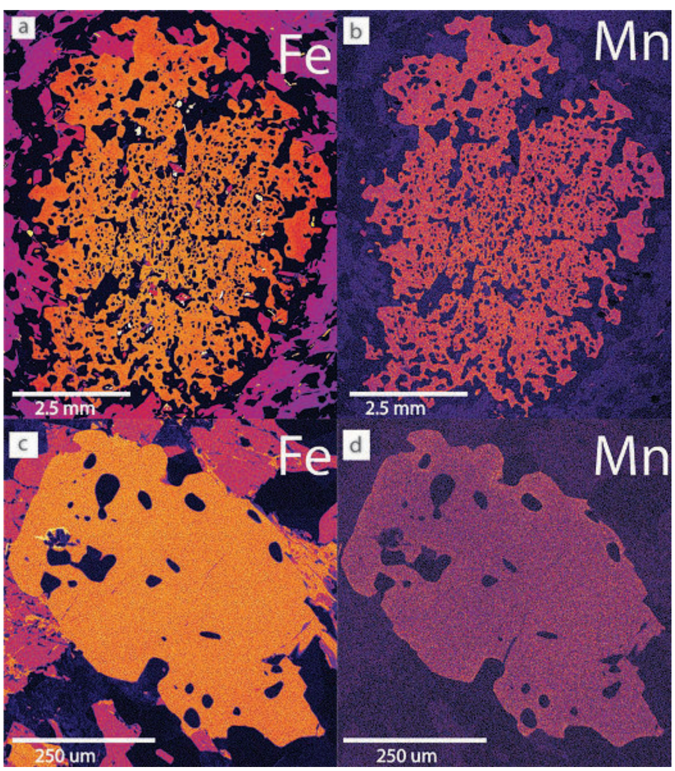

Figure 3. Elemental X-ray maps for garnet in sample 14-BB-19 (top) and 14-BB-2 (bottom). The hot colors represent high concentration and the cool colors represent low concentration. BB-19 shows enriched Fe in the core (a) and relatively steady Mn composition (b). BB-2 shows the homogeneous composition of Fe (c) and enriched rims of Mn (d).

Amphibole in the CRMS suite is chemically homogeneous. Amphibole in BB-2, BB-19, and BB-24a is classified as ferro-hornblende, amphibole in BB-3a is classified as magnesio-hornblende, and amphibole in BB-13 is classified as ferro-pargasite. These classifications were determined by the classification scheme of Locock (2014).

Plagioclase exhibits a range in variability in composition from grain to grain as well as from sample to sample. Plagioclase is generally unzoned in the majority of the samples from the CRMS, which have X_{An} = 44-54%. Whereas in most samples plagioclase is homogeneous, a few samples in the CRMS contain plagioclase that varies depending on the petrographic setting of the grain. In these samples, the plagioclase grains near or included within garnet have differing compositions than grains within the matrix. Plagioclase adjacent to garnet shows a general enrichment of anorthite from core to rim with X_{An} = 55-65% in the core, to X_{An} = 58-66% in the rim. The plagioclase in the matrix shows a general depletion of Ca from core to rim with X_{An} = 58-66% in the core and X_{An} = 55-59% in the rim.

BULK COMPOSITION/ PROTOLITH DETERMINATION

The amphibolites in the Ruby Range represent metamorphosed mafic rocks of differing ages. Karasevich and others (1981) have reported emplacement of mafic dikes and sills as early as prior to the 2.45 tectonic event, but full constraints on timing of emplacement of the Ruby Range amphibolites has not been fully established. Amphibolites in the nearby Tobacco Root Mountains have been classified as metamorphosed mafic dikes and sills (MMDS). Geochemical analysis of the MMDS in the Tobacco Root Mountains has indicated a subalkaline, tholeiitic basalt protolith with rare earth element patterns similar to basalt in continental rift settings today (Brady et al., 2004). The whole rock geochemical analyses collected for the CRMS suite of the Ruby Range in this study shows an overall similar trend with basalt and basaltic andesite protoliths (Fig. 4). The geochemical data indicate that the amphibolite

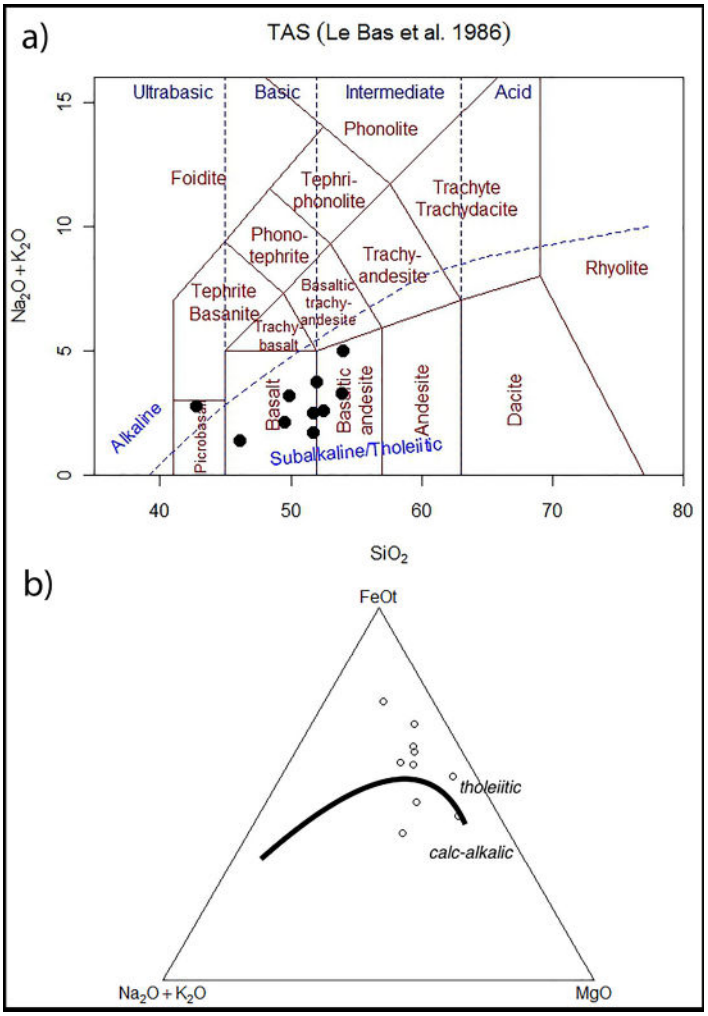

Figure 4. (a) TAS diagram for the CRMS amphibolite suite. The data show a subalkaline/tholeiitic trend with basalt and basaltic andesite composition. (b) AFM diagram for the CRMS amphibolite suite. The data show a tholeiitic fractionation trend of iron enrichment at constant alkalis. FeOt means that all iron is plotted at FeO.

in the Ruby Range may have a similar continental rift origin as the amphibolite in the Tobacco Root Mountain MMDS.

THERMOBAROMETRY

In order to determine the conditions of metamorphism recorded by the CRMS amphibolites, pressures and temperatures were determined using the best-fit av*P* and av*T* approach described above. Preliminary results for five CRMS samples are shown with their locations in Figure 1. These data place constraints on peak metamorphism at 7.4–9.9 kbar and 670–740 °C.

DISCUSSION

The results of the *P-T* calculations do not show a trend in *P-T* conditions with structural level, nor are they uniform. The structurally highest and lowest samples in the CRMS, 14-BB-2 and 14-BB-24a respectively, have similar average *P* and *T* (Fig. 1). The remainder of the samples yield variable results that predict slightly higher pressures while still being within error of one another. The results of this study suggest similar temperatures and overall higher pressures than the peak conditions given by Dahl (1980) which come from the CRMS at a different location in the Ruby Range.

The calculated values shown in Figure 1 represent samples with the most common equilibrium assemblage of the garnet amphibolites in the Ruby Range: garnet-hornblende-plagioclase-quartz. One of the complications for the remaining CRMS samples not presented in this contribution is the presence of calcite and epidote. Sample 14-BB-2 is the only calcareous garnet amphibolite included here, but calcareous minerals generally occur as alternation products in this sample (Table 1). This sample had no significant effect on av*P* and av*T* or the fit of the result when the presence of calcite or fluid composition was varied during calculations; however, the other calcareous garnet amphibolites analyzed thus far in the CRMS have yielded more variable results that require further examination. Further investigation is being done on the effects of the presence of calcite and the fluid composition on the *P-T* results for these samples.

CONCLUSIONS

Previous *P–T* investigations of metamorphic rocks in the Ruby Range have interpreted upper amphibolite facies metamorphism with peak conditions around 650–750 °C and 4–7.2 kbar (Dahl, 1980; Desmarais, 1981; Immega, 1976). The preliminary av*P* and av*T* results from the CRMS amphibolite in this study of 670–740 °C and 7.4–9.9 kbar show temperature estimates that are consistent with the previous studies done in the area, but suggest overall higher pressures.

P-T estimates from this study, along with previous studies from the Ruby Range, are consistent with estimates of peak metamorphism in the Tobacco

Root Mountains that have been correlated to the Big Sky orogeny. The data from this project could help to further correlate the metamorphism in the Ruby Range to the Big Sky orogeny and be integrated with data from other lithologies to better understand the metamorphic evolution of this important Precambrian crustal boundary.

ACKNOWLEDGEMENTS

I would like to offer my deep gratitude and thanks to my advisor, Dr. Julie Baldwin, for her support and guidance throughout this project, as well as to Dr. Tekla Harms for the constant encouragement. Thank you to the fellow Ruby Rangers for making this such an enjoyable experience. I would also like to thank the Davidson Honors College and Department of Geosciences at the University of Montana, the Montana Space Grant Consortium, and the KECK Geology Consortium.

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