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

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KECK GEOLOGY CONSORTIUM
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CLÉMENTINE HAMELIN, Smith College
Research Advisor: John B. Brady

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PETROGRAPHY, GEOTHERMOBAROMETRY, AND METAMORPHIC HISTORY OF METAPELITES FROM THE CENTRAL RUBY RANGE, SOUTHWEST MONTANA

CLÉMENTINE HAMELIN, Smith College
Research Advisor: John B. Brady

INTRODUCTION

The Ruby Range is one of several Laramide uplifted blocks of exposed Precambrian basement in the Wyoming province that was metamorphosed at 2.45 Ga and 1.71-1.79 Ga during the Big Sky orogeny. This project examines metapelites along the Stone Creek drainage, in the structurally highest unit of the Ruby Range, the Christensen Ranch Metamorphic suite (James, 1990). The purpose of this study is to determine the conditions of metamorphism (pressure and temperature) recorded in these rocks using observed mineral assemblages and compositions combined with thermodynamic modeling and geothermobarometers. Doing so will further constrain and complement our understanding of the Big Sky orogeny studied in the adjacent mountain ranges such as the Tobacco Root Mountains and the Gravelly Range.

METHODS

Twenty-one metapelite samples were collected in the summer of 2014 along the Stone Creek drainage, covering from the structural base to the top of the Christensen Ranch Metamorphic suite. Sample locations are shown in Figure 1. Outcrop and sample positions were recorded in NAD 84 UTM coordinates using a GPS device. Samples and field relationships with surrounding units were described in the field.

For *P-T* characterization using a pseudosection approach, three important steps were taken: (1) twenty-five thin sections were made and investigated using a petrographic microscope to identify minerals, reaction textures, and to determine modes; (2) bulk rock chemistry for major and trace elements including REE was obtained through XRD and INAA analyses, respectively, at Acme Labs, Vancouver Canada for nine samples; (3) five samples were further analyzed using an FEI Quanta 450 SEM with EDS for mineral chemistry quantified using natural standards, and phase maps were generated to constrain more accurately mineral modes in the rock. Samples CH1 and CH4 were selected for further investigation due to differences in bulk rock chemistry and textures.

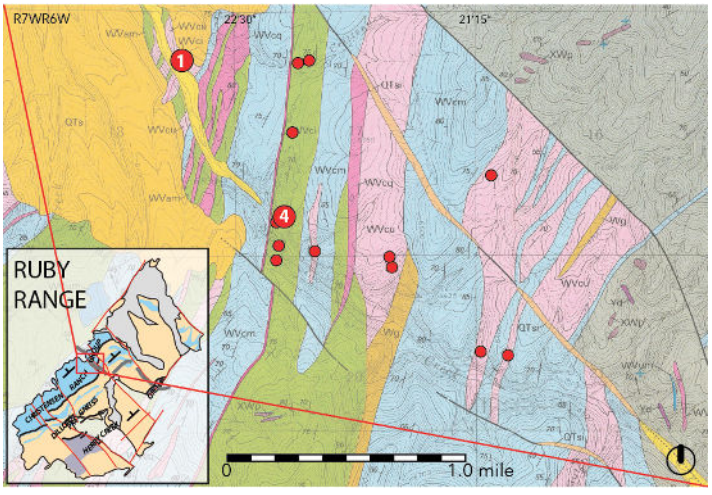

Figure 1. Sample distribution and location map along Stone Creek. Most metapelite samples were collected in the undifferentiated metasedimentary units (mapped in pink); a few samples were collected in the amphibolite unit (mapped in green). Other units mapped are calcitic and dolomitic marbles (blue), metamorphosed banded iron formation (purple) and quartzite (magenta). Note the contact with the Dillon gneiss (light olive grey) to the east of the map. (Modified from James, 1990)

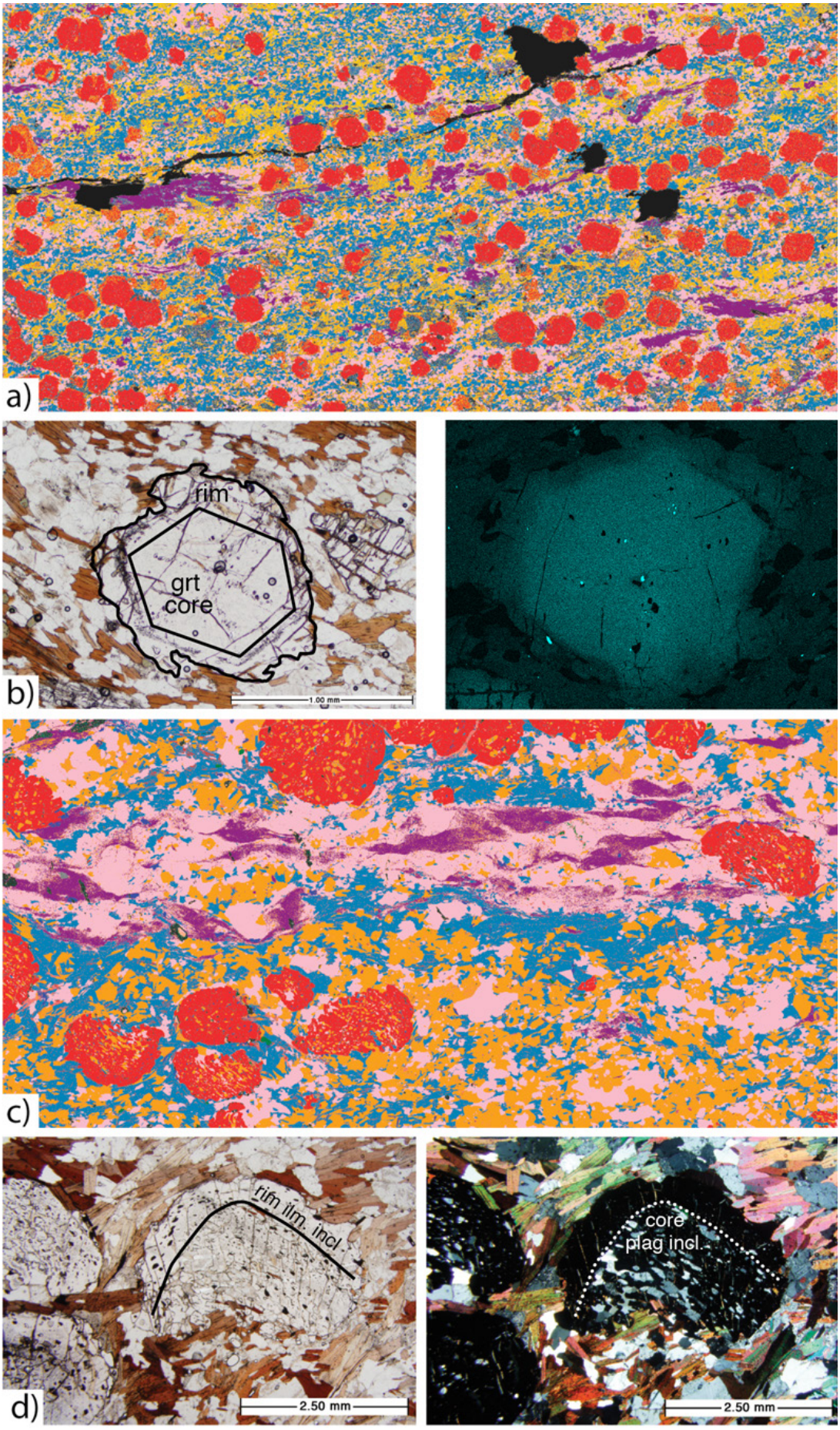

Figure 2. From top to bottom: a) EDS whole thin section phase map of CH1, b) Two garnet growth episodes in CH1 garnets: preserved original euhedral-shaped core garnet (Ca-rich) with crinkled garnet rims (Ca-poor), plane polarized view (left), Calcium elemental SEM/EDS map (right), c) EDS whole thin section phase map of CH4, d) Two garnet growth episodes in CH4 garnets: plagioclase core inclusions and ilmenite rim inclusions in plane and crossed polarized views.

Phase map colors: Red = garnet, purple = sillimanite, steel blue = biotite, pink = quartz, orange = plagioclase, yellow = K-feldspar, dark blue = oxides

RESULTS

Petrography

Metapelite samples range in texture from fine-grained and homogeneous (e.g. CH1) to coarse-grained, heterogeneous, and generally altered (hydrated and oxidized) (Fig. 2). Mineral assemblages consist of garnet + biotite + sillimanite + plagioclase + quartz ± apatite ± K-feldspar ± chlorite ± muscovite ± ilmenite ± rutile ± graphite ± tourmaline. Most samples have a schistose texture with well-developed foliation defined by abundant biotite and sillimanite CH9a and CH9b grain alignment. Two samples (CH9a and CH9b) have a more gneissic texture, with higher proportions of K-feldspar, plagioclase, and quartz. Field observations and petrography show evidence for melt in many of the samples, with the occurrence of neosome and paleosome domains in outcrop and melt-rich and restitic layers within individual samples

Garnet is anhedral and ranges in size from 1 mm to 10 cm in diameter. It is generally Fe-rich (~80% almandine) with little to no zoning, and displays flat compositional profiles. The only sample with compositionally zoned garnets is sample CH1, in which garnet has higher bulk Ca-content and shows compositional calcium and iron zoning (high-Ca cores, low Ca-rims; low-Fe cores, high-Fe rims, determined by EDS analysis) that shows two garnet-growth episodes (Fig. 2). Poikiloblastic garnets contain inclusions of quartz, plagioclase, biotite, sillimanite, and apatite; they show no compositional zoning, but have inclusion-rich cores with inclusion-free rims, or cores and rims with different inclusions, also suggesting at least two garnet growth episodes. Fe-Mg ratios in biotite are generally constant within individual samples with observed values for all samples between 1:1 and 2:3. Sillimanite occurs mostly as fibrolite, in bundles 2-15 mm long, but also occurs in its prismatic habit. Samples are generally muscovite-free, with only a few samples containing minor amounts of retrograde muscovite; samples are also kyanite- and cordierite-free. Most samples are K-feldspar-poor; only samples CH1 and CH9b contain abundant matrix K-feldspar homogeneously distributed throughout the sample.

Pseudosection geothermobarometry

These observations place the Stone Creek rocks on the NaKFMASH petrogenetic grid (Spear et al. 1999) above the K-feldspar-in and muscovite-out fields as a low T bound, and below biotite-out and orthopyroxene-in fields as a high T bound, yielding temperatures between ~650ºC and 875ºC. The same petrogenetic grid indicates pressures below the kyanite stability field and above the cordierite stability field, yielding pressures between ~3 kbar and 8-10 kbar.

Samples CH1 and CH4 were further investigated for *P-T* path constraints using a thermodynamic modeling (pseudosection) approach. Sample CH1 is fine-grained and homogeneous and contains small anhedral garnets with Ca and Fe zoning showing a first episode of garnet growth (euhedral garnet core), followed by a second episode of garnet growth (garnet rim), and an episode of garnet consumption (crinkled garnet edges). It contains abundant matrix K-feldspar and is poor in oxides. On the other hand, Sample CH4 is medium to coarse grained and heterogeneous with sillimanite and quartz layers between layers rich in biotite and poikiloblastic garnets, with ilmenite and plagioclase inclusions. Some garnets in CH4 contain inclusion trails whereas others are flattened or grew ‘ears’, showing at least two garnet growth episodes and higher strain on this rock than in CH1. CH4 contains no matrix K-feldspar and is rich in plagioclase.

Water content values from bulk rock chemistry, or LOI values, can be unreliable to assess water content for pseudosection calculations because of water loss during metamorphism, especially for rocks that have partially melted. Water content was determined using a $T\text{-}X_{H2O}$ diagram at 7.5 kbar and 10 kbar for bulk rock compositions for CH1 and CH4 to determine minimum water value needed to saturate melts from these compositions at low pressure. $T\text{-}X_{H2O}$ and *P-T* (pseudosection) diagrams were calculated using Theriak-Domino v. 03.10.09 (De Capitani and Petrakakis, 2010) and the Holland & Powell (1998) dataset 5.5 for pelites in the NCKFMASHTO system. Arbitrarily small amounts of Fe_2O_3 were added to stabilize oxides (ilmenite, rutile, magnetite), titanium was used as the mineral models are designed for the Na-Ca-K-Fe-Mg-Al-Si-H-Ti-O (NCKFMASHTO)

system. Manganese was left out, and no apatite Ca correction was done for the modeling. Contour lines for Mg/(Fe+Mg) were calculated for biotite and garnet compositions and compared to the mineral chemistry determined by SEM/EDS analysis to constrain garnet and biotite isopleths for each sample on the diagrams. Isopleths were also generated for grossular content in garnet and anorthite in plagioclase. Mineral modes at the given *P-T* point were calculated using Theriak-Domino and calculated modes were compared to actual modes.

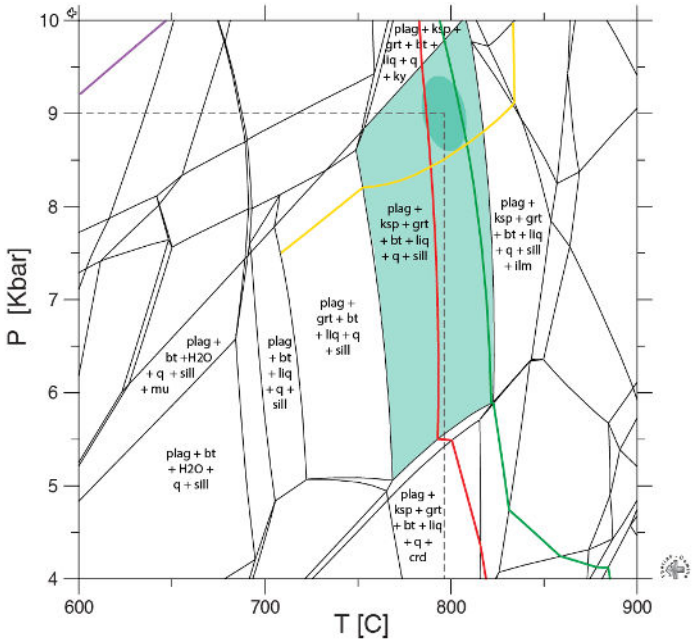

Figure 3. Contoured CH1 Theriak-Domino pseudosection with calculated isopleths shown for measured mineral compositions. Isopleths: Red = Garnet Mg/(Fe+Mg); Green = Biotite Mg/(Fe+Mg); Yellow = Garnet grossular Ca/(Fe+Mg+Ca); Purple = Plagioclase anorthite Ca/(Ca+Na+K) . The stable assemblage field (grt + bt + qtz + sill + ksp + liq) is highlighted in green. The circled area shows the rock at T,P ~ 795ºC, 9 kbar.

Bulk rock composition used for calculations (in cations): SI(46.31)TI(0.37)AL(18.29)CA(1.07)MG(5.05)FE(9.39)NA(1.11) K(6.06)F3(0.07)H(12.29)O(?)

CH1 contoured pseudosection

Using the water value determined from the T-X_{H2O} diagram, a pseudosection was calculated for each of these samples in *P-T* space from T = 600-900 ºC and P = 4-10 kbar. On the calculated pseudosection for CH1 (Fig. 3), the stable mineral assemblage grt + bt + sill + qtz + ksp (+ liq) observed in the rock (+melt) lies between T = 760-825 ºC and P = 5-10 kbar. From SEM/EDS analysis and mineral composition quantification for CH1, the Mg/(Fe+Mg) value for garnet lies between 0.14-0.18, an average of 0.16 is used (red line). The Mg/(Fe+Mg) value for biotite lies between 0.44-0.50, an average of 0.46 is used (green line). The isopleths for garnet and biotite Mg/(Fe+Mg) values are relatively vertical, and corresponding isopleths are within the stable assemblage field. They do not cross, but give an estimated temperature value around T = 795ºC (red and green lines in Fig. 3). The grossular value Ca/(Fe+Mg+Ca) for CH1 garnets is between 0.06 and 0.12, which corresponds to upper-*P* values in the stable assemblage field, between 8-10 kbar. Calculated plagioclase isopleths are in the kyanite field – based on petrographic observations and the absence of kyanite in the sample, this is very unlikely to be representative of the sample and will be ignored. Based on the pseudosection results, this places CH1 at a *P-T* value of T ~ 795ºC and P ~ 9 kbar.

CH4 contoured pseudosection

On the calculated pseudosection for CH4 (Fig. 4), the stable mineral assemblage grt + bt + sill + qtz + plag + ilm (+ liq) observed in the rock (+melt) lies between T = 690-790 ºC and P = 5-9 kbar. From SEM/EDS analysis and mineral composition quantification for CH4, the Mg/(Fe+Mg) value for garnet lies between 0.14-0.16, an average of 0.15 is used (red line). The Mg/(Fe+Mg) value for biotite lies between 0.37-0.40, an average of 0.39 is used (green line). The isopleths for garnet and biotite Mg/(Fe+Mg) values are within the stable assemblage field. They cross around T = 700ºC and P = 6.5-7 kbar. The grossular value Ca/(Fe+Mg+Ca) for CH1 garnets is between 0.04-0.06, an average value of 0.05 is used, which lies in the kyanite field above the stable assemblage field and does not match well with the rest of the isopleths. Calculated plagioclase Ca/(Ca+Na+K) values between 0.30-0.32 for this rock, however, lie in the stable assemblage field and confirm a P-value of about P = 7 kbar. Based on the pseudosection results, this places CH4 at a *P-T* value of T ~ 700ºC and P ~ 6.8 kbar.

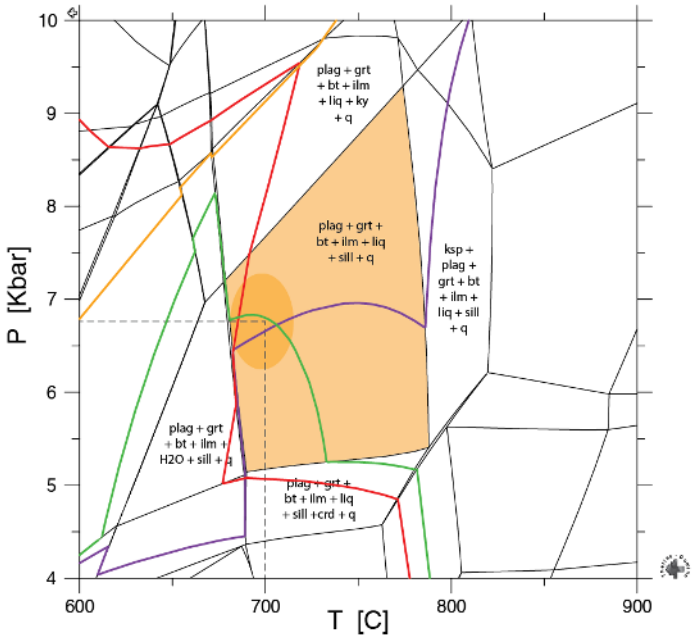

Figure 4. Contoured CH4 Theriak-Domino pseudosection with corresponding isopleths for measured mineral compositions. Isopleths: Red = Garnet Mg/(Fe+Mg); Green = Biotite Mg/(Fe+Mg); Yellow = Garnet grossular Ca/(Fe+Mg+Ca); Purple = Plagioclase anorthite Ca/(Ca+Na+K) . The stable assemblage field (grt + bt + qtz + sill + plag + liq) is highlighted in orange. The circled area shows the rock at T,P ~ 700ºC, 6.8 kbar.

Bulk rock composition used for calculations (in cations): SI(54.54)TI(0.93)AL(18.73)CA(1.46)MG(3.09)FE(8.78) NA(3.54)K(2.55)F3(0.08)H(6.32)O(?)

DISCUSSION

Constraints on *P-T* for metapelite samples (CH1 and CH4) from the Christensen Ranch Metamorphic suite using a pseudosection approach give slightly different results. Sample CH1 records *P-T* conditions of ~ 795 ºC, 9 kbar whereas sample CH4 records *P-T* conditions of ~ 700 ºC, 6.8 kbar. For rocks from a limited area and with the same mineral assemblages, we would generally expect all the samples to record similar *P-T* conditions. However, these two samples may record different points on the *P-T* path for these rocks due to partial melting and subsequent melt loss, or may have experienced reequilibration to varying degrees during retrograde metamorphism. As shown in Figure 2, garnets show at least two episodes of garnet growth, which means that the bulk rock compositions of the samples may not represent equilibrium compositions.

Figure 3 and Figure 4 show that the isopleths from contouring calculations for observed mineral compositions mostly lie in the stability field expected for the rocks, disregarding the garnet grossular contours for CH4 and plagioclase contours for CH1. These contours could be affected by the lack of apatite correction or low-Ca content of the rocks, affecting the accuracy of measurement on mineral compositions, as the calcium content in garnet varies between these two samples.

Because this analysis is based on thermodynamic modeling, errors could be induced by the models themselves and by assumptions made for calculations. Leaving out manganese end-members, not correcting for apatite, or the arbitrary choice of low Fe_2O_3 values in bulk rock compositions could be sources of error. The choice of H_2O-values is also based on the interpretation of T-X_{H2O} diagrams and changes in H_2O content affects the extent and positions of stability fields within the pseudosection diagrams.

Pseudosection results can be difficult to interpret due to issues relating to partial melting and melt loss. Evidence for partial melting in the field, reaction textures showing garnet and biotite consumption in dehydration melting reactions (Spear et al., 1999), K-feldspar poor or absent rocks with melt-loss, and K-feldspar rich rocks with possible preserved melt suggest that samples might be representative of different times in the melting history of the rocks. Bulk rock composition data might, then, represent rocks before or after melt-loss based on their compositions.

Based on the *P-T* points determined for samples CH1 and CH4, Theriak-Domino was used to calculate modal compositions (in vol% of a phase). Tables 1a and 1b show actual modes in thin section, calculated from phase maps of CH1 and CH4, with the predicted Theriak modes. The calculated and actual modes show a close match to ±2% which shows that the calculations and pseudosection diagrams match with the observed modes and compositions in the rocks.

a) CH1	Theriak Run at T = 790 °C, P = 8.5 kbar	
Phase	**OBSERVED MODES (Vol%), ± 2%**	**CALCULATED MODES (Vol%), ± 2%**
Quartz	21 %	23 %
Garnet	19 %	16 %
Biotite	31 %	33 %
Sillimanite	5 %	3 %
K-feldspar	17 %	16 %
Plagioclase	6 %	8 %
Total	99 %	99 %

b) CH4	Theriak Run at T = 725 °C, P = 7 kbar	
Phase	**OBSERVED MODES (Vol%), ± 2%**	**CALCULATED MODES (Vol%), ± 2%**
Quartz	30 %	33 %
Garnet	13 %	12 %
Biotite	23 %	19 %
Sillimanite	6 %	5 %
Plagioclase	24 %	26 %
Ilmenite	0.7 %	1.3 %
Total	96.7 %	96.3 %

Figure 5. Observed modes vs. Theriak-Domino modeled modes comparisn for CH1 (1a) and CH4 (1b). Observed modes are determined by pixel-count from SEM/EDS generated full thin section phase maps, and Theriak-Domino modeled modes are calculated with Theriak at corresponding P-T values determined from the pseudosections.

Cramer and others (2013), found no monazites with ages older than 1.78 Ga in their study of CRMS metapelites, suggesting that metapelite samples from the Christensen Ranch Metamorphic suite were metamorphosed at 1.78 Ga during the Big Sky orogeny, but had not been metamorphosed during the previous 2.45 metamorphic event. If this is the case, the pressures and temperatures recorded by these samples represent solely metamorphic conditions that pertained at least in this part of the Ruby Range during the Big Sky orogeny, unlike samples from the Dillon Gneiss or Pre-Cherry Creek suite, which possibly experienced more than one melting and melt-loss episodes from the 2.45 metamorphic event (Karasevich et al., 1981).

The Big Sky orogeny has been studied extensively in the Tobacco Roots Mountains (Harms et al., 2004; Cheney et al., 2004), and a *P-T* path for this orogenic event has been proposed by Cheney and others (2004) with a peak-*T* of 800 ºC with a pressure of ~9 kbar at peak-*T*. The *P-T* values of ~800 ºC and ~ 9 kbar for CH1 correlate with the peak-*T* determined for the Big Sky orogeny in the Tobacco Root Mountains. The lower *P-T* values of ~700 ºC and ~7 kbar calculated for CH4 could represent a re-equilibration *P-T* point on the *P-T* path, also determined for the Big Sky orogeny in the Tobacco Root Mountains (Cheney et al., 2004). Despite issues relating to partial melting and melt loss, samples CH1 and CH4 can be interpreted as recording two different points of the *P-T* path for the Big Sky orogeny in the Ruby Range, one at peak-*T* and one down pressure and temperature, during thermal reequilibration, consistent with the *P-T* path for the Big Sky orogeny previously established in the Tobacco Roots Mountains (Cheney et al, 2004).

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