Metamorphism of Biotite-Sillimanite-Garnet-Bearing Rocks from the Highland Mountains, Southwestern Montana

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Abstract

The Tobacco Root and Highland Mountains in southwestern Montana are Laramide uplifts containing Precambrian rocks which record a 1.78-1.71 Ga metamorphic and deformational event known as the Big Sky orogeny. Previous work in the Tobacco Root Mountains (TRM) yielded a clockwise P-T evolution where the highest pressures and temperatures were followed by isobaric cooling and isothermal decompression.

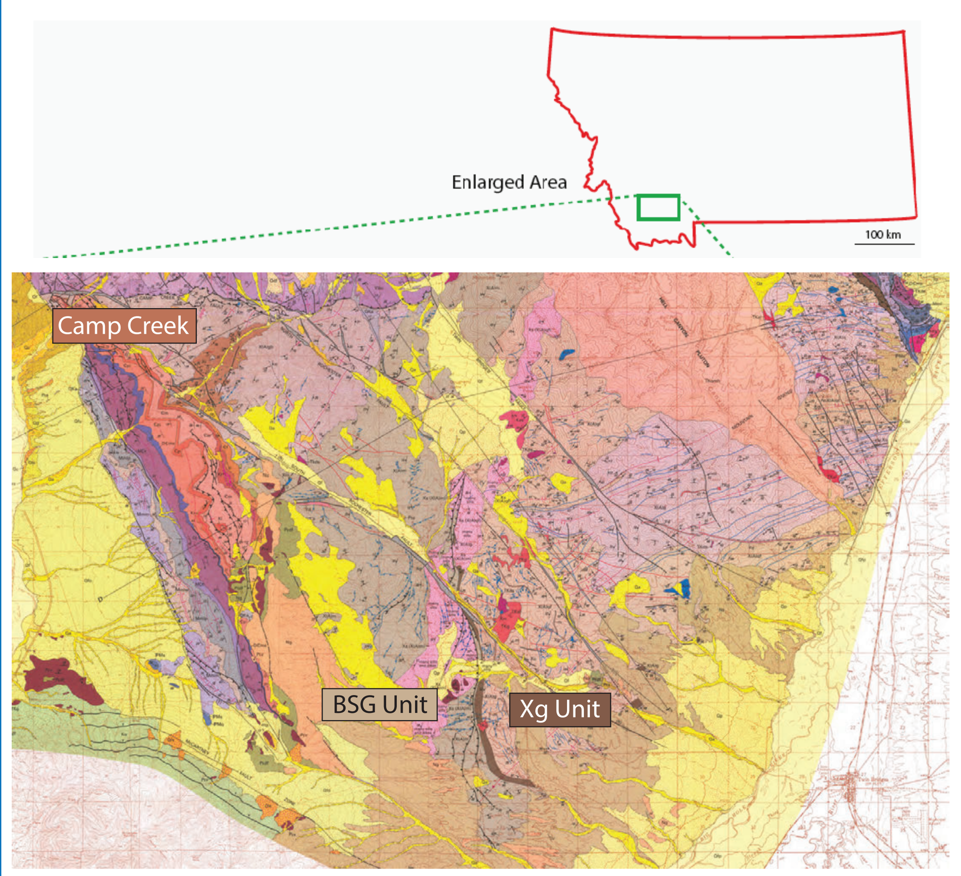
The Highland Mountains, west of the TRM, are cored by a quartzofeldspathic gneiss unit cut by metamorphosed mafic dikes and sills. A thin and diverse unit (designated Xg) partially rims the core and is mostly garnet rich gneiss with marble, quartzite, iron formation, and amphibolite. These two units are similar to suites found in the TRM. The core is mantled by a unit containing biotite-sillimanite-garnet gneiss which is unlike any in the TRM. The core and mantle are juxtaposed across a zone of mylonitization and leucocratic melt.

The mantle gneiss and the Xg unit each contain rocks with the essential mineral assemblage sillimanite + garnet + K-spar + biotite with different textures. Samples from Camp Creek on the northwestern edge of the mantle contain no kyanite, sillimanite pseudomorphs after kyanite, cordierite or orthopyroxene, whereas abundant muscovite laths cut across the fabric, indicating nearly isobaric heating and cooling at P between 4 and 8 kbar and T between 650ºC and 800ºC. Samples from between Camp Creek and the Xg unit also have no evidence of kyanite but have less abundant and more skeletal back-reacted muscovite. Samples from the Xg unit have sillimanite pseudomorphs after kyanite and contain cordierite but have no retrograde muscovite, which indicates a clockwise P-T path with heating at P>8.0 kbar and cooling at P<3.5 kbar. The absence of orthopyroxene requires T<850ºC at P=6.5 kbars. 207Pb/206Pb spot ages on monazites from Camp Creek and the Xg unit were obtained from the ion microprobe at WHOI (Brown (2008) and Pearson (2008)). The majority of the Camp Creek rocks yielded an age range from 1870-1770 Ma and most of the Xg rocks yielded an age range of 1860-1760 Ma. The younger ages overlap with the Big Sky orogeny in the TRM while the older ages indicate the Highland Mountains were experiencing metamorphism necessary to grow monazites before the TRM.

Tobacco Root Mountains' P-T Path

P-T-t path for the Tobacco Root Mountains. Taken from Cheney et al., 2004.

Highland Mountain Geography

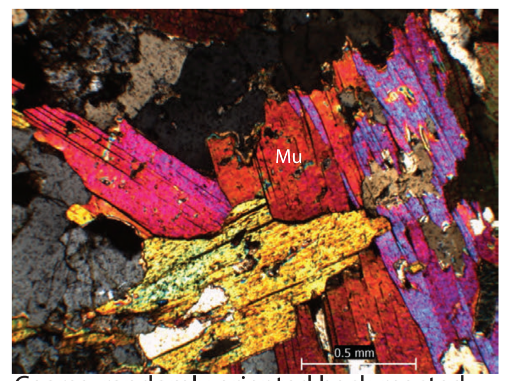


Map of Highland Mountains highlighting Camp Creek, the biotite-sillimanite-garnet (BSG) gneiss unit and the Xg unit. Modified from O'Neill et al., 1996.

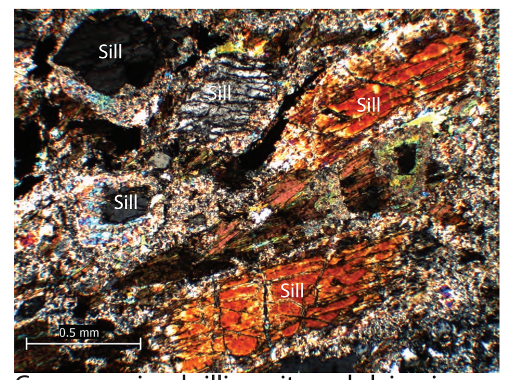
	CAMP CREEK	BSG UNIT	Xg UNIT
Mineral Assemblage	Quartz, Plagioclase, Biotite, Sillimanite, Garnet K-feldspar Rutile Ilmenite	Quartz, Plagioclase, Biotite, Sillimanite, Garnet K-feldspar Muscovite	Quartz, Plagioclase, Biotite, Sillimanite, Garnet Kyanite Cordierite Rutile Ilmenite
Hand Sample	There is a strong undulose gneissic banding of leucosome and melanosome, which is dominated by biotite. Garnet is evenly distributed and ranges from fine-grained to nearly a centimeter in diameter. Coarse sillimanite rods lie in the fabric plane and form a strong L-fabric. Rods that are perpendicular to the L-fabric are folded.	A penetrative S-fabric is defined by biotite and fine compositional banding. Garnet is concentrated in melanosome layers but is also present in leucosome.	Biotite, sillimanite and compositional banding define a moderate to strong S-fabric Garnet is evenly distributed and can be up to several millimeters in diameter. Sillimanite rods less than a centimeter in length lie in the fabric plane and form a weak L-fabric.
Mineral Textures	- Biotite and fine-grained sillimanite define a weak LS-fabric. - Garnet is subhedral to eudhedral with very few inclusions. - Sillimanite also occurs as coarse rods which are aligned in an L-fabric. - Garnet has as inclusions quartz, plagioclase, biotite and rutile. - Sillimanite has as inclusions quartz and biotite. - K-feldspar is concentrated in leucosome bands and is not present in samples with significant amounts of late muscovite or considerable chloritization. - Coarse, randomly oriented muscovite laths overprint all minerals.	- Biotite and fine-grained sillimanite or fibrolite define a strong LS-fabric. - The fabric forms lenses around subhedral to anhedral skeletal garnets which contain many inclusions. - Fabric lenses also contain randomly oriented muscovite and biotite. - Garnet has as inclusions quartz, plagioclase and biotite; - Sillimanite has no inclusions. - K-feldspar is evenly distributed as porphyroblasts throughout the matrix and leucosome. - Incomplete, randomly oriented muscovite laths overprint all other minerals.	- Biotite and aluminosilicates define a weak LS-fabric. - Garnet is subhedral to euhedral with many inclusions. - Fine-grained, anhedral kyanite is present as well as sillimanite pseudomorphs after kyanite, coarse sillimanite and fibrolite bunches. - Garnet has as inclusions quartz, plagioclase, biotite, kyanite and rutile. - Kyanite has as inclusions quartz and biotite. - Sillimanite has as inclusions quartz and rutile. - No K-feldspar is present. - There is a vermicular intergrowth of quartz and sericite alteration, which may be after cordierite.

Petrographic Thin Section Images

CAMP CREEK

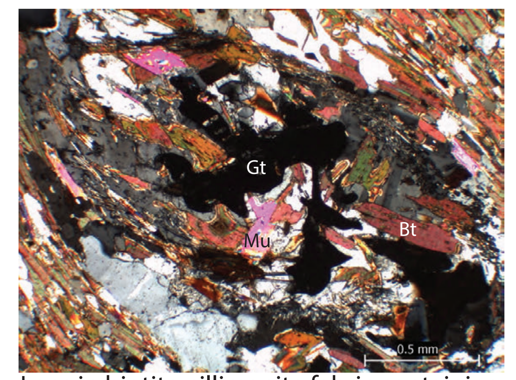


Coarse, randomly oriented back-reacted muscovite laths overprinting equilibrium assemblage. (GRV 5-5D)

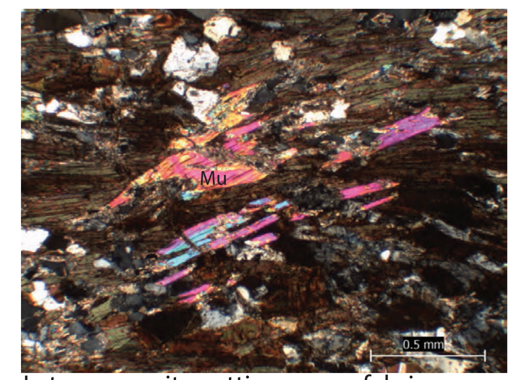


Coarse-grained sillimanite rods lying in planar fabric. (GRV 17a)

BSG UNIT

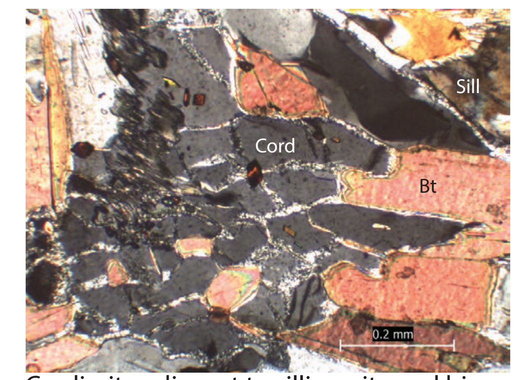


Lens in biotite-sillimanite fabric containing skeletal garnet and randomly oriented biotite and muscovite (PTH-01b)

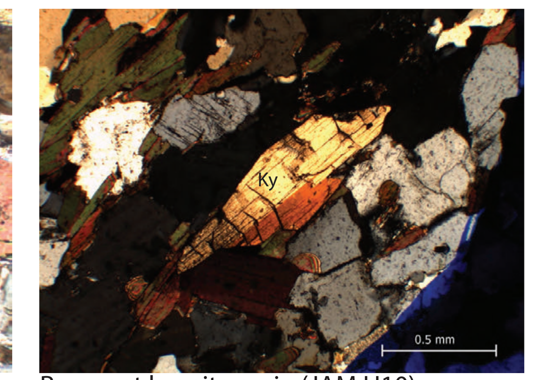


Late muscovite cutting across fabric. (PTH-01b)

Xg UNIT



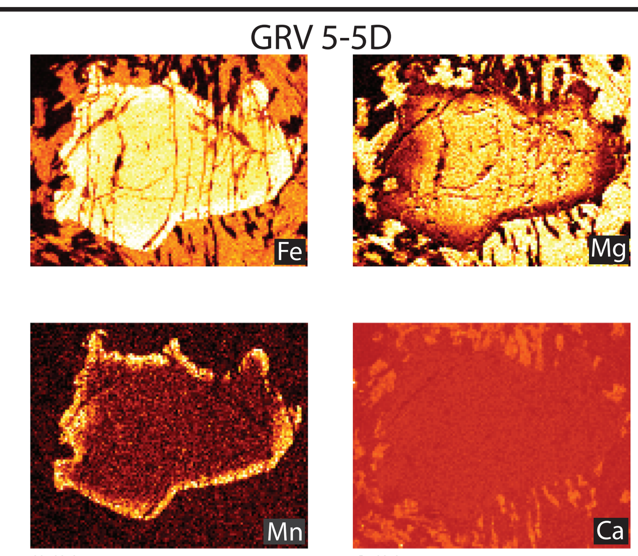
Cordierite adjacent to sillimanite and biotite. (JAM H15)



Remnant kyanite grain (JAM H10)

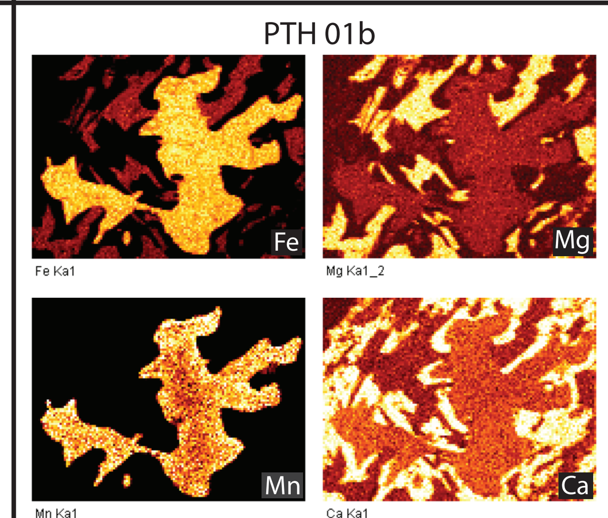
Garnet Zoning Maps

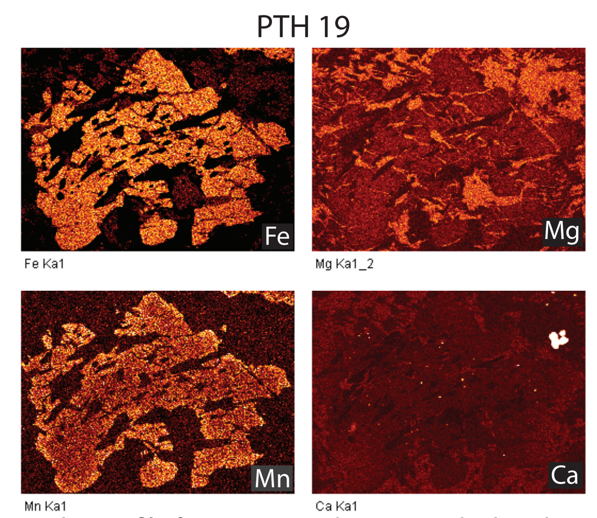
Red- Low concentration
Yellow- High Concentration



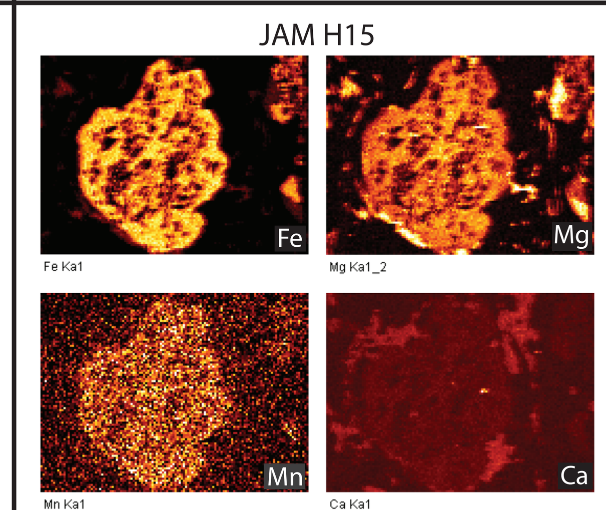
Taken from Brown, 2008.

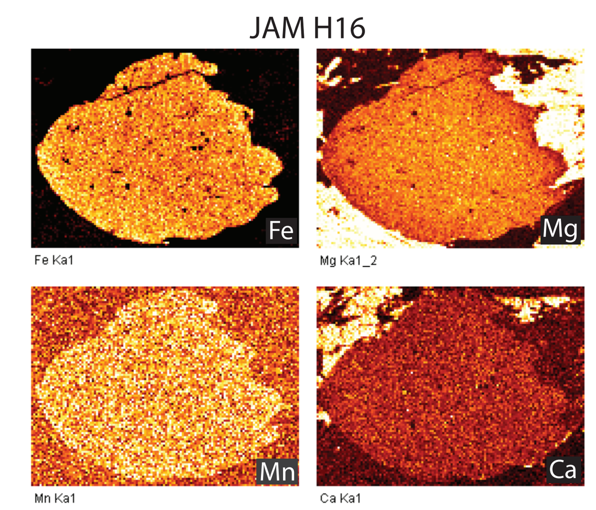
Camp Creek garnet has a very sharp zoning profile in Fe, Mg and Mn and has relatively constant Ca from core to rim. In order for the extreme zoning to be preserved, cooling had to be rapid. The flat Ca profile suggests the change in pressure was not great along the retrograde path.





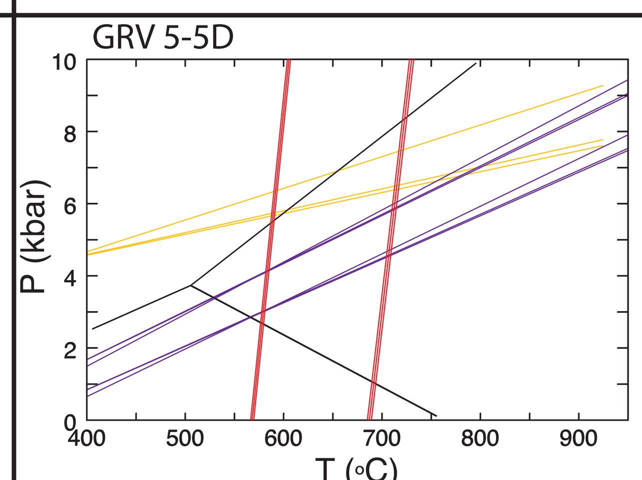
The zoning profile for BSG Unit garnet is not as extreme as the profile for Camp Creek garnet, which indicates slower cooling. The core composition of BSG garnet is nearly the same as the rim composition of Camp Creek garnet, which suggests the BSG rocks were at a lower maximum metamorphic temperature.

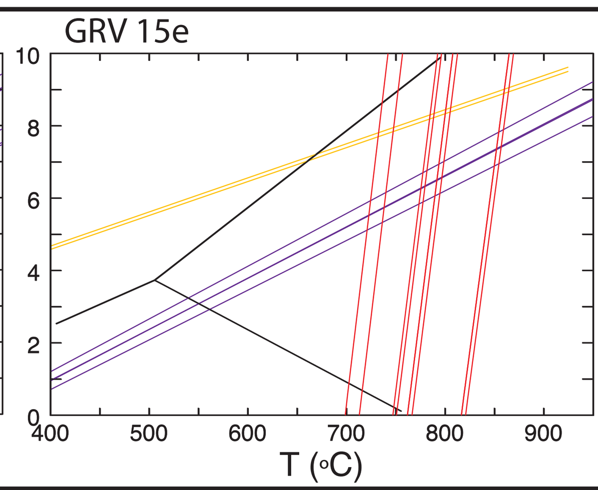


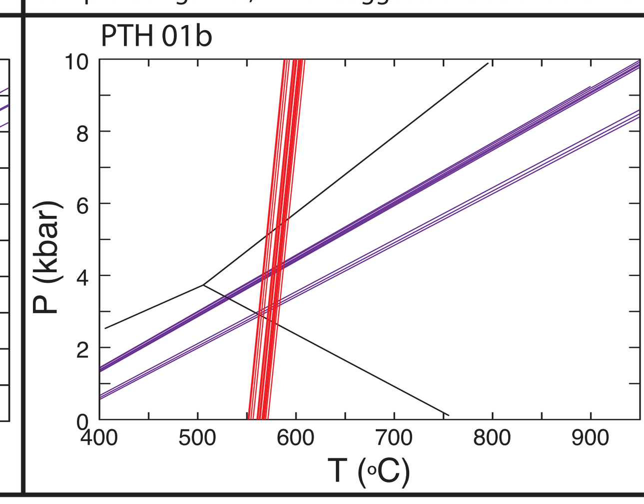


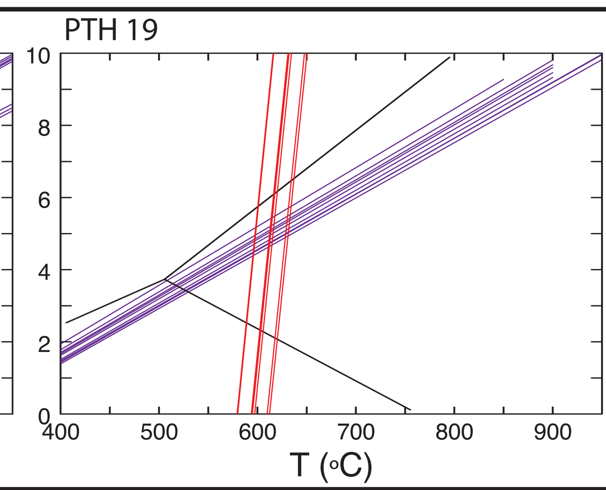
Garnet from the Xg Unit is weakly zoned in Fe, Mg, Mn and Ca, except where it is adjacent to biotite, which causes moderate Fe, Mg and Mn zoning.

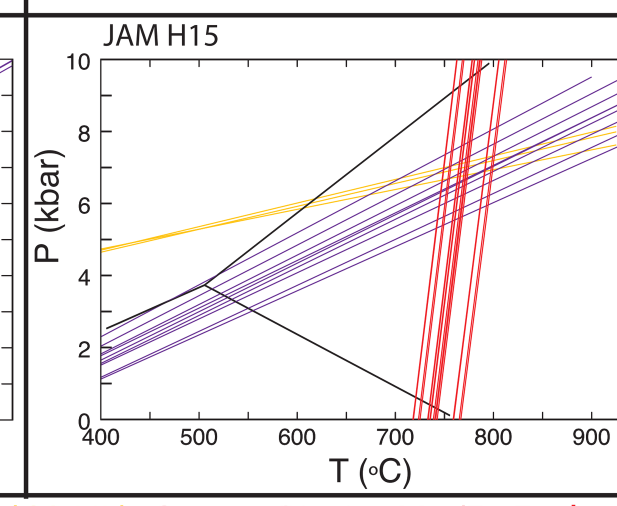
Geothermobarometry

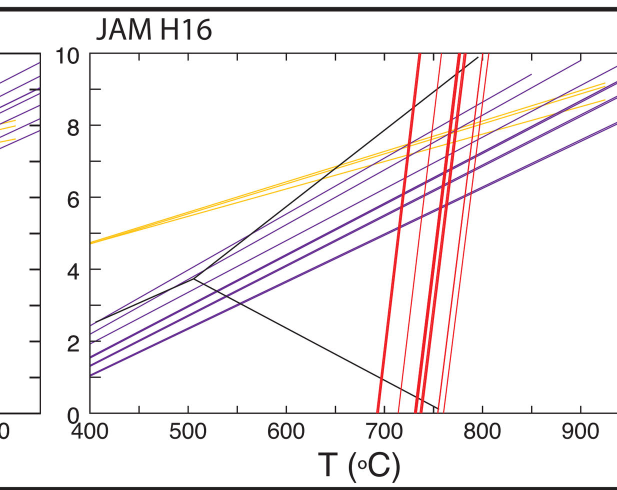












Garnet + Aluminosilicate = Quartz + Plagioclase (GASP); Garnet + Rutile = Aluminosilicate + Ilmenite + Quartz (GRAIL); Garnet-Biotite Mg/Fe Exchange

To minimize the effect of retrograde net transfer reactions on geothermometry, garnet compositions are near-rim compositions (50 microns from the garnet edge), taken along rims where garnet is pinned by plagioclase. The GRAIL reaction was only available as a geobarometer for Camp Creek and the Xg Unit where rutile and ilmenite were present.

Radiometric Dating

Metamorphic ages were determined for monazites from Camp Creek and the Xg Unit. The majority of Camp Creek ages fell in the range 1870-1770 Ma while most of the Xg Unit ages were in the range 1860-1760 Ma. These age ranges only partially overlap with the Big Sky orogeny which occurred from 1780-1720 Ma. Therefore Camp Creek and the Xg Unit were experiencing metamorphic conditions before and during the Big Sky orogeny. There are no currently documented ages for monazites which are present in the BSG Unit rocks.

Summary

- Three distinct rock suites (Camp Creek, BSG Unit and Xg Unit) in the Highland Mountains contain Precambrian metamorphosed rocks with the basic mineral assemblage quartz + plagioclase + biotite + sillimanite + garnet.

Xg Unit: Rocks contain kyanite, sillimanite pseudomorphs after kyanite, and cordierite, suggesting a clockwise P-T-t path (shown in orange below). The absence of orthopyroxene in the assemblage limits the maximum temperature below the orthopyroxene-in reaction at 800 ºC (highlighted in red below). K-feldspar is entirely absent. This could be a result of K-feldspar dissolving into the melt, which subsequently left the rock, or due to a K-poor bulk composition.

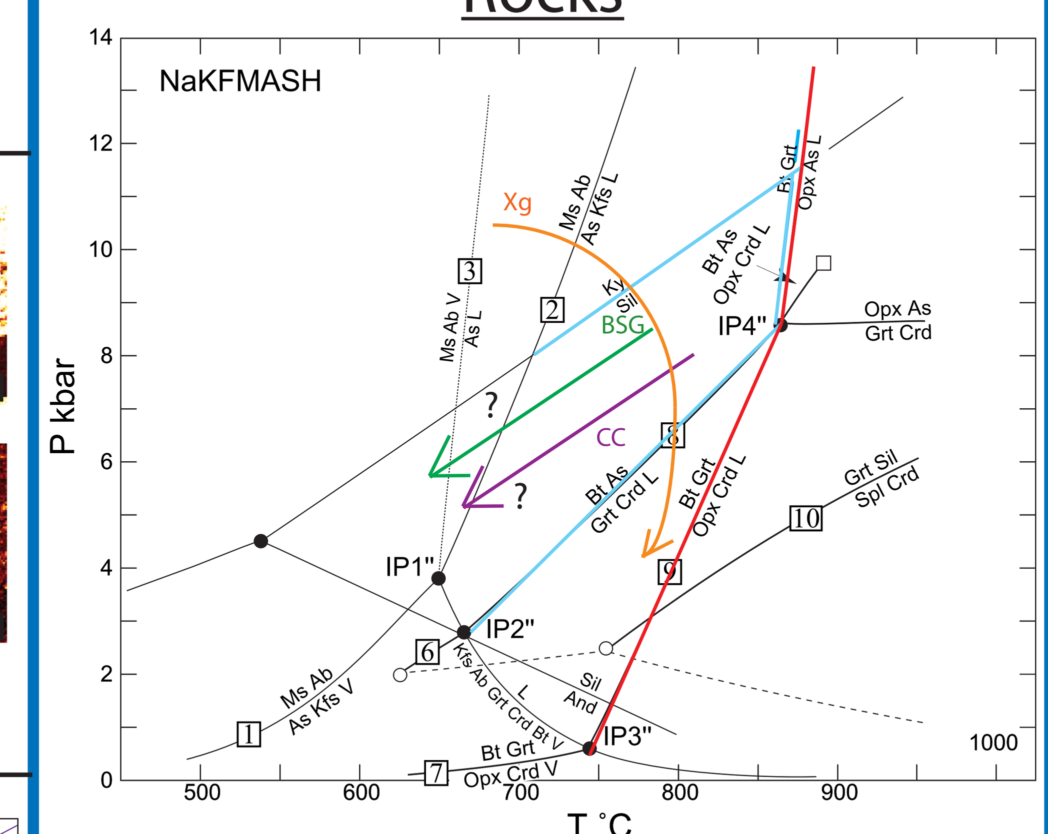
Camp Creek: There is no evidence of cordierite, kyanite or orthopyroxene, which limits the prograde P-T path between 4 and 8 kbar and T<850ºC (the region is highlighted in blue below). Garnet has extremely sharp zoning in Mg, Fe and Mn suggesting rapid cooling in order to preserve this retrograde zoning. Weak Ca zoning suggests a small change in pressure. Coarse overprinting muscovite laths are a result of the retrograde melt reaction Melt + K-feldspar + Sillimanite = Muscovite + Plagioclase. The BSG unit has similar randomly oriented muscovite overprinting the prograde assemblage but the muscovite is in poorly formed laths and in much smaller modal amounts. This could have resulted from melt being extracted from the BSG Unit.

BSG Unit: This unit mantles the Xg unit, but the rocks are more similar to the Camp Creek rocks, containing no evidence of cordierite, kyanite or orthopyroxene. They are therefore limited to the same P-T region as the Camp Creek rocks. Garnet zoning is weaker than in Camp Creek which suggests a slower cooling rate allowing time for element diffusion. Muscovite also overprints all minerals, but in much lower modal amounts and with more poorly-formed laths than in Camp Creek. K-feldspar porphyroblasts are evenly scattered throughout the rock.

- The composition of the BSG garnet cores are nearly the same as the composition of the Camp Creek garnet rims and matrix biotite compositions are similar for the two rocks, which indicates that the Camp Creek rocks reached a higher maximum metamorphic temperature. This is suggested in the geothermometry plots.

- Preliminary analyses using F. Spear's Gibbs program suggest Camp Creek and BSG retrograde P-T paths were nearly parallel. They are plotted below with Camp Creek in purple at a higher temperature than BSG in green. The precise slopes of the retrograde P-T paths taken by the BSG Unit and Camp Creek are not known, but a possible configuration is shown.

P-T Paths for Highland Mountain Rocks



Petrogenetic grid illustrating the pressure and temperature constraints on the metamorphism of the Highland Mountains. Possible metamorphic paths are shown with arrows. Modified from Spear et al., 1999.

References

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Spear, F.S., Program Gibbs, January 2009.