Figure 1: Map of Montana showing the architecture of the Big Sky orogen and cross section showing the historical architecture

In the orogen, the northeast trending metamorphic core zone (dotted diagonal ruling) is flanked to the southeast by a foreland of discrete, southeast-vergent ductile thrust faults (horizontal ruling) and to the northwest by a fossil subdivision zone and accreted, juvenile Proterozoic arc terrane (Vertical Ruling) (Harms et al., 2004). The Tobacco Root Mountains are part of the Montana metasedimentary terrain (MMT), which is made up of the Pony-Middle Mountain Metamorphic Suite (PMMMS), Spuhler Peak Metamorphic Suite (SPMS), and Indian Creek Metamorphic Suite (ICMS) (Harms et al., 2004). While different types of iron formations can be found in each metamorphic suite, the garnet gneiss being studied is from the ICMS. The ICMS is dominated by quartzofeldspathic gneisses, with lesser amounts of hornblende gneisses, silicic gneisses and garnet gneisses and meta sedimentary banded iron formations (garnet, enstatite, garnet, clinopyroxene, or grunerite), quartzites, marbles, and pelites. (Burger et al., 2004).

Figure 2: Precambrian timeline of the tectonic evolution in the metamorphic suites of the Tobacco Root Mountains.

Schematic cross sections illustrate interpreted tectonic settings of the Tobacco Root Mountains metamorphic suites during important events. Dashed lines are used for approximate ages and are constrained only by their max/min. Solid line or bars indicate known ages. The quartzofeldspathic and hornblende gneisses of the ICMS were originally formed from bimodal volcanism associated with continental arc with an extensional back arc system 3.35-3.2 Bya (Burger et al., 2004). The metasedimentary units were deposited during a period of low arc activity 3.13-3.85 Bya in a shallow sea in the back arc system (Harms et al., 2004). After metamorphism from bimodal, an orogen at 2.45 Ga, and the Big Sky orogen at 2.01-1.8 Bya, the ICMS had been metamorphosed to granulite facies. (Harms et al., 2004). Due to extreme folding and thrusting from multiple orogenic events, the stratigraphy of the metasedimentary rocks is no longer intact (Burger et al., 2004). The metasedimentary rocks form discontinuous units that have become entrapped in the older and larger gneisses (Burger et al., 2004).

Figure 3: Rock description of sample Brownish red magnetite quartz garnet gneiss. Two types of 1 mm-5cm bands are present, and are typically separated by 2mm-1.5cm grade contacts. The fine grain bands are made up of a garnet gneiss (70%), fine grained quartz (20%), and trace biotite & amphibole. The coarse grain bands has made up of fine to very coarse quartz (40%), fine to very coarse feldspar (53%), and 0-1.7mm magnetite (7%). Magnetite is exclusively found surrounded by fine-coarse grained layers. Outcrop was approximately 10m wide, discontinuous, and only partially exposed.

Figure 4: Refract light Petrographic microscope

Photomicrographs showing bands of garnet (Gr), quartz (Qtz), Grunerite (Grn), and magnetite (Mag)

A) Parallel bands of 0.1-1mm garnets and quartz, inside of an extremely fine garnet mass with interstitial quartz, 3-5mm magnetite crystals are dispersed and elongated in direction of banding.
B) Pictured is central band 5mm wide of garnets & quartz 0.1-1mm, with scattered 1.5-2mm grunerite and magnetite crystals. It is flanked to its right with a extremely fine grain band of garnet with a sharp contact. To the left of the coarser band a gradational change to a fine grained mass with interstitial quartz.

Figure 5: SEM pictures of thin sections

Photoelectron micrographs showing garnet (Gr), quartz (Qtz), Ilmenite (Im), monazite (Mz), rutile (Ru), and zircon (Zr).
A) Upper third shows a groundmass of 95% garnets (7-60μm) with 5% interstitial quartz (4-100μm), and trace rutile (30μm). The bottom third is a band of 60% garnets (40-265μm), and 40% Quartz (20-265μm). The lower band has a much larger average mineral size and contains zircon (15-50μm), and monazite (25μm). No significant difference in the garnet chemistry of rims vs cores, or smaller vs larger minerals was observed.
B) Pictured is garnet (14-24μm), 45% quartz (80-235μm) and 5% ilmenite (230-260μm). Ilmenite was found in trace amounts throughout whole rock but was found to make up to 5% in certain zones.

Figure 6: Comparative bulk rock and garnet geochemistry

A) Bulk rock chemistry. Our sample's Fe content is significantly higher than the ICMS, at the lower end compared to the BIF's. The garnet gneiss Mn content is x26.4 higher than the average ICMS rock, and only x4.4 higher than the average BIF. Our sample is around halfway between the BIF's lower Al content (Avg. 2.8%) and the ICMS' higher Al content (Avg. 13.1%). B) Garnet Chemistry. Most garnets were particularly Fe rich. The ICMS garnets have low Mn levels and high Fe-Mn variability, while the Australian garnets having low Mn levels and high Fe-Mn variability. Our sample plotted in the middle of the Australians garnet's Fe to Mn ratio variation, but had slightly more Mg.

Figure 7: Indian Creek Metamorphic Suite

Geologically metamorphic gneiss, hornblende gneiss, and lesser metasedimentary units, including banded iron formation, the ICMS' closest unit comparable to the garnet gneisses (James, 1983). Both units have higher Fe & Mn content than any other unit in the ICMS, low Al content, and also have similar elevated Cr concentrations (James, 1983). Both are found in discontinuous outcrops 10-15m wide. Both also contain banding alternating the ratio between Fe and Si.

Figure 8: Australian Garnet Gneisses

Has alternating bands of extremely fine grain garnet with interstitial quartz, and bands of fine-grained quartz, garnet, and magnetite (Heimann, 2010). Trace ilmenite, monazite, and grunerite. Geochemical & isotopic evidence suggests the protolith was an arctic exhalative iron formation related to VMS activity (Heimann, 2018). The iron oxide, chert, clay, and Mn-silicates metamorphosed to form bands of garnet, quartz, and magnetite.

Table 1: Bulk rock chemistry of Garnet Gneiss

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<thead>
<tr>
<th>Element</th>
<th>ICMS Average</th>
<th>PMMS Average</th>
<th>SPMS Average</th>
<th>Garnet Gneiss Average</th>
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<tr>
<td>Fe (%)</td>
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<tr>
<td>Mg (%)</td>
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<td>12.9</td>
<td>12.7</td>
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</tbody>
</table>

References


James, T.A., 2010, Trace ilmenite, monazite, and grunerite. Geochemical & isotopic evidence suggests the protolith was an arctic exhalative iron formation related to VMS activity (Heimann, 2018).

Heimann, H.W., 2018. The iron oxide, chert, clay, and Mn-silicates metamorphosed to form bands of garnet, quartz, and magnetite.

Conclusions

Both our sample and the Australian garnet gneiss are made primarily of banded iron-manganese gneisses, quartz, with lesser magnetite, and trace monzite, ilmenite, grunerite, and biotite (Heimann, et al., 2010). Our sample, the Australian gneiss, and the ICMS BIF all have high Fe content and elevated Mn content found in no other units in the ICMS. The Australian garnet gneiss has been interpreted as being a metamorphosed exhalative hydrothermal iron deposit related to volcanic massive sulphides. The ICMS sediments have also been interpreted as coming from a back arc marine environment, with evidence of hydrothermal alteration (Burger et al., 2004). Considering the previous information, it is most likely that the garnet gneiss of our study represents a 3.13-2.85 Ga exhalative iron formation genetically related to other banded iron formations of the ICMS. Variations in the composition of mixing seawater and hydrothermal fluids, Eh-pH conditions, and the contamination of outside sediment, caused the the variations in composition between our sample the other BIF. The oxygen at 2.45 Ga and the Big Sky Orogeny at 1.78-1.72 caused the rock in this study to be metamorphosed to the granulite facies, with the iron oxides, Mn-silicates, and clays reacting to form garnet.

Comparable Rocks

Heimann, H.W., 2018. The iron oxide, chert, clay, and Mn-silicates metamorphosed to form bands of garnet, quartz, and magnetite. 