

KECK GEOLOGY CONSORTIUM

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

April 2011
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2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING

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EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA

Faculty: *TEKLA A. HARMS*, *JOHN T. CHENEY*, Amherst College, *JOHN BRADY*, Smith College

Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO

Faculty: *DAVID P. DETHIER*, Williams College, *WILL OUIMET*, University of Connecticut

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SEDIMENT DYNAMICS & ENVIRONMENTS IN THE LOWER CONNECTICUT RIVER

Faculty: *SUZANNE O'CONNELL*, Wesleyan University

Students: *LYNN M. GEIGER*, Wellesley College, *KARA JACOBACCI*, University of Massachusetts (Amherst), *GABRIEL ROMERO*, Pomona College.

GEOMORPHIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA, U.S.A.

Faculty: *KELLY MACGREGOR*, Macalester College, *CATHERINE RIIHIMAKI*, Drew University, *AMY MYRBO*, LacCore Lab, University of Minnesota, *KRISTINA BRADY*, LacCore Lab, University of Minnesota

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GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA

Faculty: *KARL W. WEGMANN*, North Carolina State University, *TSALMAN AMGAA*, Mongolian University of Science and Technology, *KURT L. FRANKEL*, Georgia Institute of Technology, *ANDREW P. deWET*, Franklin & Marshall College, *AMGALAN BAYASAGALN*, Mongolian University of Science and Technology.

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LATE PLEISTOCENE EDIFICE FAILURE AND SECTOR COLLAPSE OF VOLCÁN BARÚ, PANAMA

Faculty: *THOMAS GARDNER*, Trinity University, *KRISTIN MORELL*, Penn State University

Students: *SHANNON BRADY*, Union College. *LOGAN SCHUMACHER*, Pomona College, *HANNAH ZELLNER*, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION

Faculty: *JADE STAR LACKEY*, Pomona College, *STACIL LOEWY*, California State University-Bakersfield

Students: *MARY BADAME*, Oberlin College, *MEGAN D'ERRICO*, Trinity University, *STANLEY HENSLEY*, California State University, Bakersfield, *JULIA HOLLAND*, Trinity University, *JESSLYN STARNES*, Denison University, *JULIANNE M. WALLAN*, Colgate University.

EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING

Faculty: *JOHN CRADDOCK*, Macalester College, *DAVE MALONE*, Illinois State University

Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

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Keck Geology Consortium: Projects 2010-2011
Short Contributions— Big Sky Orogen

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA

Project Faculty: TEKLA A. HARMS, JOHN T. CHENEY, Amherst College, JOHN BRADY, Smith College

PROTOLITH DETERMINATION OF PRECAMBRIAN MYLONITIC ROCKS ADJACENT TO THE MADISON MYLONITE ZONE, HENRYS LAKE MOUNTAINS, SOUTHWEST MONTANA AND IDAHO

JESSE DAVENPORT, College of Wooster

Research Advisor: Shelley Judge

PETROGRAPHIC AND GEOTHERMOBAROMETRIC ANALYSES OF METASEDIMENTARY ROCKS IN THE HENRYS LAKE MOUNTAINS, IDAHO AND MONTANA

KRISTINA DOYLE, Amherst College

Research Advisor: Tekla Harms

GEOCHRONOLOGY OF PRECAMBRIAN META-GABBRO IN THE HENRYS LAKE MOUNTAINS, SOUTHWEST MONTANA AND IDAHO

B. PARKER HAYNES, University of North Carolina - Chapel Hill

Research Advisor: Drew S. Coleman

PETROGENESIS AND DEFORMATION OF PRECAMBRIAN QTZ-DOL MARBLE UNITS IN THE GRAVELLY RANGE AND REYNOLDS PASS, HENRYS LAKE MTNS, SW MT AND ID

DANIELLE LERNER, Mount Holyoke College

Research Advisor: Steve Dunn and Michelle Markley

PETROGENESIS OF PRECAMBRIAN IGNEOUS AND META-IGNEOUS ROCKS SOUTH OF THE MADISON MYLONITE ZONE, HENRYS LAKE MOUNTAINS, SW MONTANA AND IDAHO

CALEB O. LUCY, Williams College

Research Advisor: Reinhard A. Wobus

STRUCTURAL ANALYSIS OF PRECAMBRIAN MYLONITE ZONES, HENRYS LAKE MOUNTAIN, SOUTHWEST MONTANA AND IDAHO

ALIANORA WALKER, Smith College

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PETROGRAPHIC AND GEOTHERMOBAROMETRIC ANALYSES OF METASEDIMENTARY ROCKS IN THE HENRYS LAKE MOUNTAINS, IDAHO AND MONTANA

KRISTINA DOYLE, Amherst College
Research Advisor: Tekla Harms

INTRODUCTION

Metasedimentary rocks can be found throughout the Henrys Lake Mountains with a variety of metamorphic grades and mineral assemblages. For this project, rocks were collected from areas mapped as mica schist, although they are certainly not all part of the same unit, and in many areas are not actually mica schist. The metasedimentary rocks can be divided into four important groups; high grade, garnet bearing mica schists found in the Henrys Lake village suite and at Schoolhouse Canyon; finer grained, amphibole rich, biotite-plagioclase-quartz rocks found at the top of Divide Creek Road; chlorite rich rocks with possible retrograded garnet and staurolite found near Deer Mountain; and low grade chlorite and biotite schists found at Saddle Mountain, Anthill Creek, Horn Mountain and Lone Tree Pass (Fig. 1).



Figure 1. Map showing locations of the seven key sites for this paper. Horn Mountain lies to the north, slightly off of the map, and was not included in order to present the other, more important sites in the highest resolution possible.

METHODS

At most stations, samples were chosen that had a mineral assemblage and fabric representative of the

dominant rock type in that outcrop. In areas with visible garnet and staurolite, I chose samples that included several grains of each, as well as samples from any layers with smaller or no index minerals for comparison.

At Amherst, thin sections were cut of 24 samples from across the study area, particularly from those areas with visible index minerals. The thin sections were viewed under a petrographic microscope to determine mineral assemblages, analyze textures, and find evidence of zoning in biotite and garnet. Evidence of mineral growth order and textural sequence were also examined. Lastly, samples with garnet present were analyzed to determine if monazite is present, from which the metamorphism of the rock can be dated.

Seven of the 24 samples were analyzed on the scanning electron microscope (SEM) to determine chemical composition and fine tune mineral identification, as well as determine pressure and temperature conditions in those rocks using garnet, plagioclase, biotite and/or muscovite reaction data. Thin sections were polished and carbon coated prior to analysis.

PETROGRAPHY

Henrys Lake and Schoolhouse Canyon

Rocks samples in the Henrys Lake village and Schoolhouse Canyon are primarily garnet and staurolite bearing mica schists. At the Henrys Lake village, some outcrops consist of fine grained schist, but the majority are medium grained schist. Garnets appear throughout the section, scattered in some areas and more concentrated (making up at least 30% of the rock) in others; ranging in size from 2-10 mm. One very different sample from the same area has 1-2 mm grains of kyanite, 2-4 mm staurolite grains, and clumps of sillimanite, but no garnets.

Three samples from the Henrys Lake village suite were viewed under the petrographic microscope and prepared for the SEM, two from the medium grained, garnet rich section of the outcrop (samples 10-KD-9B and 10-KD-9C) and one from the aluminosilicate rich layer where garnet was not present (sample 10-KD-9E).

Sample 10-KD-9B contains 20% garnet porphyroblasts, 25% quartz, 30% biotite, 10% plagioclase and 5% chlorite in the matrix, and <1% each of staurolite, monazite, zircon and apatite. The thin section has one 10 mm garnet and several 1-3 mm ones. The large garnet is subhedral and the core contains remnants of a previous fabric, defined by inclusions of quartz, biotite and staurolite. The matrix fabric has well defined foliation and biotite grains wrap around the garnet. The smaller garnets have very few inclusions and are primarily euhedral. They are also wrapped by the matrix grains, indicating that all garnets grew prior to the matrix. SEM transects demonstrate that Mn levels increase near the edges of all garnets, indicating possible alteration, but clear signs of zoning were found, as levels of all other elements are relatively stable across the garnets. Sample 10-KD-9C is the only sample containing both muscovite and garnet from the Henrys Lake village suite. It has a mineral assemblage of 30% quartz, 30% biotite, 25% muscovite, 10% garnet, and 5% plagioclase.

Sample 10-KD-9E contains 30% quartz, 30% biotite, 10% plagioclase, and 5% muscovite in the matrix, and 10% staurolite, 5% kyanite, and 5% sillimanite porphyroblasts. Unlike all other samples from the Henrys Lake village, no garnet was found in this sample. Quartz and plagioclase appear to be the first formed minerals in the sample, as all other minerals cross cut them. Biotite and muscovite were the second minerals to form. Staurolite cross cuts the quartz, biotite, and plagioclase and is the largest mineral in the sample, with an average size of 2-3 mm. Kyanite and sillimanite appear to be the most recently formed minerals. In several areas, kyanite has replaced staurolite. Kyanite grains are 1-2 mm and typically euhedral, but in some places have been pseudomorphed by sillimanite (Fig. 2). Sillimanite also appears in gaps between other grains, indicating that it was the last formed mineral.

Three samples from Schoolhouse Canyon were also chosen for analysis, 10-KD-27A, 10-KD-27C, and 10-KD-27G. All three samples have similar mineral assemblages and were chosen due to the prevalence of muscovite and garnet.

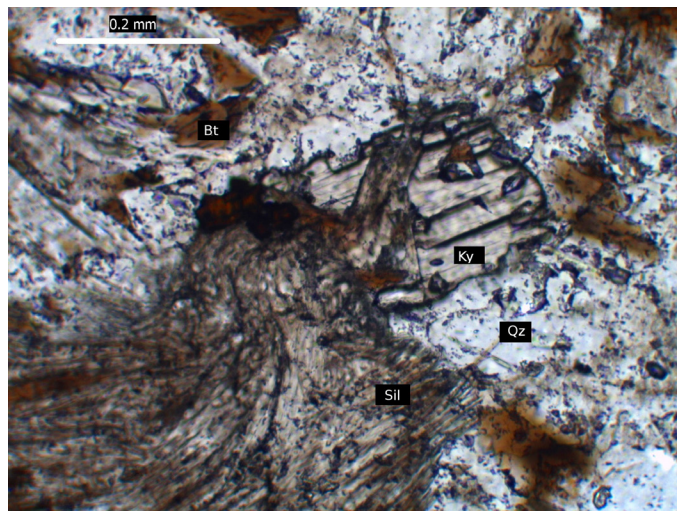


Figure 2. Sillimanite pseudomorphing kyanite. Sample 10-KD-9E, Plane light.

Samples 10-KD-27A and 10-KD-27G contain 50% quartz, 15% biotite, 10% garnet, 5% chlorite, 15% plagioclase and 5% muscovite. The mineral assemblage of 10-KD-27C is 40% quartz, 15% biotite, 10% muscovite, 15% plagioclase and 10% garnet.

The grain sizes of all Schoolhouse Canyon samples are smaller than those in the Henrys Lake village rocks, and garnets are euhedral and have few to no inclusions (Fig. 3). Like the garnets in the Henrys Lake village suite, the Schoolhouse Canyon garnets are unzoned. They have a much higher Mn content than the Henrys Lake village garnets, but also have Mn spikes near the rims, indicating that the edges of these grains have also been retrograded. In one garnet from sample 10-KD-27C, Mg and Ca content varies by up to 0.05 atoms per 12 oxygen ions, with larger amounts near the rim of the grain. In other samples, variations in Mg and Ca content are present, but do not correlate to any specific part of the garnets.

Divide Creek Road

Samples from Divide Creek Road are characterized by a matrix of 1-2 mm biotite, quartz and plagioclase with local chlorite. Samples were collected because of

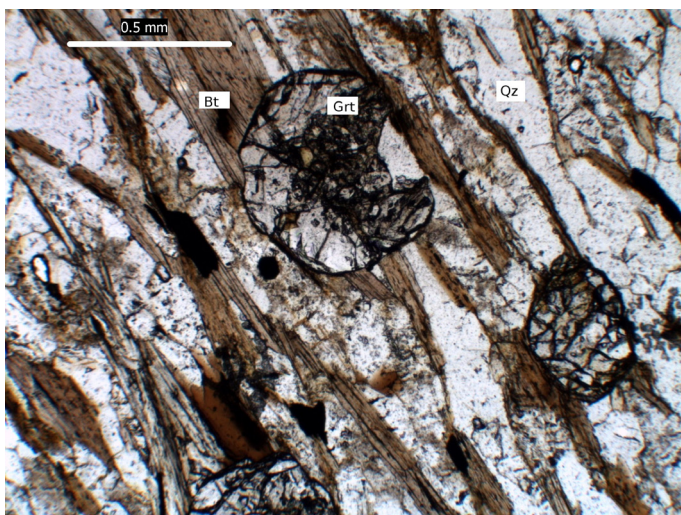


Figure 3. Well defined matrix of biotite, quartz and plagioclase overgrown by euhedral garnets. Sample 10-KD-27A, plane light.

the presence of 4-5 mm subhedral grains of amphibole. Sample 10-KD-26A has a mineral assemblage of 40% amphibole, 30% biotite, 20% quartz and 10% chlorite. The matrix is weakly foliated and overgrown by the large amphibole grains, which appear in clusters. Some of these amphibole grains lie parallel to the matrix and bend around fold hinges, indicating that deformation occurred during or after amphibole growth. The rims of 40-50% of the amphibole grains are replaced by chlorite and quartz.

Deer Mountain

A third distinct assemblage occurs at Deer Mountain, where samples taken are primarily chloritic but appear to be a retrograded version of a much more complicated mineral assemblage. All samples from the Deer Mountain area have largely the same features, typified by sample 10-KD-31D, in which there is 70% chlorite, 10% amphibole, 10% quartz, 5% biotite, 5% muscovite, and <1% anisotropic minerals. The matrix, which is made up of 0.5-2 mm chlorite grains with well defined alignment, wraps around the larger grains. The large grains appear to be of two distinct types. About 50% of the grains appear to be 1-7 mm long staurolite and/or garnet retrograded to chlorite with well defined lineation around the grain edges and more random orientation in the cores (Fig. 4). Many of these grains, particularly those that appear to be retrograded garnets, have inclusions of anisotropic

minerals found nowhere else in the sample. The other 50% appear to be retrograded lithic fragments; anhedral grains in a wide range of sizes (<1-7 mm) primarily made up of differently oriented clumps of chlorite with randomly oriented grains of quartz and biotite throughout. Several grains appear to have broken along foliation and/or cleavage planes (it is impossible to tell which, as they have been entirely replaced by chlorite and may have been either mineral grains or lithic fragments). New fabric has grown between the broken sections of the grains. Amphibole grains, which are 3-4 mm and have no preferred orientation, appear throughout the sample. In many places they are partially replaced by chlorite.

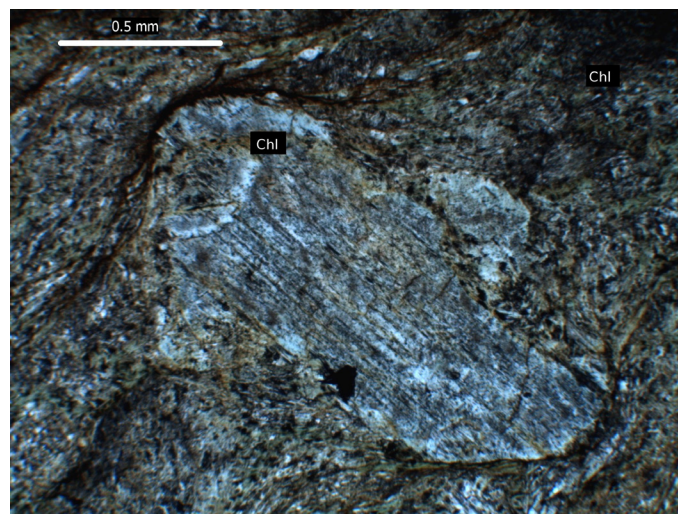


Figure 4. Chlorite replacement of 1mm grain of an unknown mineral, as well as well defined foliation of current chlorite matrix. Sample 10-KD-31A, plane light,

Saddle Mountain, Anthill Creek, Horn Mountain, and Lone Tree Pass

The remaining samples are various types of low grade metamorphic rocks.

The Saddle Mountain sample, 10-KD-17, has a mineral assemblage of 50% chlorite, 20% quartz, 20% biotite and 10% plagioclase. All minerals in the sample align with the foliation, which is very well defined, and all go to extinction at the same time.

The sample from Anthill Creek, 10-KD-30A, also has a well defined foliation. The mineral assemblage is about 60% quartz, 40% biotite, 15% chlorite and

5% muscovite. The biotite and chlorite align with the foliation. Muscovite has overgrown the other minerals and lies perpendicular to foliation.

Two very different samples were collected from Horn Mountain. Sample 10-KD-18 is 70% quartz, 25% plagioclase, and 5% chlorite. The quartz and plagioclase have a weak foliation. Chlorite is present in clumps between grains, with no preferred orientation. Sample 10-KD-20 is 70% plagioclase, 20% quartz and 10% biotite and 10% chlorite. The fabric is much like that of sample 18.

The Lone Tree Pass sample, 10-KD-2A, is finely foliated and consists of 70% chlorite, 15% quartz and 15% biotite. All grains are aligned with the foliation, and all are <0.5 mm. Some areas of the sample appear to have a different foliation, possibly areas where chlorite has replaced larger grains (amphibole, garnet) in a manner similar to the Deer Mountain samples. These areas are much less well defined than those at Deer Mountain, however.

METAMORPHIC CONDITIONS

Pressure and temperature data were calculated for Henrys Lake village sample 10-KD-9B using a Grt-Bt geothermometer (Hodges and Spear, 1982) and a Grt-Bt-Pl-Qz geobarometer (Hoisch, 1990) (Fig. 5). SEM data were carefully analyzed to determine the most accurate biotite and plagioclase analyses, disregarding any readings in which the weight percent totals were much higher than expected for that mineral. Such readings were assumed to be altered minerals or faulty SEM analyses. Several analyses were made using different Bt-Grt pairs.

Muscovite was found in one sample from the Henrys Lake village, but plagioclase analyses from the sample were not accurate enough to provide reliable P/T data.

Since muscovite is present in all of the Schoolhouse Canyon samples, a wider range of P/T data could be obtained. Temperature was calculated for all samples using Bt-Grt reaction data, using the calibration by Hodges and Spear (1982). Pressure was plotted for Grt-Ms-Pl-Qz (Hodges and Crowley, 1985; Hoisch, 1989), Gt-Bt-Pl-Qz (Hoisch, 1990) and Grt-Ms-Bt-

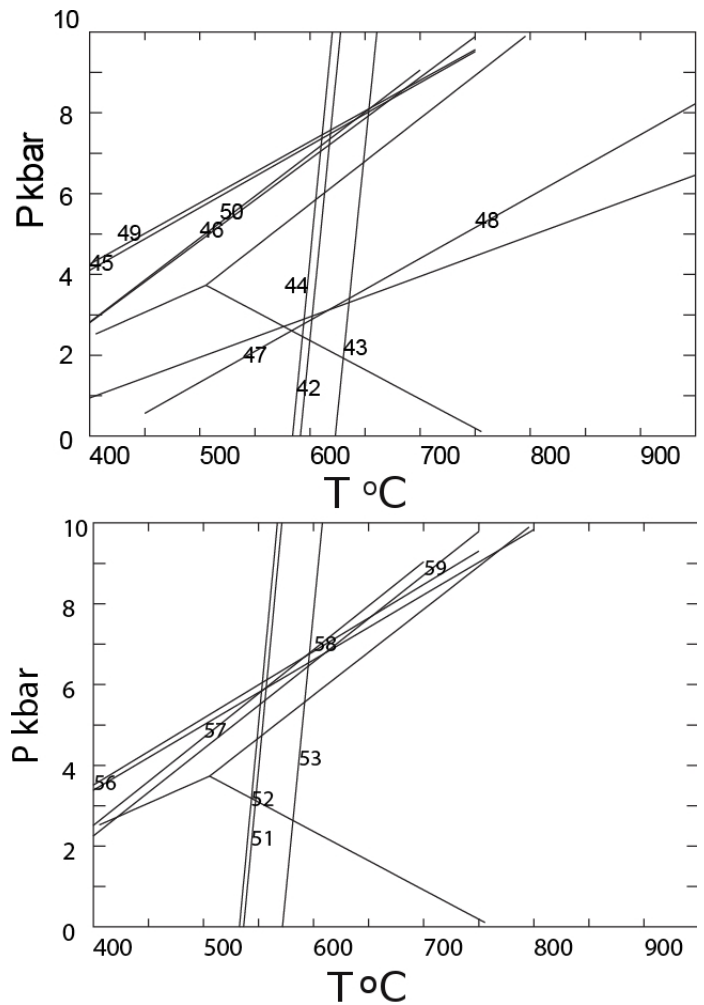


Figure 5. P/T conditions of sample 10-KD-9B (top) and 10-KD-27C (bottom). Three Bi-Grt pairs are plotted for each sample. Each temperature line correlates to two pressure lines, one for the Fe end member and one for the Mg endmember. The lines are correlated as follows For sample 9B: 42, 45, & 46; 43, 47 & 48; and 44, 49 & 50. For sample 27C: 51, 56, & 57; 52, 58, & 59. The pressures correlating to line 53 plotted higher than the top of the graph.

Pl (Hoisch, 1990) reactions (Fig. 5). Both Fe and Mg end members were used to plot the Hoisch calibrations.

Although the lack of garnet in sample 10-KD-9E means no pressure and temperature data can be obtained from these rocks, the aluminosilicates present help to confirm the pressure and temperature analyses for other samples. The presence of sillimanite and

kyanite means that the suite must have reached pressures and temperatures high enough for those minerals to form. When plotted, the data from sample 27C falls in the kyanite field. For sample 9B, two plots fall in the kyanite field and one in the sillimanite field. Sillimanite is found replacing kyanite throughout sample 9E, indicating that the protolith entered P/T conditions suitable for kyanite growth before decreasing in pressure and/or temperature to allow sillimanite growth.

The metasedimentary rocks commonly occur near the dolomite marble studied by Lerner (2011), and appear to have formed under similar P/T conditions. The Henry's Lake village suite, by far the highest grade metasedimentary suite in the area, occurs next to a suite of high grade, tremolite bearing marble. Temperatures of metamorphism were calculated from samples in the mica schist and marble from this area, and results were very similar.

CONCLUSIONS

The Henry's Lake village and Schoolhouse Canyon samples have similar mineral assemblages, and likely had similar protoliths, although they have been metamorphosed to different grades. The Divide Creek Road suite has a different mineral assemblage and is derived from a different protolith, but may have been metamorphosed at the same time and under similar conditions as the rocks from the Henry's Lake village and Schoolhouse Canyon suites.

The Henry's Lake village rocks include signs of progressive metamorphism. The oldest visible phase is a fine grained foliation preserved as inclusions in garnets. The large garnets, evidence of a second phase, are wrapped by a new foliation of biotite, quartz, and plagioclase. This last phase, growth of a new fabric around the garnet porphyroblasts, may be able to be dated using monazites found in the matrix biotite.

At Schoolhouse Canyon, the matrix is overgrown by euhedral garnets, in clear contrast to the subhedral, matrix wrapped garnets found in the Henry's Lake village samples. This indicates that the Henry's Lake Mountain rocks experienced a phase of metamorphism that the Schoolhouse Canyon rocks did not.

The chlorite rich rocks, particularly those from Deer Mountain, add an interesting dimension to the puzzle. Although they have been almost entirely retrograded to chlorite, the remnant fabrics and shapes of remnant grains suggest that they may have previously had a mineral assemblage very similar to that found in Schoolhouse Canyon and the Henry's Lake Village.

Looking further into the correlation between the biotite schists and the amphibole/chlorite schists as well as dating the metamorphism of the biotite schists using monazites found in the Henry's Lake Mountains and Schoolhouse Canyon is a necessary step in determining the history of these rocks. In the completion of this project, these two goals are the next step.

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