2012-2013 PROJECTS

TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE: SHUMAGIN ISLANDS AND KENAI PENINSULA, ALASKA
Faculty: JOHN GARVER, Union College, CAMERON DAVIDSON, Carleton College
Students: MICHAEL DELUCA, Union College, NICOLAS ROBERTS, Carleton College, ROSE PETTIETTE, Washington & Lee University, ALEXANDER SHORT, University of Minnesota-Morris, CARLY ROE, Lawrence University.

LAVAS AND INTERBEDS OF THE POWDER RIVER VOLCANIC FIELD, NORTHEASTERN OREGON
Faculty: NICHOLAS BADER & KIRSTEN NICOLAYSEN, Whitman College.
Students: REBECCA RODD, University of California-Davis, RICARDO LOPEZ-MALDONADO, University of Idaho, JOHNNY RAY HINOJOSA, Williams College, ANNA MUDD, The College of Wooster, LUKE FERGUSON, Pomona College, MICHAEL BAEZ, California State University-Fullerton.

BIOGEOCHEMICAL CARBON CYCLING IN FLUVIAL SYSTEMS FROM BIVALVE SHELL GEOCHEMISTRY - USING THE MODERN TO UNDERSTAND THE PAST
Faculty: DAVID GILLIKIN, Union College, DAVID GOODWIN, Denison University.
Students: ROXANNE BANKER, Denison University, MAX DAVIDSON, Union College, GARY LINKEVICH, Vassar College, HANNAH SMITH, Rensselaer Polytechnic Institute, NICOLLETTE BUCKLE, Oberlin College, SCOTT EVANS, State University of New York-Geneseo.

METASOMATISM AND THE TECTONICS OF SANTA CATALINA ISLAND: TESTING NEW AND OLD MODELS
Faculty: ZEB PAGE, Oberlin College, EMILY WALSH, Cornell College.

GEOLOGY, PALEOECOLOGY AND PALEOClimATE OF THE PALEOGENE CHICKALOON FORMATION, MATANUSKA VALLEY, ALASKA
Faculty: CHRIS WILLIAMS, Franklin & Marshall College, DAVID SUNDERLIN, Lafayette College.
CRETACEOUS TO MIOCENE EVOLUTION OF THE NORTHERN SNAKE RANGE METAMORPHIC CORE COMPLEX: ASSESSING THE SLIP HISTORY OF THE SNAKE RANGE DECOLLEMENT AND SPATIAL VARIATIONS IN THE TIMING OF FOOTWALL DEFORMATION, METAMORPHISM, AND EXHUMATION
Faculty: MARTIN WONG, Colgate University, PHIL GANS, University of California-Santa Barbara.
Students: EVAN MONROE, University of California-Santa Barbara, CASEY PORTELA, Colgate University, JOSEPH WILCH, The College of Wooster, JORY LERBACK, Franklin & Marshall College, WILLIAM BENDER, Whitman College, JORDAN ELMIGER, Virginia Polytechnic Institute and State University, MICHAEL KENNEY, University of California-Santa Barbara.

THE ROLE OF GROUNDWATER IN THE FLOODING HISTORY OF CLEAR LAKE, WISCONSIN
Faculty: SUSAN SWANSON, Beloit College, JUSTIN DODD, Northern Illinois University.
Students: NICHOLAS ICKS, Northern Illinois University, GRACE GRAHAM, Beloit College, NOA KARR, Mt. Holyoke College, CAROLINE LABRIOLA, Colgate University, BARRY CHEW, California State University-San Bernardino, LEIGH HONOROF, Mt. Holyoke College.

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Students: CLAUDIA CORONA, Williams College, HANNAH MONDRACH, University of Connecticut, ANNETTE PATTON, Whitman College, BENJAMIN PURINTON, Wesleyan University, TIMOTHY BOATENG, Amherst College, CHRISTOPHER HALCSIK, Beloit College.

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Faculty: MARTIN WONG, Colgate University, PHIL GANS, University of California-Santa Barbara.

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Research Advisor: Martin Wong

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METAMORPHIC CORE COMPLEX EVOLUTION: VERTICAL STRAIN GRADIENT IN THE NORTHERN SNAKE RANGE DECOLLEMONT
JORY LERBACK, Franklin & Marshall College
Research Advisor: Zeshan Ismat, Martin Wong, Phillip Gans

GEOCHEMISTRY AND GENESIS OF JURASSIC GRANITOIDS FROM THE NORTHERN SNAKE RANGE, NV
WILL BENDER, Whitman College
Research Advisor: Kirsten Nicolaysen

INTRUSIVE AND DEFORMATIONAL HISTORIES OF THE FOOTWALL ROCKS IN THE CENTRAL PART OF THE NORTHERN SNAKE RANGE, NEVADA
MICHAEL KENNEY, University of California—Santa Barbara
Research Advisor: Phil Gans
METAMORPHIC CORE COMPLEX EVOLUTION: VERTICAL STRAIN GRADIENT IN THE NORTHERN SNAKE RANGE DECOLLEMONT

JORY LERBACK, Franklin & Marshall College
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INTRODUCTION

The Basin-and-Range province, western United States, extends, west to east, from central Utah to eastern California and, north to south, from the southern border of Canada to Northern Mexico. The Basin-and-Range province is characterized by horizontal extension of the crust. Extension began ~30 my ago, with peak periods of extension taking place 23 mya, and still continues today (Cooper et. al. 2010). There is a steep geothermal gradient in the Basin-and-Range due to crustal thinning. The crustal thinning and extension is accommodated by normal faults.

Although normal faults typically form with steep (~60°) dips, those exposed in the Basin-and-Range preserve a wide range of dips. Some of the gently dipping faults were originally steeply dipping, but have been cross-cut and progressively rotated by younger normal faults (i.e., Proffett's rule). Some expose the gently dipping listric portion of deep normal faults. Metamorphic core complexes preserve some of the most gently dipping normal faults, portions of some that dip <5°. The reason for these gentle dips may be varied and continues to be intensely debated. Here, I focus on the Northern Snake Range metamorphic core complex (east-central NV).

Metamorphic core complexes are not only characterized by extremely gently dipping normal faults, but also by their extreme extension (e.g. 30-50 km [Gans, 198]). Because of this extension, high-grade mylonitic footwall rocks are brought into contact with cataclastic hanging wall rocks.

This study focuses on the vertical strain gradient preserved in the mylonitic footwall of the Northern Snake Range metamorphic core complex. The footwall is composed of late Pre-Cambrian to Cambrian metasediments and quartzite mylonites. Here, I have examined the quartzites close to the Northern Snake Range decollement (NSRD). Previous workers have recognized vertical strain gradients in these quartzites (Cooper et. al. 2010), however, the details and significance of this strain gradient have, up to now, not been clearly defined. Moreover, the fracturing in the footwall may have occurred concurrently or after shearing along the NSRD. Detailed analysis of the cross-cutting relationships preserved within the footwall may help clarify this.

I have conducted detailed microstructural and EBSD analyses along several vertical transects throughout the quartzites in the footwall to more clearly document the variation in deformation close to the NSRD. In more detail, the objectives of this paper are two-fold:

(1) More clearly understand the role of the footwall shear zone directly below the NSRD.

(2) Determine if fractures are present in the footwall quartzites, and if so, what is their relationship to the plastic deformation.

I will attempt to estimate kinematics and temperatures of deformation by quantifying this observed gradient examining chemical and structural queues. This strain gradient may indicate a change in Miocene strain caused from the decollement, or an overprinting of ductile Miocene deformation on top of even older deformation structures.
DATA COLLECTION

Forty-two sites were studied along Hendry’s Creek, Snake Range, NV. The sites were distributed along 6 vertical transects throughout the footwall of the Snake Range metamorphic core complex (Fig. 1). The transects extend from west to east. Oriented hand samples were collected at each site. The samples extend from the pCm (Prospect Mountain Quartzite) unit, close to the Snake Range decollement, to the pCm-5 unit, deeper into the footwall (Fig. 2). These units are quartzite mylonites, with some feldspar, micas and iron-oxide deposits.

At each site, GPS coordinates were recorded, bedding was measured, as well as other structural features, such as faults, quartz veins and folds. Morphological descriptions were also made at each site.

Hand samples were cut and polished along the z plane, the plane of lengthening, for microscopic analysis. The detailed microstructural analysis conducted along transects A, B and C are focused on here (Fig. 2). Thin sections were analyzed using a petrographic microscope and Image Pro Plus, an image analysis software program (Figs. 3 A, B). Grain shape, fractures, iron-oxide and feldspar grains were quantified using a...
point counter, along a horizontal and vertical transect near the center of each thin-section (Fig. 3B). Strain was not measured because the rocks are mylonites and so the values may be unreliable, depending upon how many stages of recovery and recrystallization the rocks have undergone.

Samples from each transect were also analyzed with an SEM-EBSD (electron backscatter diffraction detector) attachment. The entire thin section within sight of the SEM with a 100 nanometer step was analyzed. Using HLK/Channel 5 software, crystal orientations were mapped and contoured (Fig. 5).

RESULTS

Shear sense indicators, such as foliated quartz grains, mica fish and feldspar tails, in all of the thin sections studied, show top-to-the-east sense of shear. The EBSD data also clearly shows top-to-the-east sense of shear. Both are consistent with several previously published papers (e.g. Miller et. al., 1983., Wernicke, 1981). The details of the deformation observed under a petrographic microscope and SEM are described in more detail below.
The quartzite foliation progressively flattens out (i.e. closer to 90 degrees) toward the decollement. Transects A and C reveal a more dramatic steepening of foliation with depth, while transect B is more subdued.

Both the mean grain sizes increased with depth (Fig. 4A). Transects A and C showed high positive slopes, indicating an increase in size with depth, while transect B showed a smaller slope for the mean size. pCm-3 generally showed the sharpest increase in size. From West to East, mean grain sizes decreased for top and bottom units, while the middle units increased.

The average aspect ratio of the best-fit ellipses decreases (i.e., more circular) away from the NSRD (Fig. 5D), with a notable decrease at pCm-3 (Fig. 4B).

The ratio of equant quartz grains to ribbon quartz grains increases with depth. In other words, there is a higher proportion of ribbon quartz close to the NSRD. There is a notable drop in ribbon quartz at pCm-3.

Feldspar is present in two units closest to the NSRD. A very small amount is also preserved in pCm-3. There tends to be more mica (lineations and ‘clumps’) in units that have less/no feldspar.

Iron-oxide precipitates are most abundant at in the units closest to the NSRD, with the highest percentage in pCm-1. Each instance was subeuhedral in shape.

Steep fractures are preserved in pCm-1, -2, and -3 and overprint the plastic deformation. There is a general decrease in the number of fractures away from the NSRD, with a peak in pCm-3.

The EBS transect data shows a general trend of the C-axis of each contoured pole map tipping top-east and bottom west, with the A- and B- crystal faces in equidistant locations. Pole plots and contour maps showed similar data, agreeing with the top-east shear. Closer to the NSRD, the variance from horizontal/the degree of tilt increases, especially in transect C (Fig. 5).

In summary, (1) The quartz grain foliation progressively flattens out towards the NSRD, ranging from ~80° in the pCm-5 to ~90° in the pCm. (2) Average grain size increases with depth. (3) Ribbon and small quartz grains were generally in horizontal bands, i.e. parallel to the sense of shear. The amount of quartz ribbon dramatically increased in the units closest to the decollement (pCm and pCm-1). (3) Small, relatively equidimensional quartz grains formed tails on feldspar augens, preserving top to the east shear. (4) Feldspar is concentrated in the two units closest to the decollement. pCm-3 preserves a small amount of feldspar. Moreover, the amount of mica progressively increases in the units further from the decollement (pCm-3 and -5) in the form of well-defined laminations, oriented parallel to the sense of shear, or randomly oriented clumps clustered near equidimensional quartz grains. (5) There is a peak in grain size and fractures in pCm3 (Fig. 5 B,E).

**DISCUSSION AND INTERPRETATION**

There is a progressive decrease in feldspar and increase in mica from the units close to the decollement to the lower units. This suggests that the protolith sandstones of the quartzite beds were different in composition, or that the feldspar was chemically altered to mica and quartz at deeper levels. Close to the decollement (pCm), the feldspar porphyroblasts form tails of small, equidimensional quartzite grains. This also suggests some high temperature deformation and chemical alteration of the feldspar grains.

In the units closest to the decollement, the quartz grains are stretched into ribbon quartz grains, with axial ratios up to ~7. This suggests that the top to the east shear was active during recovery and recrystallization.

pCm-3 is a distinguished unit, not only because there seemed to be a change in grain size, aspect ratio, and composition, but there here is a high concentration of steep fractures. These fractures overprint the mylonite deformation and are likely associated with normal faulting in the hanging wall. The large size, the relatively equant shape and the presence of feldspar in the pCm-3 may explain this high concentration of steep fractures. Smaller grains tend to retard fracture growth -- grains boundaries are difficult to break. Therefore, fractures may reach a ‘critical length’ to form propagating ‘runaway fractures’ (Paterson, 1976; Sibson, 1977). Moreover, the feldspar grains are
relatively large in this unit and fracture under higher temperatures than quartz, further increasing the potential for fracture growth.

The quartz grains become progressively larger and more equidimensional (i.e. lower aspect ratio) away from the NSRD.

The foliation progressively increased towards ~90° closer to the NSRD. In addition, the aspect ratio of the quartz grains increased upsection. Both features indicates increased shear towards the NSRD. The top units, pCm, pCm-1 and pCm-2, may be categorized as a zone of high shear strain currently ~200m thick, compared to the units below, which show lower shear strain (pCm-3-5).

The EBSD data also suggests increasing shear strain towards the NSRD. And that temperatures were at least 300° C, in order to plastically deform quartz. Feldspar is not plastically deformed, which suggest that temperatures did not reach 450° C.

A possible cause for the uplift and extension found in the NSRD may have been because normal faults were forming in the hanging wall of the then steeply dipping decollement (Miller et. al. 1983). These faults formed during ductile deformation and at depths as shallow as 8km (because of a high geothermal gradient [Lewis et. al., 1999]), the younger faults (~60° [Passchier and Trouw 1996]) rotated the decollement into the current or near current faulting angle of 1-10° (Miller et al. 1983). The hanging wall would have risen, losing pressure and temperature, near the end of the mylonitic formation, which would have allowed the younger set of normal faults to pass through some of the still cooling section and are manifested as steep fractures in pCm and pCm-3.

However, to conservatively and simply interpret the data collected in this study: there is higher shear strain at top, and a high pressure/temperature regime downsection.

Future studies may find more samples within transects and compare transect data from valleys both north and south of Hendry’s Creek. Samples may be analyzed with further detail, especially to use selected representative thin sections to analyses under the EBSD using a higher step and smaller matrix size to observe the microstructures in finer detail for a more detailed and accurate quantification of strain markers.

REFERENCES


