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

April 2013
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Keck Geology Consortium: Projects 2012-2013
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JORY LERBACK, Franklin & Marshall College
Research Advisor: Zeshan Ismat, Martin Wong, Phillip Gans

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 PreCambrain to Cambrain metasediments and quartzite mylonites. Here, I have examined the quartzites close to the Northern Snake Range decollemont (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 decollemont, 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 decollemont, to the pCm-5 unit, deeper into the footwall (Fig. 2). These units are quartzite mylonites, with some feldspar, micas and iron-oxide deposits.

Figure 1 Location map showing location of samples, represented by sample numbers within the Cove Quadrangle in the Snake Range Mountains of Eastern Nevada (USGS 7.5 minute Quad). Samples shown here are along the North Side of Hendry's Creek.

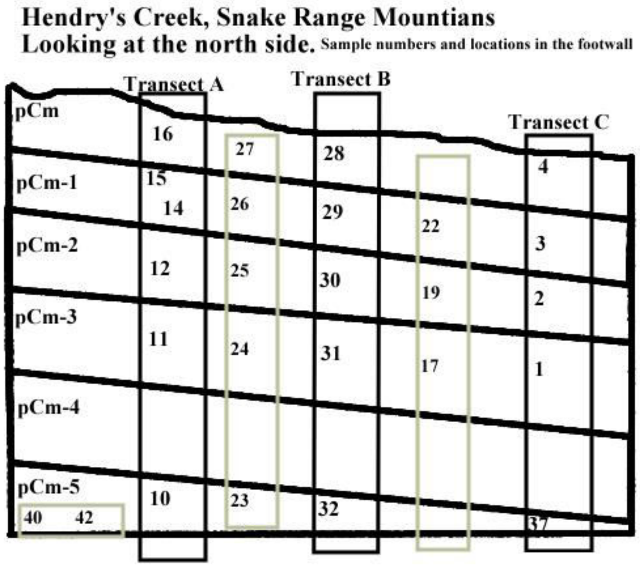

Figure 2 Diagram of the north side of Hendry's Creek showing representative vertical location of each sample. Transect numbers are correlated with groups of samples, and transect representative letters are shown as well as the representative numbers.

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

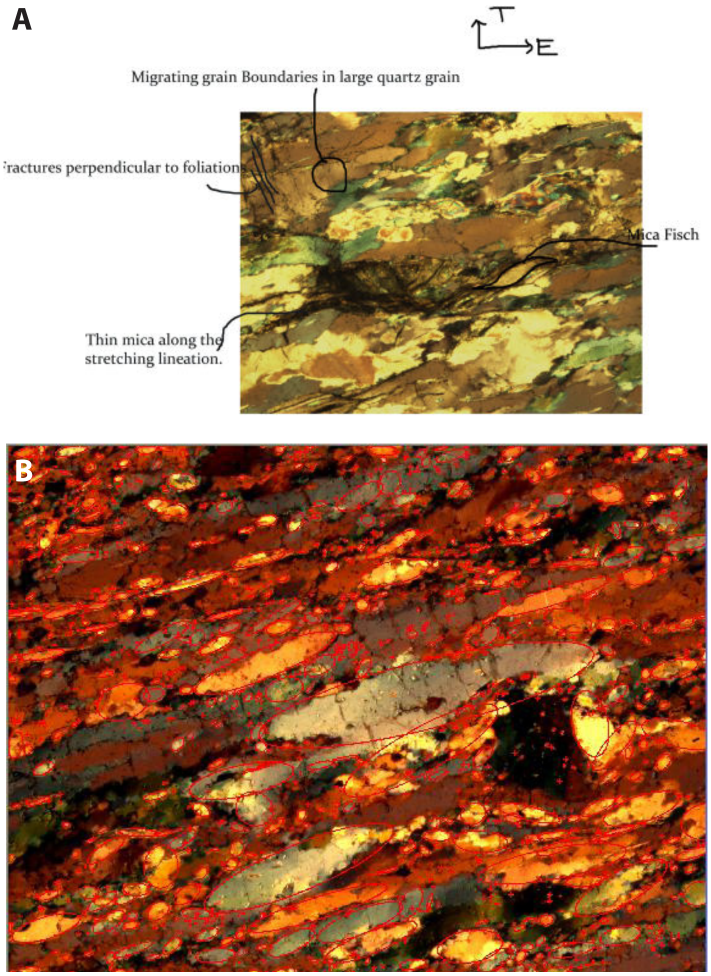

Figure 3 Digital petrophtographs showing data collection techniques using a 4x objective to make direct comparisons. A) Example petrophotograph of sample 40 (p€m-5) explanations of qualitative phenomena(not easily quantified). B)S ample 14 shows the height and width of transects for iron and feldspar quantification, overprinted with best fit strain ellipses from which angle, aspect ratio and grain sizes were approximated.

Only grains with an aspect ratio close to 1 and ribbon quartz were counted with the point counter. Quantitative analyses of best-fit strain ellipses were all conducted using 4x objective on the microscope, in order to make direct comparisons between sites.

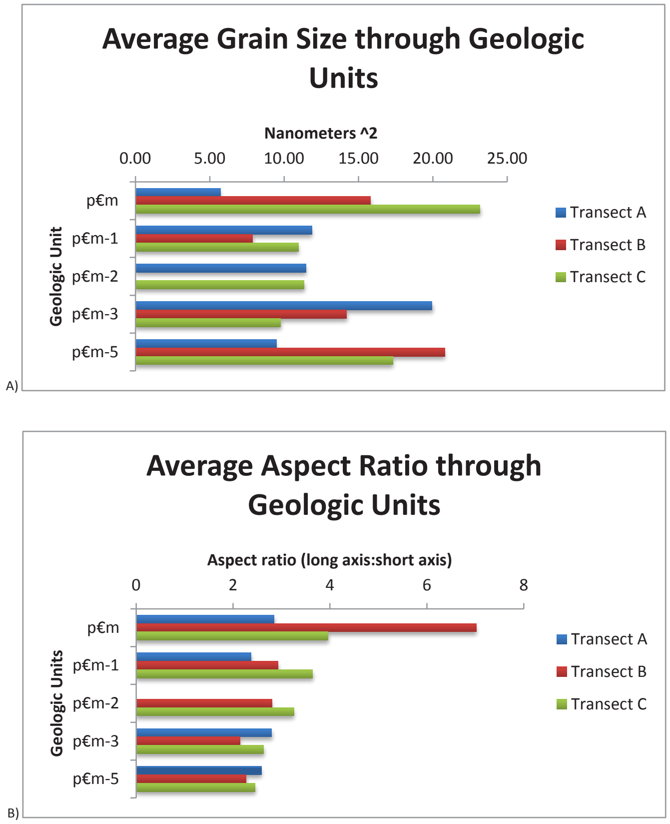

Figure 4 Graphical representations of collected data for transects A, B, and C using strain ellipse data. A) Average grain siz . B) Average aspect ratio (ellipticity).

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.

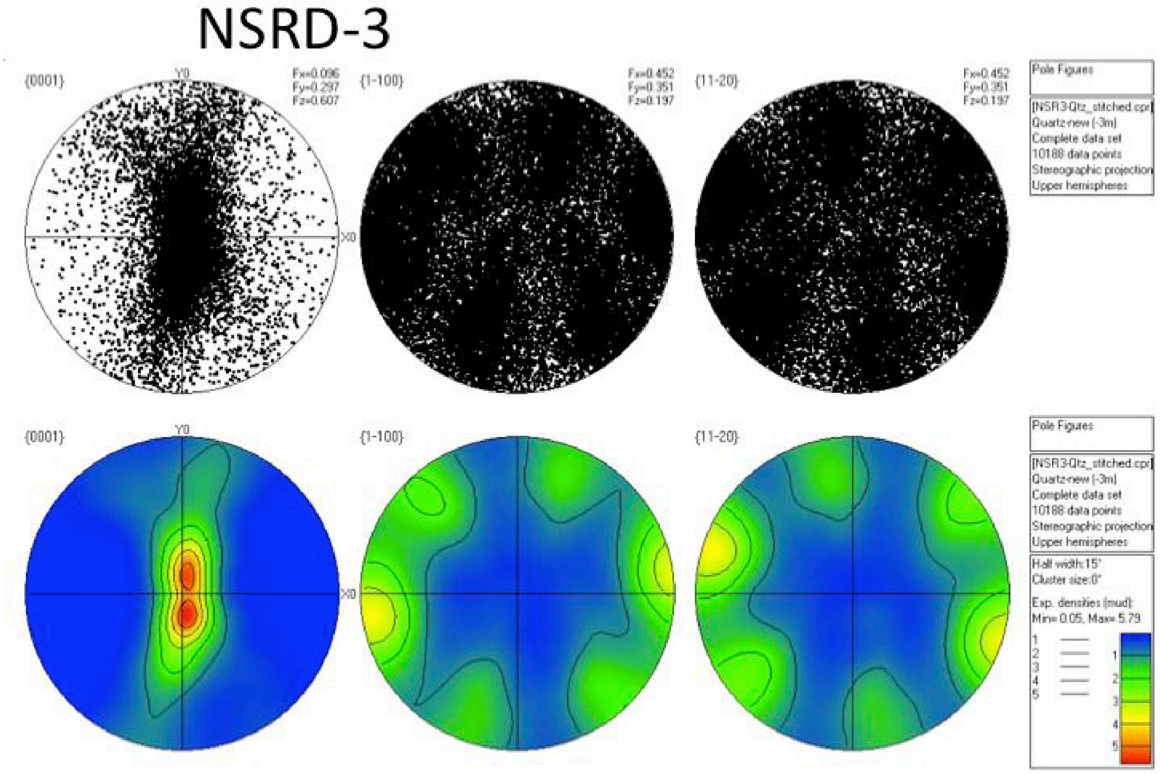

Figure 5 Representative pole plot and contour display from pCm-1, showing the orientation of quartz crystal faces from C-, A- and B- orientations.

The quartzite *foliation* progressively flattens out (i.e. closer to 90 degrees) toward the decollemont. 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 decollemont (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 decollemont. pCm-3 preserves a small amount of feldspar. Moreover, the amount of mica progressively increases in the units further from the decollemont (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 ploastically 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 decollemont (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 decollemont 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.

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