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STRAIN PATH AND THERMAL HISTORY OF QUARTZITE IN THE DEEP CRUST OF ANDEAN-STYLE OROGENIC PLATEAUS: A CASE STUDY FROM THE WOOD HILLS, NV

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INTRODUCTION

Orogenic plateaus are a significant tectonic feature on Earth, with modern examples including the Tibetan plateau and the Andean Altiplano (Vanderhaeghe et al., 2002). Slow, large-scale surficial motion of these plateaus has been recorded, but the nature of the deformation in the interior of these plateaus is difficult to document and is therefore not well understood (Vanderhaeghe et al., 2002; Bai et al., 2010). Recent geodynamic models of the Western United States suggest that contractional deformation and crustal thickening of the Sevier orogenic belt led to the formation of a high elevation plateau in the hinterland of the orogen during the Late Cretaceous (Fig. 1) (Decelles, 2004; Snell et al., 2014; Long et al., 2015). This plateau–which is no longer preserved–has been termed the "Nevadaplano" due to its assumed similarity to the present-day Andean Altiplano plateau (Long et al., 2015). Cenozoic extension dissected this plateau and exposed its deep crust, providing an opportunity to directly examine rocks deformed in the interior of a continental plateau.

The Ruby Mountain-East Humboldt Range (RM-EHR) metamorphic core complex of northeastern Nevada is an exhumed portion of the lower crustal channel of the Nevadaplano (Fig. 1) (Long et al., 2015). This study utilizes analysis of quartz fabric, microstructure, and crystallographic preferred orientation (CPO) in order to investigate the deformational history of the Wood Hills, a mountain range in the RM-EHR metamorphic core complex, as a means to better understand deep crustal deformation of orogenic plateaus.

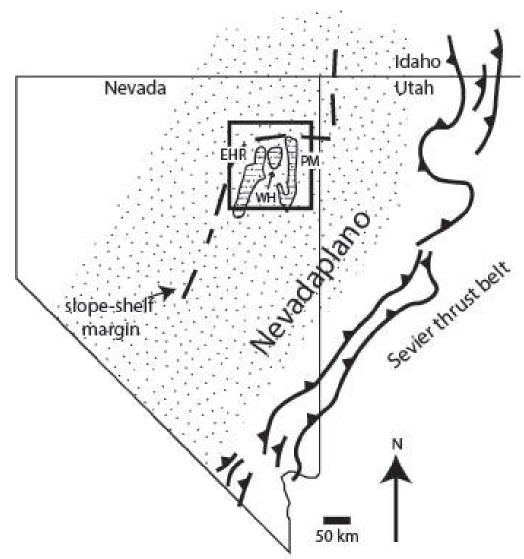

Figure 1. Tectonic map of northeastern Nevada. The stippled region is the hinterland of the Sevier thrust belt that makes up the orogenic plateau of the "Nevadaplano." EHR = East Humboldt Range, WH = Wood Hills, PM = Pequop Mountains. Adapted from Camilleri (1998).

METHODS

Field

I collected 22 oriented samples of Eureka Quartzite during July of 2015 in the Wood Hills of northeastern Nevada. The Eureka Quartzite is a clean quartzite, making it ideal target for microstructural and CPO analysis. Furthermore, it crops out at a variety of locations throughout the Wood Hills, so it can be used to document regional changes in metamorphic grade and structural level in the study area: ten samples that we collected are from the northern Wood Hills, nine are from central Wood Hills, and

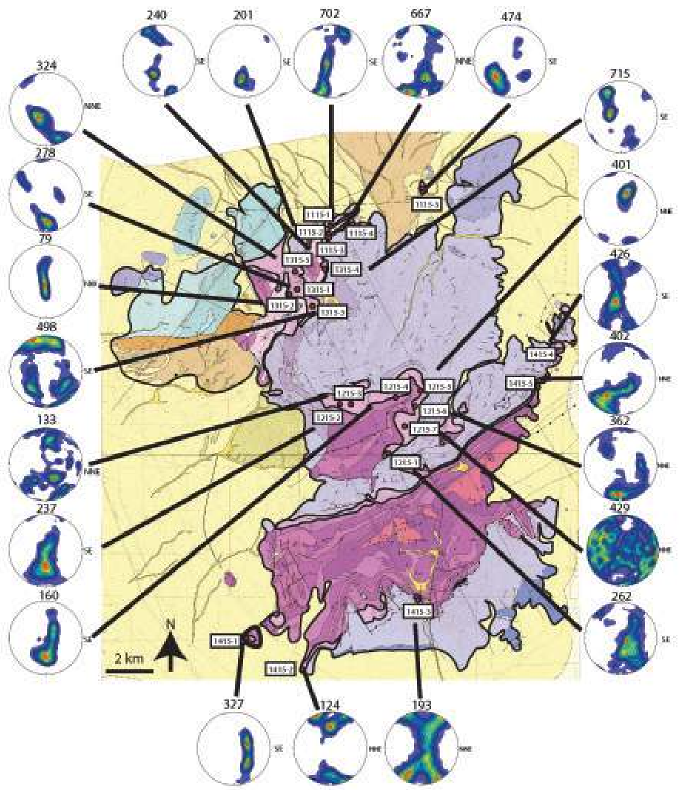

Figure 2. Geologic map of the Wood Hills. The Eureka quartzite is the light pink unit outlined in black, and it is also a metamorphic unit in the footwall of the Windermere thrust. It crops out in southern, central, and northern Wood Hills, where we collected three samples, nine samples, and ten samples respectively. Samples are marked by red dots, with sample numbers in white boxes. C-axis fabrics of all samples collected in the Wood Hills are on the outside of the map. Numbers above pole figures tell average grain size of the sample in microns. The geologic map was adapted from Camilleri (2010).

three are from the south (Fig. 2). Outcrops were highly fractured, especially near the extensional shear zone in the northwestern Wood Hills, making confident identification of foliation planes difficult, particularly given the generally uniform lithology. There were often multiple apparent lineations, making it difficult to record lineation with confidence. At several outcrops, multiple potential foliations and lineations were documented in case data rotations were necessary during analysis of quartz fabric data. Sample sites were selected based on a geologic map of the Wood Hills created by Camilleri (2010), and were collected with the aim of creating a sample suite with rocks from as many regions of the Wood Hills as possible in order to classify changes with structural level and metamorphic grade.

Electron Backscatter Diffraction (EBSD) and Data Processing

The samples were analyzed on a Zeiss EVO MA 15, Scanning Electron Microscope (SEM) at Washington and Lee University using an Oxford Instruments EBSD detector and Aztec software. Operating conditions were an accelerating voltage of 25 kV, a probe current of 20 nA, and a working distance between 25-30 mm. The SEM was operated in low-vacuum mode at a pressure of 20-30 Pa. Step size ranges from 4-60 microns, depending on grain size of the sample. The EBSD data were processed and analyzed using the MTEX toolbox for Matlab (Hielscher and Schaeben, 2008). Pole figures, average grain size, and grain maps were created in MTEX using code created by Jeffrey Rahl (personal collaboration).

Thermometry

The opening-angle of a quartz CPO fabric is the angle between the two crossed girdles; this angle changes as a function of temperature (Kruhl, 1998). Quartz c-axis fabric opening-angle thermometry is an empirically derived thermometer that provides quantitative temperature estimates for when quartz fabrics were locked in during deformation (Kruhl, 1998). Quartz is believed to work as a thermometer due to temperature-based changes in the relative abundance of activity of different slip systems of quartz (Passchier and Trouw, 1996). Quartz c-axis opening-angles increase as deformation temperature increases in a linear fashion, so deformation temperature can be calculated from quartz c-axis fabric opening-angles with an uncertainty of ±50°C (Law, 2014). The quartz opening-angle thermometer has been calibrated for quartzites deformed under approximate plane strain conditions exhibiting single-girdle pole figure patterns (Law, 2014). I therefore measured the opening angles of all appropriate samples, and used the line of best fit for the relationship between opening angle and temperature created by the studies of Kruhl (1998) and Morgan and Law (2004) to estimate deformation temperatures in the Wood Hills.

RESULTS

Classification

Samples show a range of microstructure and quartz fabric that tend to vary in regional patterns; all data are plotted in Figure 2. Based on microstructural analysis and CPO data, most of the samples can be categorized into three groups. These groups were created based on average grain size, dominant strain type, and commonalities of microstructural features.

Group 1

Group 1 samples (1415-3 and 1415-2) are located in the southernmost Wood Hills. These samples are characterized by a fine grain size, averaging at ~150 microns. Type-I crossed girdle c-axis fabrics suggest that coaxial plane strain dominates and a-axis fabrics confirm that there is also a component of flattening strain, especially in 1415-3.

In thin section, quartz crystals are slightly elongate but reminiscent of original grain shape. Microstructure is indicative of relatively low-temperature deformation.

Group 2

Group 2 samples (1115-1, 1115-4, 1215-1, 1215-2, 1215-4, 1215-5, 1215-5, 1415-5) are located in central to northern regions of the Wood Hills. Average grain size ranges from ~200 - 700 microns, increasing to the north. CPO fabrics range from asymmetric crossed girdles to single girdles with top-SE asymmetry, suggesting plane strain with a high component of top-SE simple shear. Regional CPO trends suggest increasing component of simple shear to the north based on an increasing asymmetry of c-axis fabrics (Fig. 2).

The dominant recrystallization mechanism changes from central to southern Wood Hills. There is a combination of grain boundary migration and subgrain rotation in samples from central Wood Hills, but there is predominantly grain boundary migration in samples from northern Wood Hills (Fig. 3).

Group 3

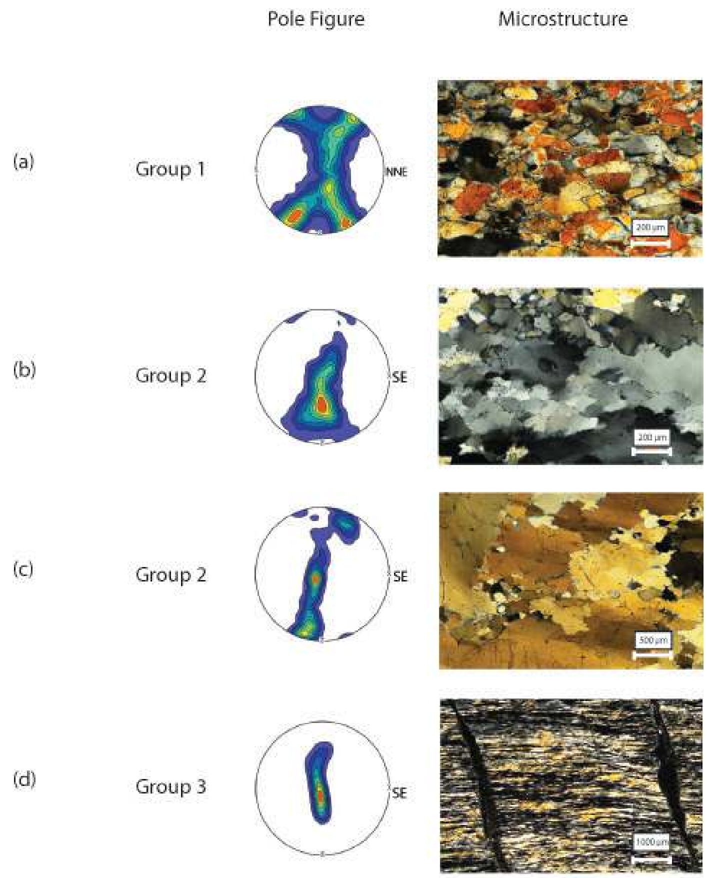

Figure 3. Representative pole figures and photomicrographs (XPL) of samples in each group. (a) shows the symmetric crossed girdle and low-temperature deformation microstructure representative of Group 1; (b) shows asymmetric crossed girdle and subgrain rotation/grain boundary migration microstructure representative of centrally located samples in Group 2; (c) shows the asymmetric single girldes, large grain size, and grain boundary migration representative of Group 2 samples collected in the northern Wood Hills; (d) shows single Y-maxima and mylonitic fabric representative of Group 3 samples.

Group 3 samples (1115-2, 1115-3, 1115-5, 1315-1, 1315-2, 1315-5) are clustered in the northwestern corner of the Wood Hills. These samples are characterized by an average grain size of ~200 microns. This is a clear reduction in average grain size from the other samples in the northern Wood Hills, whose average grain sizes range from ~475 - 700 microns. Group 3 samples are also distinct from other samples in the northern Wood Hills in their CPO fabrics: they exhibit elongated Y-maxima fabrics indicating dominant prism <a> slip ± rhomb <a> slip. This type of fabric indicates non-coaxial plane strain with a combination of pure and simple shear under medium to high-grade conditions.

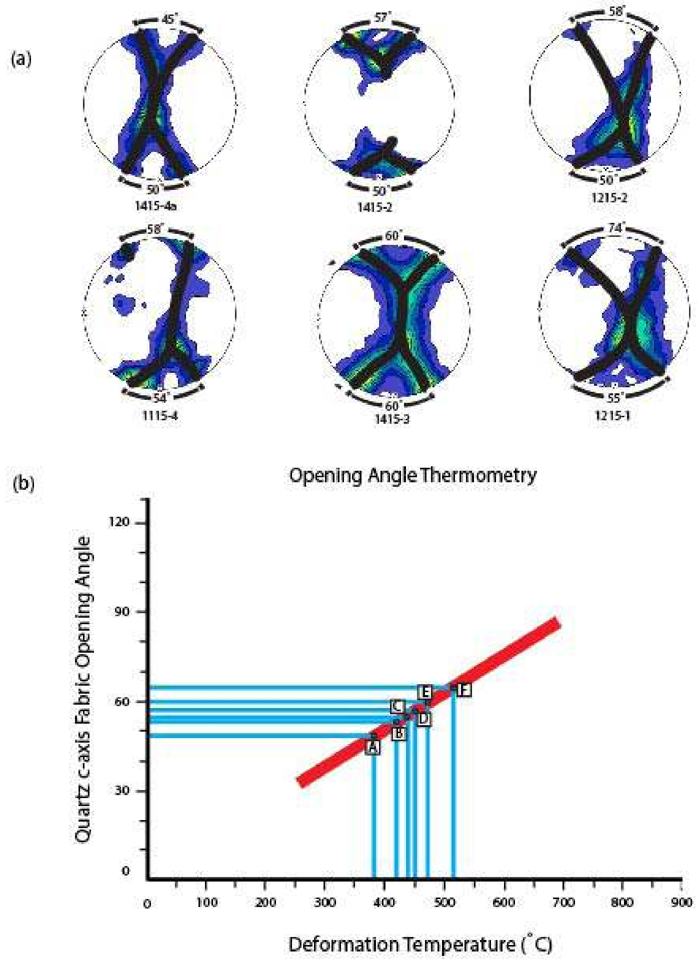

Figure 4. (a) Opening angles of all samples with clear crossed girdles. The averages of the two measurements were used to calculate temperature of deformation. (b)Calculated deformation temperatures of samples 1415-4a (A), 1415-2 (B), 1215-2 (C), 1115-4 (D), 1415-3 (E), and 1215-1 (F) using line of best fit for the relationship between deformation temperature and opening angle created by Morgan and Law (2004).

In thin section, most of these samples appear mylonitic (Fig. 3). Boundaries between large parent grains are interlobate due to grain boundary migration, but the dominant mechanism of recrystallization is subgrain rotation. These two modes of recrystallization indicate deformation under medium to high temperatures (Trouw et al., 2010). Samples of smaller average grain size exhibit a higher degree of mylonitization. In the most highly mylonitized samples (1115-3, 1315-2, for example), shear sense in both CPO asymmetry and in the microstructure is top-NW.

Thermometry

Quartz opening-angle thermometry places the Eureka quartzite in the amphibolite facies, with calculated temperatures ranging from 380°C - 515°C (Fig. 4). This is consistent with the microstructure of these samples, which exhibit medium- to high-temperature deformation styles of subgrain rotation and grain boundary migration. There does not seem to be a strong regional trend related to temperature based on this method of thermometry; temperatures remain fairly consistent from the south to the north of the Wood Hills based on this method of thermometry. In contrast, variations in recrystallization style exhibit a smooth transition from low- to medium-temperature recrystallization mechanisms in southern Wood Hills to high-temperature recrystallization mechanisms in the northern Wood Hills.

DISCUSSION

Regional Trends

Increasing grain size and change in dynamic recrystallization regime from southern to northern Wood Hills from Group 1 to Group 2 suggest increasing metamorphic grade and deepening structural level to the north. Opening-angle thermometry infers temperatures in the Wood Hills as generally in amphibolite facies, which is consistent with the findings of Camilleri and Chamberlain (1997). Coaxial deformation is dominant in the southern Wood Hills, but this gives way to non-coaxial plane strain with increasing components of simple shear to the north. This is inconsistent with the findings of Camilleri (1998), which documented coaxial strain throughout the Wood Hills.

Based on the reduced grain size and drastically different CPO fabrics of Group 3 rocks from other Group 1 rocks in the same region, I propose that these deformation fabrics resulted from the Tertiary episode of extension that resulted in overprint of original Mesozoic fabrics in the northwestern Wood Hills. Furthermore, in thin section, Group 3 samples appear mylonitic, and certain samples (1115-3, 1315-2) exhibit the top-NW asymmetry observed in the mylonitic shear zone of the East Humboldt Range: this consistent with the idea that they represent the younger period of extension and overprint. Elongated Y-maxima fabrics indicate dominant prism <a> slip ± rhomb <a> slip and plane strain with a component of simple shear under medium-to high-grade conditions.

Tectonic Interpretation

The Wood Hills were centrally located in the deep crust of the Nevadaplano, a high elevation plateau in the Sevier hinterland (Fig. 1) (Camilleri and Chamberlain, 1997). Contraction was primarily accommodated by thrusting along two major top-SE thrust faults. Asymmetry in crossed and single girdles, primarily in Group 2 fabrics, often indicates top-SE shear, which is consistent with deformation due to the top-SE thrusting during Mesozoic contractional events. An increasing component in generally top-SE directed simple shear in plane strain at deeper structural levels suggests that these were greatly influenced by Mesozoic thrust fault structures during contraction; in contrast, samples from shallower structural levels exhibit primarily coaxial flattening strain, suggesting that they were primarily deformed by the weight of the overlying crustal wedge. The NNE-trending lineation and top-NNE fabrics are difficult to interpret with known existing structures in the region, and should therefore be investigated further. These findings are a model for the deep crustal activity of modern analogs of the Nevadaplano, such as the Altiplano region of the Andes, where structurally deeper rocks are influenced by contractional structures, whereas structurally shallower rocks are affected dominantly by the overlying load of upper crustal material.

These older, contraction-related crossed and single girdle fabrics were variably overprinted by single Y-maxima during Tertiary extension in the northwestern corner of the Wood Hills. Past studies have shown that extension and mylonitization of original fabrics resulted in top-NNW shear sense in the mylonitic zone (Camilleri, 1998). This is consistent with the asymmetry of CPO in Group 3 samples, which, when apparent, exhibit top-NW shear in both CPO asymmetry and in microstructure.

CONCLUSIONS

Change in dominant recrystallization mechanism from subgrain to grain boundary migration from the south to the north is consistent with past studies that have shown increasing metamorphic grade and deepening structural level to the north (Camilleri, 1998). However, increasing asymmetry in CPO fabrics suggest that there is an increasing component of simple shear recorded in rocks farther north, which was previously believed to be deformed by dominantly pure shear. The increasing influence of simple shear to the north may be attributed to a greater influence of Mesozoic contractional faulting at deeper structural levels.

In the northwestern-most region of the Wood Hills, original fabrics are variably overprinted by top-NW mylonitic fabrics associated with Tertiary extension. These rocks document medium- to high-grade deformation under plane strain with dominant prism <a> ± rhomb <a> slip during exhumation of the Wood Hills.

Multiple lineation sets and CPO fabrics from both Mesozoic contraction and Tertiary extension and exhumation suggest highly heterogeneous deformation. Regional changes in strain type and deformation temperatures suggest that deformation is highly localized along faults and shear zones and that deformation varies in style as a function of structural level, metamorphic grade, and proximity to fault structures in the middle to lower crust of orogenic plateaus.

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REFERENCES

Bai, D., Unsworth, M.J., Meju, M.A., Ma, X., Teng, J., Kong, X., Sun, Y., Sun, J., Wang, L., Jiang, C., Zhao, C., Xiao, P., and Liu, M., 2010: Nature Geoscience, v. 3, p. 358-362.

Camilleri, P.A., 2010, Geologic map of the Wood Hills, Elko County, Nevada: Nevada Bureau of Mines and Geology, scale 1:48,000.

Camilleri, P. A., 1998, Prograde metamorphism, strain evolution, and collapse of footwalls ofthick thrust sheets: a case study from the Mesozoic Sevier hinterland U.S.A.: Journal ofStructural Geology, v. 20, p. 1023-1042.

Camilleri, P.A., and Chamberlain, K.R., 1997, Mesozoic tectonics and metamorphism in thePequop Mountains and Wood Hills region, northeast Nevada: Implications for thearchitecture and evolution of the Sevier orogen: GSA Bulletin, v. 109, p. 74-94.

Decelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and Foreland basin system, western U.S.A.: American Journal of Science, v. 304, p. 105-168.

Hielscher, R., and Schaeben, H., 2008, A novel pole figure inversion method: specification of theMTEX algorithm: Journal of Applied Crystallography, v. 41, no. 6, p. 1024-1037.

Kruhl, J.H., 1998. Reply: prism- and basal-plane parallel subgrain boundaries in quartz: amicrostructural geothermobarometer: J. Metamorph. Geol., v. 16, p.14-146.

Law, R.D., 2014, Deformation thermometry based on quartz c-axis fabrics and recrystallizationmicrostructures: A review: Journal of Structural Geology, v. 66, p. 129-161.

Long, S.P., Thompson, S.N., Reiners, P.W., and DiFiori, R.V., 2015, Synorogenic extensionlocalized by upper-crustal thickening: An example from the Late Cretaceous Nevadaplano: Geology, v. 43, p. 351-354.

Morgan, S.S., and Law, R.D., 2004, Unusual transition in quartzite dislocation creep re-gimesand crystal slip systems in the aureole of the EJB pluton, California: a case for anhydrousconditions created by decarbonation of adjacent marbles: Tectonophysics, v. 384, p. 209-231.

Passchier, C.W., and Trouw, R.A.J., 1996, Microtectonics: Germany, Springer, 92-96 p.

Snell, K.E., Koch, P.L., Druschke, P., Foreman, B.Z., and Eiler, J.M., 2014, High elevation of the 'Nevadaplano' during the Late Cretaceous: Earth and Planetary Science Letters, v. 386, p. 52-63.

Vanderhaeghe, O., Medvedev, S., Beaumont, C., and Jamieson, R.A., 2002, Evolution of orogenic wedges and continental plateaus: Insights from thermal-mechanical models with subduction basal boundary conditions: Geophysical Journal International, v. 153, p. 27-51.