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MECHANISMS AND PATTERNS OF STRAIN RELATED TO LATE MESOZOIC TECTONIC SHORTENING ON THE INDEPENDENCE THRUST, PEQUOP MOUNTAINS, ELKO COUNTY NEVADA

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INTRODUCTION

The Pequop Mountains in northeastern Nevada offer a unique opportunity to characterize the structural and metamorphic history of the shallowest part of the East Humboldt Range-Wood Hills-Pequop Mountains (EHR-WH-PM) crustal section. Previous work in the area documents an exceptionally complete Lower Cambrian to Triassic section in the footwall of the Independence Thrust – a southward ramping fault with a modest stratigraphic throw of approximately 3 km (Fig. 1)(Camilleri, 2010). At higher structural levels a low-angle normal fault known as the Pequop Fault juxtaposes Permian against Ordovician strata and may represent the upper crustal "breakaway zone" for the EHR-WH detachment fault system (Fig. 1) (Camilleri, 2010). Camilleri and Chamberlain (1997) document a steep metamorphic field gradient increasing with depth from unmetamorphosed sedimentary strata to amphibolite facies Cambrian Prospect Mountain Quartzite at the west-central base of the range; in addition, they document a Late Cretaceous age for peak metamorphism based on a U-Pb age of 84.1 ± 0.2 Ma on metamorphic sphene. The excellent structural, stratigraphic and metamorphic constraints of the Pequop Mountains provide an ideal opportunity to investigate the effects of burial and thrusting on deformation and thermal structure at the leading edge of an orogenic wedge. This study focuses on microstructures and crystallographic preferred orientations (CPOs) with the objective of characterizing kinematics and deformation mechanisms as a function of both structural depth and proximity to the leading edge of a thrust wedge.

METHODS

Sampling Strategy

To delineate variations in deformation mechanisms and kinematics, six quartzite and two marble tectonite samples were collected from a range of structural levels and various structural positions relative to the Independence Thrust (Fig. 1). Six of these samples came from the footwall and two from the hanging wall.

Optical Microscopy, Electron Backscatter Diffraction (EBSD) and Data Processing

Thin sections were cut perpendicular to foliation and parallel to lineation when visible. Samples with no discernible lineation were cut at ~115°, parallel to the statistically dominant lineation orientation in the Pequop Mountains (Camilleri 1998; 2010). Standard doubly-polished thin sections were further polished using colloidal silica to prepare for SEM-EBSD analysis. Optical observations of microstructures and deformation mechanisms were made to determine optimal sites for EBSD analysis.

Crystallographic analysis was performed on a Zeiss EVO MA 15 Scanning Electron Microscope (SEM), located at Washington and Lee University with an Oxford Instruments EBSD detector running Aztec software. Operating conditions were an accelerating voltage of 25 kV, a probe current of 20 nA, and a working distance of ~27 mm. Step sizes ranged from 6-30 µm, depending on the size of the area being mapped and the grain size of the sample. The raw EBSD data were processed and analyzed using MATLAB and the MTEX toolbox (Hielscher and Schaeben, 2008) with pole figure, grain size, and grain map output built using MTEX code created by Jeffrey Rahl. Figure 2 presents the resulting pole figures.

RESULTS

Deep Structural Levels

Cambrian Prospect Mountain Quartzite. Samples 070715-1 and 070715-2 are from the Cambrian Prospect Mountain Quartzite and represent the deepest structural levels exposed in the Pequop Mountains – about 2 km beneath the Independence Thrust (Fig. 1). Sample 070715-1 is extremely coarse grained with a mean grain size of nearly 500 µm and some grains ranging up to 5000 µm. Quartz grains commonly envelope dispersed, fine muscovite flakes that are well-aligned parallel to foliation. Grain shape foliation is slightly inclined, suggesting a contribution from ESE-directed shear. The coarse grain size combined with the relative lack of mica concentrations at grain boundaries and the finely interdigitating quartz grain boundaries all suggest recrystallization by rapid grain boundary migration (Stipp et al., 2002). Micas commonly localize subgrain boundaries and may indicate earlier grain boundaries. Sample 070715-2, a deformed quartz pebble conglomerate shows a similar microstructure, but the micas are coarser, less tightly aligned with foliation, and commonly curve around quartz grains, pinning and thus preserving original grain boundaries. The suppression of grain boundary migration enabled this sample to preserve a mean grain size of ~300 µm that at least partly reflects original grain dimensions.

The two samples yield contrasting crystallographic preferred orientations (CPOs), with 070715-1 showing the strongest CPO of any quartzite away from the Independence Thrust. In contrast, 070715-2 shows a much lower intensity CPO that strongly resembles CPOs observed from lower strain rocks at higher structural and stratigraphic levels (Figs. 2a and b).

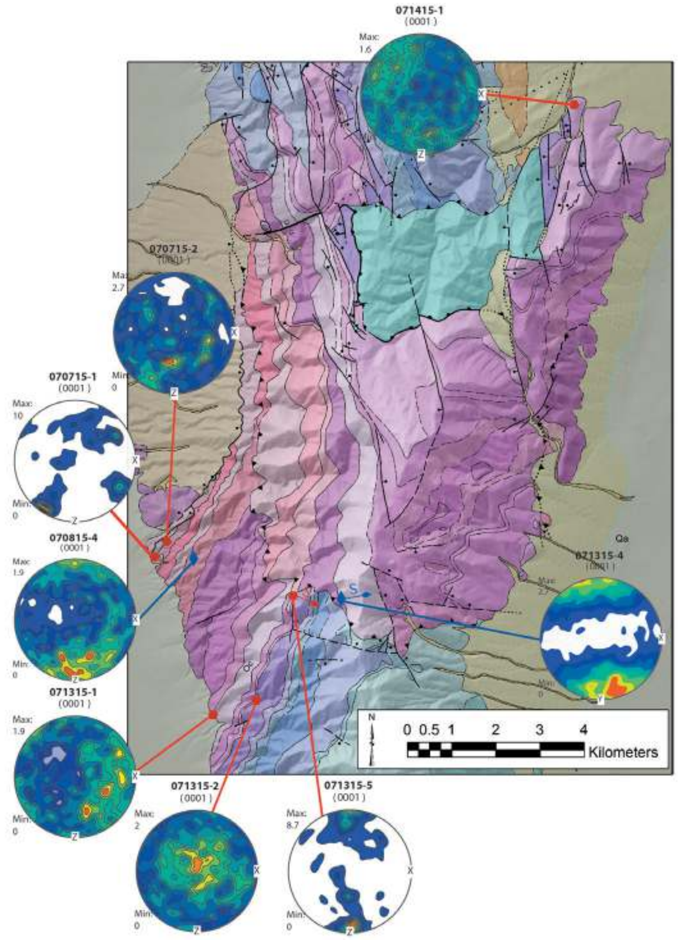

Figure 1. Geologic map of the Pequop Mountains. Red filled circles indicate quartzite sample localities and blue filled diamonds indicate marble. Sense of shear on the thrust is indicated with "S" labeled arrows. C-axis pole figures show sample number in bold above each pole figure with maximum multiples of uniform density marked to the top left. Geologic map adapted from Camilleri (2010).

The contrast in CPOs may reflect the effect of grain boundary migration, which would amplify maxima in "soft" orientations ideally positioned to accommodate the imposed strain with the least work. Both samples exhibit crossed girdle c-axis pole figures, but 070715-2 is more diffuse with a peak at just 2.7x m.u.d., in contrast to the 10x m.u.d. maxima exhibited in the crossed-girdle c-axis pole figure for 070715-1. In this configuration, the crystals are ideally oriented for balanced, antithetic slip on basal <a> and prism <c> slip systems in a nearly coaxial strain regime. The large opening angle (90^{o}) of sample 070715-1 normally would indicate deformation temperatures of 600^{o}-700^{o}C (Kruhl, 1998; Law, 2014); however, in light of the low strains in these rocks, low strain rates may have enabled these slip systems to operate

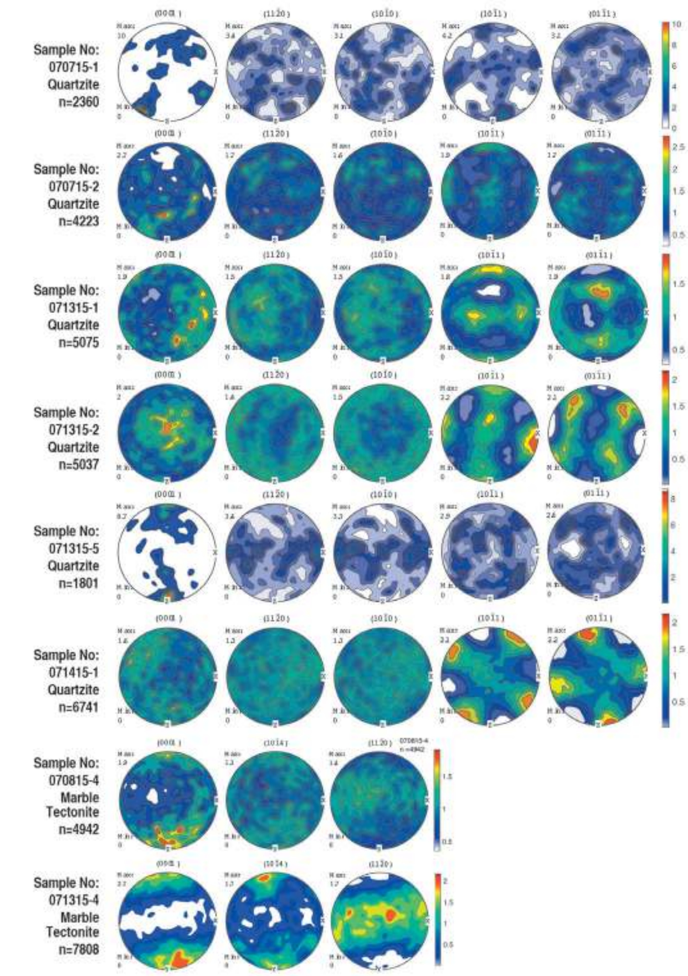

Figure 2. Generated lower-hemisphere CPO pole figures for all samples analyzed. Rows a to f present five pole figures (c, a, m, r, and z) for each of the six quartzite samples; rows g and h show three pole figures for each of the marble tectonite samples,. Total number of measurements (n) used in generating each CPO given beneath each sample label.

at slightly lower temperatures. Howland (this volume) reports a temperature estimate of 505±18°C for this same area of the Pequop Mountains.

Both samples also exhibit a distinctive feature of the quartz CPOs from the Pequop Mountains: a well-developed preferred orientation of the three positive rhombs (r) subparallel to the X, Y and Z strain axes, respectively. One hypothesis for the origin of this pattern is that grains near this orientation may have a strong tendency to rotate toward this configuration, but once there the rhomb slip systems are inactivated due to the lack of resolved shear stresses. Slip can continue on prismatic and/or basal systems, however. If correct, this hypothesis implies that the preferred rhomb positions may be sensitive indicators of the instantaneous strain axes. If so, then the slight counterclockwise rotation of the positive rhombs relative to X and Z in 070715-1 could imply a dextral subsimple shear with relatively low kinematic vorticity whereas, the closer alignment of the positive rhombs with X, Y, and Z in 070715-2 would imply a more nearly coaxial strain.

Dunderberg Formation Marble Tectonite. Sample 070815-4 is a fine grained Upper Cambrian marble with a similar relationship to the fault as the above quartzite samples. It shows a generally uniform grain size in the range 100-200 μm, though locally with coarser grains ≥ 400 μm in diameter. It also displays a well-developed grain shape foliation, and grain size variations parallel to foliation. The CPO for this sample exhibits a weakly defined, off-center c-axis girdle with a maximum at just 1.9x m.u.d. near the Z strain axis (Fig. 2g). The near-correspondence of the c-axis peak with the pole to foliation suggests an approximately coaxial strain path similar to the nearby quartzites.

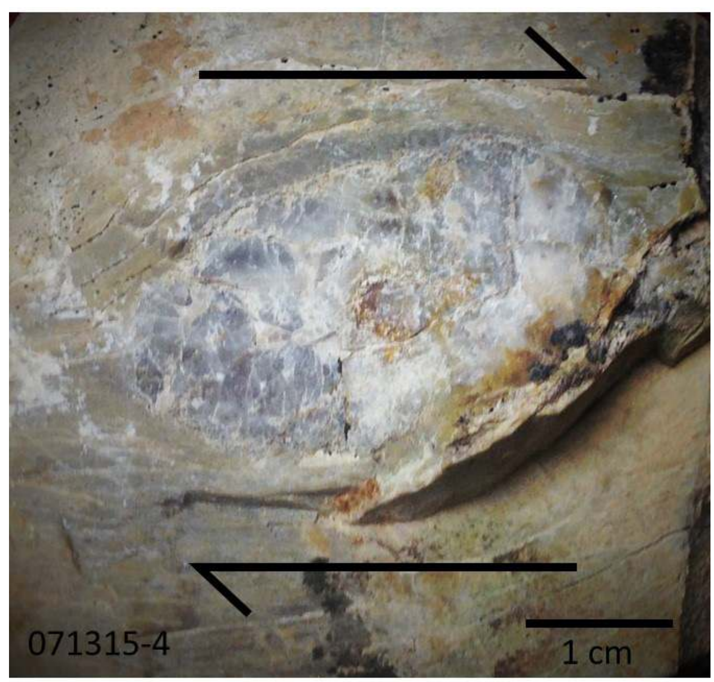

Figure 3. Sample 071315-4 from the Cambrian Notch Peak formation showing asymmetric recrystallized chert boudin. Sample is oriented in this photograph such that east is to the right. Scale bar and inferred shear-sense arrows are indicated.

The Independence Thrust

Samples 071315-4 and 071315-5 are both from intermediate structural levels very near (within 100 m) the Independence Thrust. Sample 071315-4 from the Cambrian Notch Peak formation occupies the immediate hanging wall of the thrust and contains finely recrystallized chert nodules that commonly show a clear, east-directed sense of asymmetry (Fig. 3). The mylonitic marble matrix shows intense grain size reduction (20-50 µm grain size) and a well-defined grain shape fabric with an inclination of ~30^{o} indicating a dextral (top-to-east) shear-sense. Sample 071315-5 is a sample of vein quartz collected from the approximate stratigraphic position of the Ordovician Eureka quartzite in the immediate footwall of the thrust (< 100 m from the fault zone). This sample has extremely coarse, spectacularly deformed quartz grains, some penetrated by shear bands and conspicuous warps in the crystal structure (Fig. 4). A prominent carbonate vein also transects the sample. Where shear bands transect the large quartz grains they commonly show subgrain polygonization and intense dynamic recrystallization. In some areas, thin zones of cataclastically deformed microbreccia are also evident, suggesting that deformation occurred near the brittle-plastic transition for quartz (~300^{o}C).

Both the calcite CPO for sample 071315-4 and the quartz CPO for sample 071315-5 strongly confirm the east-directed shear-sense inferred from field and optical observations. Barnhoorn and others (2004), in torsion experiments on Carrara marble, noted that marble CPOs developed two c-axis maxima:

Figure 4. Photomicrograph of sample 071315-5 in cross-polarized light. Sample was collected in the immediate footwall of the thrust (< 100 m from the fault zone). This sample has extremely coarse, spectacularly deformed quartz grains, some penetrated by shear bands and conspicuous warps in the crystal structure. Image dimensions are approximately 27mm x 46mm.

one perpendicular to the shear zone and one oblique and opposite to the sense of shear. Additionally, the a-axis maxima form a slightly antithetically tilted girdle relative to the shear zone. The EBSD results from sample 071315-4 show both of these features indicating an east directed shear-sense (dextral in the pole figure) (Fig. 2h). In quartz, the asymmetry in the c-axis CPO is inclined in the same direction as the sense of shear (Lister and Dornsiepen, 1982; Schmid and Casey, 1986; Passchier and Trouw, 2005), so sample 071315-5 also indicates an east directed sense of shear (Fig. 2c). The quartz c-axis pole figure also shows a strong alignment (m.u.d. 8.7) of c-axes perpendicular to the inferred shear plane, and positioning of an a-axis maximum parallel to X. This configuration represents a near-perfect alignment for simple shear on the basal <a> system – the lowest temperature deformation mechanism commonly observed in quartz. Thus, this CPO also supports thrust deformation under lower greenschist facies conditions, consistent with a nearby temperature estimate of 330±32°C from calcite-dolomite thermometry (Howland, this volume).

Shallower Structural Levels Away from Independence Thrust

Samples 071315-1 and 071315-2 are from intermediate structural levels distal (~3.5 km) from the Independence Thrust (Fig. 1). 071315-1 is a nearly undeformed quartz sandstone from the base of the Ordovician Pogonip Group, Unit C (Kanosh sandstone). It is a fine grained, locally cross-bedded quartz sandstone with little to no mica and no evidence of grain shape foliation. Microscopic evidence of crystal-plastic strain, such as undulose extinction or subgrain development in quartz is largely absent, but the sparse calcite cement shows evidence of dynamic recrystallization. Sample 071315-2, Ordovician Eureka quartzite with some graphite layers present in outcrop, is very similar to sample 071315-1; it appears undeformed, but some grains exhibit deformation lamellae. Both of these samples are from the footwall of the fault.

The final sample analyzed, 071415-1, is also Eureka quartzite but comes from the highest structural levels sampled in the northeastern Pequop Mountains: in the hanging wall and ~12 km away from the Independence

Thrust. Although it is one of the least deformed samples collected, it shows weak undulose extinction and localized incipient subgrain development. In addition, a localized micro-breccia overprint suggests periodic excursions into the brittle regime.

Despite their virtually undeformed character under both field and microscopic observation, all three samples show distinctively similar quartz CPOs, with weak to nearly absent CPOs in the **c**, **a**, and **m** pole figures, but with surprisingly well-defined CPOs in **r** and **z** (Fig. 2). The most characteristic feature of these CPOs is the alignment of the positive rhombs parallel or at low angles to the inferred finite strain axes based on regional relationships; however, in one case (071415-1), it is the negative rhombs (**z**) rather than the positive rhombs that align most closely with the inferred finite strain axes.

DISCUSSION

Kinematics of the Independence Thrust

Kinematic indicators from asymmetric recrystallized chert boudins and asymmetric fabrics in the marble mylonite sample 071315-4 (Fig. 3), along with EBSD CPO results from the same sample all indicate east-directed shear on the Independence Thrust. EBSD analysis of sample 071315-5, a deformed quartzite, also indicates broadly east-directed shear, and the presence of thin zones of cataclasis suggests deformation near the brittle-plastic transition in quartz (approximately 300^{o}C) (Fig. 4). The CPO of this sample indicates the dominance of the low-temperature basal <a> slip system, consistent with a calcite-dolomite temperature estimate of 330±32°C from this same area (Howland, this volume). Given the eastward transport direction along the Independence Thrust, the southward ramping of the thrust across Paleozoic stratigraphy may represent a lateral ramp, and it is possible that the displacement on the fault could significantly exceed its ~3 km stratigraphic throw.

Deformation Mechanisms Transitions

Away from the thrust fault, microstructural and CPO observations indicate lower intensity strain at moderate temperatures. Sample 071315-2 has a CPO with the c-axis parallel to the Y, indicating prism <a> slip, which may develop at amphibolite facies or at lower temperatures (greenschist facies) if strain rates are low (Lister and Dornsiepen, 1982). More characteristically, the quartz sandstones are only weakly deformed and show very weak c-axis CPOs; in contrast, the marble tectonites (070815-4 and especially 071315-4) display much higher strains and better defined CPOs. This suggests that strain was strongly partitioned into the more easily deformed marbles at the low metamorphic grades characterizing most of the Pequop Mountains.

Samples from the deepest structural levels exhibit microstructures and CPOs suggesting higher strain and higher temperature deformation. Sample 070715-1 displays the strongest CPO of the quartzites sampled outside the immediate fault zone, and the large opening angle between maxima in the XZ plane suggests higher temperature deformation. These observations are consistent with temperatures of 505±18°C or greater as documented by Howland (this volume); this may reflect emplacement of a pluton in the shallow subsurface. Diapiric upwelling of such a body and stretching of the overlying country rock could also explain the greater strains and attenuation observed at the deepest exposed structural levels.

Rhomb-dominated CPOs. The most characteristic quartz CPO of the Pequop Mountains is defined by the alignment of the positive rhombs (r faces) perpendicular to the X, Y, and Z strain axes, respectively. This CPO is an unusual one and suggests that even at the lowest grades and under incipient strain conditions, quartz shows a strong tendency to rotate or preserve positive rhombs in low resolved shear stress positions. Consequently, this mechanism may provide a previously unrecognized approach to tracking instantaneous strain axes even in incipiently deformed rocks. Future work will focus on testing this hypothesis.

CONCLUSION

Macroscopic, microscopic, and crystallographic evidence all indicate east-directed shear on the Independence Thrust. Moreover, observed deformation mechanisms and strain partitioning into marble at shallow to intermediate levels suggest that emplacement of the thrust occurred under greenschist facies conditions. Additionally, the deformation mechanisms observed correlate well with Howland's temperature results (this volume) indicating a steep metamorphic field gradient. The higher temperature deformation of the Prospect Mountain Quartzite at depth (T > 500^{o}C), along with the significant thinning of this unit relative to those at slightly higher structural levels, could record stretching in the flattening field over the roof of a pluton or diapiric mass in the shallow subsurface.

REFERENCES

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 orogeny. GSA Bulletin, v. 109, p. 74-94.

Barnhoorn, A., Bystricky, M., Burlini, L. and Kunze, K., (2004). The role of recrystallisation onthe deformation behaviour of calcite rocks: large strain torsion experiments on Carraramarble. Journal of Structural Geology, 26(5), pp.885-903.

Hielscher, R., and Schaeben, H., (2008). A novel pole figure inversion method: specification ofthe MTEX 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.

Lister, G. S., & Dornsiepen, U. F. (1982). Fabric transitions in the Saxony granulite terrain. *Journal of Structural Geology*, *4*(1), 81-92.

Passchier, C. W., & Trouw, R. A. J. (2005). Microtectonics. 2nd. *Berlin, Sopringer–Verlag*.

Schmid, S. M., & Casey, M. (1986). Complete fabric analysis of some commonly observed quartz c-axis patterns. *Mineral and Rock Deformation: Laboratory Studies: The Paterson Volume*, 263-286.

Stipp, M., Stuünitz, H., Heilbronner, R., & Schmid, S. M. (2002). The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700 C. *Journal of Structural Geology*, *24*(12), 1861-1884.