

*Tectonics*

Supporting Information for

**Relating quartz crystallographic preferred orientation intensity to finite strain magnitude in the Northern Snake Range metamorphic core complex, Nevada: a new tool for characterizing strain patterns in ductilely sheared rocks**

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**Introduction**

Supporting information for this paper includes text that gives information on analytical methods for finite strain analyses, structural thickness measurements, quartz crystallographic preferred orientation (CPO) analyses, and mica area percentage analyses. Two tables are included, which provide supporting information for finite strain, quartz CPO distributions, mica area percentage analyses (Table S1) and structural thickness measurements (Table S2). Figures include annotated photomicrographs showing representative examples of finite strain analyses, Rf-φ graphs for each finite strain analysis, cross sections used for measuring structural thicknesses, quartz CPO pole plots, and annotated photomicrographs showing representative examples of mica area percentage analyses.

Text S1: Analytical methods and supporting data for finite strain analyses

We utilized methods outlined in Long et al. (2020) and the text below partly reproduces their wording. We analyzed two foliation-normal thin sections each from 31 of our 38 total finite strain samples (Table S1). One thin section was cut parallel to lineation, which approximates the XZ strain plane (thin sections ending with ‘A’), and one was cut normal to lineation, which approximates the YZ strain plane (thin sections ending with ‘B’). For seven of our finite strain samples from the Hendry’s Creek transect (JL1-202, JL1-204, JL1-205, 33, 38, 40, and 46) a single, lineation-parallel thin section was analyzed, due to a lack of sufficient material left over to cut a lineation-normal billet.

For each thin section, we utilized the Rf-φ method (e.g., Ramsay, 1967; Dunnet, 1969; Ramsay and Huber, 1983) to quantify a 2D strain ellipse. The final elongation (Rf; the ratio of the long axis to the short axis) and φ (defined here as the angle of inclination of the long axis measured relative to foliation) were measured for ≥30 elongated, detrital quartz ribbons on photomicrographs of each thin section. Photomicrographs were taken with the apparent dip of tectonic foliation oriented horizontal, ESE (for ‘A’ thin sections) or NNE (for ‘B’ thin sections) toward the right-hand side, and structurally-upward toward the top.

Grain boundaries of deformed quartz ribbons were traced in Adobe Illustrator, with the areas of quartz ribbons filled in solid white and all mineral phases other than quartz filled in solid black (Fig. S1). This binary image was then imported into the National Institutes of Health (NIH) program ImageJ (Schneider et al., 2012), and individual quartz ribbons were modeled as ellipses using the ‘fit ellipse’ measurement tool. This generated an image of the fit ellipses (Fig. S1) and a table of long axis length, short axis length, and long axis orientation (φ) values for each grain, which were then used to populate Rf-φ graphs for each thin section (Fig. S2). Representative photomicrographs, binary images, and fit ellipses are shown on Figure S1, and Rf-φ plots showing data from individual quartz ribbons measured on each thin section are shown on Figure S2.

For all analyses, the mean of all φ values is reported as the overall φ value for the thin section. Analyses from all thin sections resembled ‘situation B’ of Figure 5.5 of Ramsay and Huber (1983); for these analyses, the tectonic ellipticity (Rs) of each thin section was measured using the harmonic mean of all Rf values (e.g., Lisle, 1977a, 1977b, 1979). Uncertainties reported for Rs and φ represent 1 standard error of all measurements (Rs values and uncertainties are rounded to the nearest single decimal place, and φ values and uncertainties are rounded to the nearest degree). Uncertainties in Rs yielded a total range between ± 0.1-2.3, and uncertainties in φ yielded a total range between ± 0-6°. Uncertainties typically ranged between ± 0.1-0.2 for samples with Rs ≤3.0, ± 0.2-0.8 for samples with Rs between 3.0-10.0, ± 0.6-1.5 for samples with Rs between 10.0-20.0, and ± 1.1-2.3 for samples with Rs >20.0. φ was measured relative to the apparent dip of tectonic foliation and is therefore equivalent to the parameter θ’ defined by Ramsay and Huber (1983).

The sign convention used for φ in ‘A’ thin sections is down-to-the-WNW relative to foliation (counterclockwise from foliation in the photomicrographs, consistent with a top-to-the-ESE shear-sense) is positive, and down-to-the-ESE relative to foliation (clockwise from foliation in the photomicrographs, consistent with a top-to-the-WNW shear-sense) is negative. The sign convention used for φ for ‘B’ thin sections is down-to-the-SSW relative to foliation (counterclockwise from foliation in the photomicrographs, consistent with a top-to-the-NNE shear-sense) is positive, and down-to-the-NNE relative to foliation (clockwise from foliation in the photomicrographs, consistent with a top-to-the-SSW shear-sense) is negative.

The Rs and mean φ values for the 2D strain ellipses from each ‘A’ and ‘B’ thin section were combined to generate a 3D strain ellipsoid for the sample (e.g., Long et al., 2020). For all analyses, the Z axis was assigned an Rs value of 1.0 in both ellipses, and the Rs values of both 2D ellipses were then directly compared to assign the X and Y strain directions (X>Y) and the relative magnitudes of the axes of the 3D strain ellipsoid. In order to approximate 3D strain in the seven samples where only 2D strain ellipses were available (JL1-202, JL1-204, JL1-205, 33, 38, 40, and 46), the average lineation-normal (Y) extension value (13±6%) calculated from all 3D ellipses from Hendry’s Creek transect samples was applied to the 2D strain ellipses of these samples. For all 31 of the samples that we obtained 3D strain ellipsoids from, Rs in the lineation-parallel ‘A’ thin section was greater than Rs in the lineation-normal ‘B’ thin section. Additionally, for all thin sections that we analyzed, the shortening (Z) direction of the 2D strain ellipse was within ±10° of normal to the apparent dip of foliation. This justifies the use of mesoscopic foliations and mineral stretching lineations to approximate the principal strain directions within the studied rocks.

Eleven finite strain ellipsoids from Lee et al. (1987) were incorporated into our dataset and included thin section measurements from eight samples from the Salt Creek transect (JL1-116, 115, 157, 149, 150, 148, 151, and 152) and stretched pebbles from 3 outcrops in the Hendry’s Creek transect (SP4, JL2-32, and JL2-91). Lee et al. (1987) calculated Rs values for their 3D strain ellipsoids using similar methods to ours, where the X strain direction is foliation- and lineation-parallel, the Y strain direction is foliation-parallel and lineation-normal, and the Z direction is foliation-normal. For details on the methods and results regarding the 11 analyses incorporated into our study, readers are referred to Lee et al. (1987).

Table S1 (see accompanying Excel table): Locations, orientations, finite strain data, quartz crystallographic preferred orientation (CPO) data, and mica area percentage results from all samples from this study (as well as the 11 finite strain analyses of Lee et al., 1987 and the 12 CPO samples of Gébelin et al., 2015). Samples are organized by transect and from WNW to ESE.

Figure S1: Annotated photomicrographs showing representative examples of quartz ribbon measurements for Rf-φ analyses. See Table S1 for a guide to sample numbers. All photomicrographs were taken in cross-polarized light, with the apparent dip of foliation oriented horizontal (arrow points structurally-upward). Three figures are shown for each sample: 1) a photomicrograph on the left; 2) a binary image of traced quartz ribbons (with white fill; all other parts of the thin section are shown with black fill) in the center; and 3) the ImageJ output figure after performing the ‘fit ellipse’ function on the right.

Figure S2 (following 10 pages): Rf-φ graphs plotting the natural log of final ellipticity (Rf) versus the orientation of the long axis (φ) for individual quartz ribbons from each pair of thin sections from each finite strain sample. See Table S1 for a guide to sample numbers. φ is measured relative to the apparent dip of tectonic foliation, which is oriented at 0° for each thin section (i.e., horizontal in the accompanying photomicrograph). See Text S1 above for details on the sign convention used for φ. The Rs value reported for each sample is the harmonic mean of all measured quartz ribbons (e.g., Lisle, 1977a, 1977b, 1979), and the φ value reported for each sample is the mean of φ values for all quartz ribbons. Errors reported for Rs and φ represent 1 standard error of all measurements. All analyses resembled ‘Situation B’ of Figure 5.5 of Ramsay and Huber (1983).

Text S2: Methods and supporting data for macro-scale structural thickness measurements of the Prospect Mountain Quartzite

We utilized published geologic maps and cross sections (Young, 1960; Whitebread, 1969; Gans et al., 1985; Rodgers, 1987; Miller et al., 1994, 1995, 2007; Gans et al., 1999; Lee et al., 1999; Johnston, 2000; Long et al., 2022) to measure regional trends in structural thickness for the Lower Cambrian Prospect Mountain Quartzite (from here on abbreviated ‘Cpm’). Thicknesses were measured only where both the top and bottom contacts of the Cpm are exposed and are not in contact with intrusive rocks. Where available, we measured structural (i.e., foliation-normal or bedding-normal) thicknesses of the Cpm from published cross sections, including Long et al. (2022) for the Schell Creek Range, Rodgers (1987) for the Deep Creek Range, Gans et al. (1985) for the subsurface of Spring Valley, Whitebread (1969) for the Southern Snake Range, and Lee et al. (1999) for one locality in the Northern Snake Range (Table S2). To enhance the number of structural thickness datapoints for critically important areas of the Northern and Southern Snake Ranges, we drafted 21 new cross sections (Fig. S3, Table S2). Lines of section were drawn normal to unit contacts whenever possible and were chosen to minimize the impact of structures that may affect unit thickness, such as normal faults or fold axes. Where applicable, the local average dip of tectonic foliation was used to approximate the dip of contacts. When no foliation attitude measurements were available, the dip of contacts was assumed to be horizontal (e.g., Miller et al., 1983; Lee et al., 1987) or a dip angle was constrained using interactions of geologic contacts with topography along the cross section. If apparent thinning or thickening was evident at the scale of an individual cross section, then two separate thickness measurements were made and both were used in our thickness compilation (e.g., Hendry’s Creek cross sections 6, 7, and 11; Table S2). Thicknesses obtained from the Cpmwere used to support the contour map shown on Figure 8 in the main text. Contours were modeled in ArcGIS using the spatial analyst ‘contour’ tool and ‘natural neighbor’ interpolation (Sibson, 1981). Additionally, we assumed that thickness measurements are approximately consistent for several 10’s of km along strike, particularly for regional measurements in regions adjacent to the Northern Snake Range (e.g., Deep Creek, Schell Creek, and Southern Snake Ranges).

Table S2 (see accompanying Excel table): Compilation of cross section-based structural thickness measurements used in the construction of the contour map shown on Figure 8 in the main text. Accompanying cross sections 1-21 are from our study and are shown on Figure S3; all other listed cross sections were presented in the cited source publications.

Figure S3 (following 3 pages): A) Simplified map of cross section locations, and B) cross sections of portions of the Northern Snake Range and Southern Snake Range that were used to measure structural thicknesses of the Cpm based on the geologic mapping of Miller et al. (1994, 1995, 2007), Gans et al. (1999), Lee et al. (1999), and Johnston (2000). Cross section numbers are keyed to cross section lines on the map in A. Arrows point structurally upward. No vertical exaggeration was used and lower and upper unit contacts were assumed to be parallel. Our resulting thickness measurements are summarized in Table S2.

Text S3: Methods of quartz CPO data collection, calculation of intensity parameters, and measurement of mica area percentage

We measured the orientations of quartz *c*-axes within polished, foliation-normal, lineation-parallel thin sections of 45 samples (Table S1) using a Crystal Imaging Systems G60 automated crystal fabric analyzer from Russell-Head systems at the University of British Columbia, Okanagan. We utilized the same methods as those described in Long et al. (2020), and detailed descriptions of instruments that operate using the same theoretical approach are included in Wilson et al. (2007) and Peternell et al. (2010). The fabric analyzer determines the trend and plunge of the *c*-axis for each pixel in a composite image of the entire thin section, producing an achsenverteilungsanalyse (AVA) diagram (e.g., Sander, 1950) that is used to build a spatially referenced CPO distribution using a variety of plane- and cross-polarized images to verify minerology. The CPO distributions measured using this method produce equivalent results to those measured using electron backscatter diffraction (EBSD), x-ray goniometry, and neutron diffraction (e.g., Wilson et al., 2007; Peternell et al., 2010; Hunter et al., 2017). For each sample, we randomly selected a minimum of 1,000 representative quartz grains using Crystal Imaging Systems fabric analyzer software, to support constructing a pole figure. Pole figures for all samples (Fig. S4) are plotted on equal-area stereonets, and were generated using the custom R scripts of Larson (2023).

We utilized EBSD to measure crystallographic orientations of quartz *c*- and *a*-axes within foliation-normal, lineation-parallel thin sections of 30 total samples, consisting of 14 of our newly collected samples and 16 thin sections from samples that were originally analyzed using a universal stage and published in Lee et al. (1987) (Table S1). Methods were the same as those described in Langille et al. (2010). Measurements were performed using an FEI Quanta400F scanning electron microscope with an HKL Technologies Nordlys II EBSD camera at the University of California, Santa Barbara. The scanning electron microscope used a thermal field emission source with 20 kV accelerating voltage and ~5nA of beam current, at a working distance of ~15 mm and 70° of tilt. Data were collected using a beam-raster over a ~1 mm2 area with stage movement between rastered areas and variable step size. Step size was typically no larger than the average grain size within a given sample. Approximately one orientation was measured per grain and as many as 1,000 grains were selected at random, and were plotted on pole figures. Quartz *c*-axis pole figures (generated using the custom R scripts of Larson, 2023) for all samples analyzed using EBSD are shown in Figure S4.

Following data collection and the selection of grains to support the pole figures, the 75 total samples that were analyzed by both the optical fabric analyzer (n = 45) and EBSD (n = 30) were processed together using the custom R scripts of Larson (2023), in order to calculate the intensity (i.e., non-randomness) of CPO development. Two CPO intensity parameters were calculated for each sample: cylindricity (B) of Vollmer (1990) and the density norm (Jpf) of Larson et al. (2020; 2023). Cylindricity was measured by calculating the point (P), girdle (G), and random (R) end-member CPO types (Vollmer, 1990), which are determined by matrix summation of eigenvalues assigned to each end-member, where P + G + R = 1. Cylindricity is the sum of the non-random components (B = P + G), and varies between a value of 0, which represents a completely random CPO distribution, and a value of 1, which is a completely non-random CPO distribution. The density norm (Jpf) was calculated as the L2 norm of the spherical density distribution (e.g., Kilian and Heilbronner, 2017; Larson et al., 2020; 2023). The density norm ranges between a value of 1 for a completely random distribution and infinity for a completely non-random distribution (Mainprice et al., 2015). Both parameters were calculated using the custom R scripts of Larson (2020) and are listed for each sample on Table S1. Additionally, Gébelin et al. (2015) presented P, G, R, and cylindricity values for their 12 quartz CPO samples (which were also calculated using the methods of Vollmer, 1990), but density norm values are unavailable for these samples (Table S1).

The presence of mica in quartz-rich rocks has been shown to affect the development of quartz CPO distributions (e.g., Starkey and Cutforth, 1978; Little et al., 2015) and may play a role in controlling the grain size of dynamically recrystallized quartz (e.g., Song and Ree, 2007; Herwegh et al., 2011). Additionally, a higher degree of interconnectivity between mica grains can decrease the strength of quartz-bearing rocks, even when the mica is not in direct contact with quartz (Hunter et al., 2016). To determine if mica content affected the cylindricity and density norm values that we calculated from our samples, we measured the area percentage of mica within polished thin sections of 57 of the samples that we analyzed for quartz CPO distributions. We utilized methods outlined in Starnes et al. (2020), which involved outlining the boundaries of all mica grains visible in a representative photomicrograph of each thin section using Adobe Illustrator, creating a binary image of the outlined grains, and using the National Institutes of Health software program ImageJ (Schnieder et al., 2012) to calculate the total area percentage of mica in each photomicrograph (representative examples are shown on Fig. S5).

Figure S4 (following 9 pages): Quartz CPO pole plots for all samples (plotted on equal area stereonets and contoured relative to multiples of a random distribution; generated using the custom R scripts of Larson, 2020) with sample number, corresponding Rs[X/Z] value from finite strain analyses (when applicable), cylindricity (B), density norm (Jpf), and the number of *c*-axes plotted (n). All pole plots are oriented as shown for sample 02, with ESE on the right-hand side, tectonic foliation as horizontal, and mineral stretching lineation toward the right.

Figure S5: Representative examples of mica area percentage measurements. Three figures are shown for each sample: 1) a photomicrograph on the left (taken in cross-polarized light) with mica grains outlined in red; 2) a binary image of traced mica clasts (with black fill; all other parts of the thin section are shown with white fill) in the center; and 3) the ImageJ output figure after performing the ‘area’ function.

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