Vorticity and Kinematic Analysis of the Cordillera Blanca Shear Zone, Peru

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(Original signatures are on file with official student records.)
Vorticity and Kinematic Analysis of the Cordillera Blanca Shear Zone, Peru

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Corey Flynn
December 2021
ACKNOWLEDGEMENTS

I would like to thank the Earth and Planetary Sciences Department at the University of Tennessee for supporting my academic and research efforts. Micah Jessup for invaluable guidance through constructing and carrying out my research project. To Zachary Michels for collaborative efforts on this thesis and much enthusiasm that I would have been lost without. To Seth Kruckenberg for providing the inspiration for this project. And lastly, my committee members Nick Dygert and Bob Hatcher for providing constructive feedback during critical moments.
ABSTRACT

Quantitative vorticity analyses applied to naturally deformed rocks are essential for studying kinematics in shear zones and can be performed using a range of methods, which have been developed over the last two decades. An understanding of vorticity, or the contribution of pure vs. simple shear, can permit for the modeling of shear zone development in a deformed region. Recent (5 Ma-present) deformation in the Cordillera Blanca Shear Zone of the Peruvian Andes has exposed sections of the middle crust at the surface, allowing for observation and analysis of shear zone processes. Oblique grain-shape (OGS) analysis and crystallographic vorticity analysis were employed to determine the kinematic vorticity number and the orientation of the vorticity normal surface in the CBSZ. We also propose a new method of OGS analysis utilizing electron backscatter diffraction data to determine vorticity values as well as the orientations of flow apophyses and Instantaneous Stretching Axes (ISA). Calculated vorticity values and flow apophyses orientations were used to calculate the convergence vector between the Nazca and South America Plates. The use of vorticity analysis for modeling plate motion has yet to be used on such a young system where the angle of convergence is known.
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Chapter 1:
Introduction

Large fault systems are often rooted in shear zones where deformation is accumulated below the brittle ductile transition zone (Fossen, 2017). These shear zones can cause strain localization that ranges from microscale to several kilometers in width (Fossen, 2017). Studying the kinematics of shear zones can help untangle the complex, tectonic evolution of the Earth’s crust (Xypolias, 2010). Traditionally it was accepted that shear zones provided an ideal model for simple (non-coaxial) shear (Ramsay and Graham, 1970; Ramsay, 1980). Studies have shown that shear zones have rarely undergone purely non-coaxial deformation but have experienced deformation featuring both non-coaxial and coaxial (pure shear) components. It is then more appropriate to characterize shear zones based on the degree of non-coaxiality (Law et al., 1984, 1986; Platt and Behrmann, 1986). Characterizing the contributions of pure and simple shear created a need to find practical ways to interpret the degree of non-coaxiality (Xypolias, 2010). One way of achieving this is by calculating a kinematic vorticity number ($W_k$) (Truesdell, 1953; Means et al., 1980).

Vorticity is defined as the relative contributions of pure and simple shear (Xypolias, 2010). The kinematic vorticity number, $W_k$, is an instantaneous measurement of the contributions of pure and simple shear (Truesdell, 1953; Means et al., 1980). $W_k$ has values equal to or between 0 and 1, and flow with $W_k$=0 is represented completely by pure shear and a $W_k$=1 is represented by completely by simple shear. The degree of non-coaxiality then increases with increasing $W_k$ values. Equal contributions of pure and simple shear occur at $W_k$= 0.71 which is also referred to as general shear (Xypolias, 2010). For certain methods of vorticity
analysis, it is more appropriate to represent the vorticity number with a mean kinematic vorticity number \(W_m\) (Passchier, 1987; Fossen and Tikoff, 1997, 1998; Jiang, 1998; Xypolias, 2010).

The orientation of the vorticity vector is significant with the vorticity vector representing the line around which internal particle flow is the greatest (Xypolias, 2010). The orientation of the vorticity vector relative to the instantaneous stretching axes (ISAs) defines the geometry of a shear zone. When the vorticity axis is parallel with one of the ISA’s, the shear zone is said to be monoclinic (Fig. 1a). When the vorticity axis is at an angle to the ISA’s the shear zone is said to be triclinic (Fig. 1b) and interpreting kinematics becomes more complicated. It is often assumed that the vorticity profile plane or the surface normal to the vorticity vector is perpendicular to fabric foliation and parallel to the stretching lineation. This is often how samples are cut to interpret the kinematics of deformed rocks. Careful analysis needs to be performed to ensure that kinematic interpretations are made from a surface parallel to the vorticity profile plane. A new method from Michels et al. (2015) called Crystallographic Vorticity Axis (CVA) analysis permits determination of the vorticity axis orientation using electron backscatter diffraction data (EBSD).

Subduction along the west coast of South America between the Nazca and South American Plates has been active since the Jurassic (James, 1971). The geometry of the down-going slab has cycled between shallow to flat and steeper until its current flat slab configuration (James, 1971; Jordan et al., 1983; Ramos, 1999). In the Peruvian flat slab segment, the Cordillera Blanca marks the highest mountains of this portion of the Andes and the second highest for the entire Andes (Fig. 2).
Figure 1. Schematic diagram showing the orientation of the vorticity vector (w) relative to the vorticity profile plane and the ISA’s. a) Vorticity axis parallel to one of the ISA’s representing a monoclinic flow geometry. b) Vorticity axis at an angle to the ISA’s representing a triclinic flow geometry. From Xypolias (2010).
The tectonically active Cordillera Blanca detachment, an ~200-km-long normal-sense fault zone in the Peruvian Andes, exhumed the Cordillera Blanca Shear Zone (CBSZ) in the footwall during syn-convergent extension. It occurs almost entirely in the leucogranodioritic Cordillera Blanca batholith (CBB) (Atherton and Sanderson, 1987; Petford and Atherton, 1992; McNulty et al., 1998), which was emplaced at 14–5 Ma (Mukasa, 1984; McNulty et al., 1998; Giovanni, 2007; Hughes et al., 2019). Movement on the Cordillera Blanca detachment fault initiated at approximately 5 Ma (Giovanni et al., 2010). Several different models were proposed to explain the timing. One invoked deformation in the CBSZ initiated during the emplacement of the CBB (Hughes et al., 2019). The Cordillera Blanca detachment exposes rocks from the middle crust ranging from undeformed leucogranodiorite to ultramylonite in the CBSZ (Atherton and Sanderson, 1987; Petford and Atherton, 1992). The structurally highest position of the CBSZ includes a zone of cataclastic rocks that marks a detachment surface that is roughly parallel to the shear zone (Petford and Atherton, 1992). In places these are truncated by steep normal faults.

We utilize Oblique Grain Shape vorticity analysis, Crystallographic Vorticity Axis analysis, quartz c-axis crystallographic preferred orientation plots, electron backscatter diffraction (EBSD) data, and low angle, intragranular misorientation data to characterize and quantify the kinematics of the Cordillera Blanca Shear Zone. We propose a new method for Oblique Grain Shape Vorticity Analysis using my EBSD data and the MTEX toolbox in MATLAB. Mean kinematic vorticity ($W_m$) values in addition to the orientation of the Instantaneous Stretching Axis (ISA) and oblique flow apophyses ($A_1$) permit the calculation of the convergence vector between the Nazca and South American Plates (Fossen, 2010). Because the angle of convergence between the Nazca and South American Plates has been constant for
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the last 12 Ma (Figure 3) (McNulty et al., 1998), calculating a convergence vector enables the calibration of methods proposed by Fossen (2010) and Kruckenberg et al. (2019). This approach of using vorticity analysis to get at convergence vectors has not yet been employed on a young system such as the Cordillera Blanca detachment.
Figure 3. Diagram showing the convergence vector (082°) between the Nazca and South American Plates. Vector is broken into normal-N and arc-parallel-P components. Thick black regions represent active volcanic arcs and the Cordillera Blanca Batholith is represented by CBB. Modified from Dewey and Lamb (1992) after Fitch (1972). From McNulty et al. (1998).
Chapter 2: Geologic Background

2.1 Geologic Setting

Subduction of the Nazca Plate along the western margin of the South American Plate has been occurring since the Jurassic, alternating between steep and flat-slab configurations until the present (James, 1971; Jordan et al., 1983). Above the Peruvian flat-slab segment is the Cordillera Blanca Range, cored by the granodiorite-leuconodiorite Cordillera Blanca Batholith (Atherton and Sanderson, 1987; Petford and Atherton, 1992; Gutscher et al., 1999; McNulty and Farber, 2002; Hughes et al., 2019). The Cordillera Blanca Range forms the western boundary of the Marañón fold-and-thrust-belt. Arc-related magmatism formed the 15-54 Ma Cordillera Negra to the west of the Cordillera Blanca before migrating eastward coinciding with the intrusion and cooling of the Cordillera Blanca Batholith from 13-5 Ma (Mukasa, 1984; Petford and Atherton, 1992; Giovanni, 2007; Scherrenberg et al., 2014, 2016; Hughes et al., 2019).

Emplacement conditions of the Cordillera Blanca batholith are estimated between 90-300 MPa and 720-800°C based on mineral assemblages in the contact aureole and amphibole thermobarometry of batholith lithologies (Petford and Atherton, 1992; McNulty and Farber, 2002; Margirier et al., 2016; Hughes et al., 2019). Following the intrusion of the Cordillera Blanca batholith, rapid cooling at 200°C/Myr lasted from 13-4 Ma until slowing to 25°C/m.y. from 4 Ma until the present (Margirier et al., 2015; Hughes et al., 2019). Along with arc-related magmatism, crustal shortening migrated eastward from the Marañón fold-and-thrust belt to the modern day Subandean fold-and-thrust belt. Accommodating this shortening, movement initiated along the Cordillera Blanca detachment at 5 Ma with extension of 12-15 km of normal-sense
displacement (Bonnot, 1984; Giovanni et al., 2007, 2010; Hughes et al., 2019). The Cordillera Blanca detachment exposes the ductilely deformed Cordillera Blanca shear zone (CBSZ), which can be seen in a series of incised ravines (quebradas) that cut the range orthogonally exposing a full transition of brittle-to-ductile fabrics (Fig. 4) (Wise and Noble, 2003; Hughes et al., 2019).

2.2 Structural Framework

Mean orientation of the Cordillera Blanca detachment strikes 156 and dips 30° as derived from a DEM generated from Shuttle Radar Topographic Mission data (Fig. 5) (opentopo.com) (Hughes et al., 2020). This is roughly subparallel to mylonitic foliation where mean foliation in the Quebrada Rajururi strikes 136 and dips 32°, 153 and 22° in the Quebrada Gatay, 162 and 27° and 189 and 30° in the Quebrada Ishinca (Fig. 5) (Hughes et al., 2020).

The upper boundary of the CBSZ is formed by the Cordillera Blanca detachment surface (Fig. 6A). A full transition from undeformed granodiorite to ultramylonite is exposed in these transects permitting for sampling the full spectrum of undeformed to ductile to brittle lithologies. Rocks in the CBSZ become increasingly mylonitized nearing the upper boundary of the shear zone (Petford and Atherton, 1992; Hughes et al., 2019, 2020). Quartz rich domains contain microstructures covering the range of fabrics described by Stipp et al. (2002a, 2002b) (Fig. 6). Upper structural levels near the detachment are dominated by bulging grain recrystallization (BLG), or a combination of BLG and subgrain rotation recrystallization (SGR) (Fig. 6B). Intermediate structural levels are dominated by SGR microstructures (Fig. 6C) (Hughes et al., 2019). The deepest structural positions are associated with the presence of grain boundary migration (GBM) (Fig. 6D). The strong presence of quartz microstructures provide qualitative estimates on deformation temperatures that are discussed in the following section.
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2.3 Deformation Conditions

Deformation of the CBSZ were evaluated by Hughes et al. (2020) using quartz microstructures, two-feldspar asymmetric strain induced myrmekite thermometry, and TitaniQ thermometry. Quartz microstructures provided qualitative temperature estimates using an experimentally calibrated model for dynamically recrystallized quartz bulging, subgrain rotation, grain boundary migrations, and chessboard extinction (Fig. 7). In the Quebrada Gatay, quartz microstructures record temperatures of 280-500°C near the detachment surface and increase to 630°C around 393m at the deepest structural levels (Hughes et al., 2020). Microstructural trends are less defined in the Rajururi and Ishinca transects where the presence of GBM and CB in the Quebrada Rajururi without the presence of higher strain structures indicate temperatures of 500°C to over 630°C during deformation (Hughes et al., 2020). Microstructures in the Ishinca transect indicate temperatures of 400°C to over 630°C during deformation due to the presence of BLG, SGR, GBM, and CB (Hughes et al., 2020).

Quartz and feldspar were used to characterize the phases that were associated with the rheology at different depth, including the deep areas of magmatic feldspar. Two-feldspar geothermometry of samples containing asymmetric strain-induced myrmekite (ASIM) yielded deformation temperature estimates of 440 ± 15 °C to 460 ± 28 °C at -100 to 393 meters below the detachment surface in Quebrada Gatay (Fig. 7) (Hughes et al., 2020). Titanium-in-Quartz (TitaniQ) geothermometry yielded a similar 451 ± 60 to 489 ± 33 °C 124 to 393 meters (Fig. 7) (Hughes et al., 2020). In the Q. Rajururi ASIM yielded deformation temperatures of 404 ±31 to 461 ± 20 from 21 to 65 meters below the detachment surface (Fig. 7) (Hughes et al., 2020). ASIM also yielded deformation temperatures of 426 ± 18 to 419 ± 22 from 22 ± 22 to 46 ± 21 meters below the detachment surface in the Quebrada Ishinca (Fig. 7) (Hughes et al., 2020).
Quartz CPOs generated from electron backscatter diffraction (EBSD) analysis indicate dominant prism \(<a>\) and rhomb \(<a>\) slip in the CBSZ (Hughes et al. 2019). Paleopiezometry yielded estimates of differential stress ranging from 16.5 ± 13 MPa to 71.5 ± 36 MPa using the Holyoke and Kronenberg (2010) piezometer (Hughes et al., 2019). The highest calculated stresses are associated with the deepest structural levels. Extension along the detachment since 5 Ma has occurred at approximately 2.4-3 mm/yr (Bonnot, 1984; Giovanni, 2007; Giovanni et al., 2010; Hughes et al., 2019). Assuming strain rate equals velocity/width (Platt and Behr, 2011b), strain rates were approximately equal to 1.7 to 6.3 \(\times 10^{-13}\) s\(^{-1}\) for 450m and 150m during the evolution of the shear zone (Hughes et al., 2019).

Hughes et al. (2020) applied a similar approach to Hughes et al. (2019), but added two more transects for Quebradas Rajururi (340 m thick transect) and Ishinca (49 m thick transect). They estimated for the shear zone thickness along strike as well as a compilation of structural data for many transects (Fig. 5). Their data are from recrystallized quartz paleopiezometry, ASIM two-feldspar thermometry, and structural analysis. Quartz CPO’s generated from EBSD analysis indicate dominant prism \(<a>\) and rhomb \(<a>\) slip and two samples with prism \(<c>\) slip in the CBSZ. Applying the wet quartz flow law of Hirth et al. (2001), in conjunction with the Holyoke and Kronenberg (2010), piezometer yields ranges of 19.1-64.3 MPa (Hughes et al., 2020). Temperatres from ASIM and TitaniQ thermometry yielded values of 410 ± 30 °C to 470 ± 36 °C and 450 ± 60 and 490 ± 33 °C. Hughes et al., (2019) calculated microstructurally-derived strain rates at 3.8 \(\times 10^{-14}\) to 3.7 \(\times 10^{-12}\) s\(^{-1}\). Microstructurally-derived using Holyoke and Kronenberg (2010) are 4.9 \(\times 10^{-15}\) to 3.7 \(\times 7.0 \times 10^{-13}\) s\(^{-1}\). The highest strain (2-9 \(\times 10^{-12}\) s\(^{-1}\)) rates occur around 150 m below the detachment near the deepest brittle overprinting (Hughes...
Figure 7. Temperature vs structural depth profiles during deformation for the Quebradas Rajururi, Gatay and Ishinca. Quartz recrystallization microstructures have associated temperature ranges with them where BLG is bulging grain recrystallization, SGR is subgrain rotation recrystallization, GBM is grain boundary migration recrystallization, and CB is chessboard extinction. Quartz recrystallization microstructure classification comes from Stipp et al. (2002b). Microstructure temperature ranges shown by grey bars in depth profiles. Presence of microstructure provides qualitative temperature estimates that are backed up quantitatively by TitaniQ and ASIM analysis shown in both the depth profiles and inset. Taken from Hughes et al. (2020).
et al., 2019). They reported on the presence of an elevated geothermal gradient of 50-100°C/km under the Cordillera Blanca detachment during the deformation of the CBSZ.
Chapter 3:

Methods

21 samples were analyzed from the quebradas Gatay, Ishinca, Rajururi, Honda, and Santa Cruz. Samples were collected on previous trips to the Cordillera Blanca in 2011 and 2013 by Micah Jessup’s research group. Thin sections from samples were cut perpendicular to foliation and parallel to lineation. Prior research focused on kinematic indicators, microstructures, deformation temperatures, differential stress, crystallographic preferred orientation, electron backscatter diffraction, strain rates, and strength profiles (Hughes et al., 2019; 2020). For my thesis, I used electron backscatter diffraction data that was acquired previously to create my own quartz crystallographic preferred orientation plots, crystallographic slip system analysis, and crystallographic vorticity analysis. Crystallographic vorticity analysis data was modeled for the 3-D fabric elements (i.e., the foliation pole and stretching lineation) to establish a common geographic reference frame for each sample. Backscatter diffraction data were also implemented into a new method of oblique grain-shape vorticity analysis. Additionally, this new oblique grain shape vorticity analysis calculated the theoretical orientations of ISA\textsubscript{1} and flow apophyses. 3-D fabric elements were used to rotate vorticity axis orientations from CVA analysis as well as the calculated ISA\textsubscript{1} and flow apophyses orientations from the sample reference frame into the established geographic reference frame. The oblique grain-shape vorticity analysis was applied to thin sections using the traditional petrographic approach as well as new method based on electron backscatter diffraction data. The results of the oblique grain-shape vorticity analysis were combined with crystallographic vorticity analysis for plate vector modeling.
3.1 Electron Backscatter Diffraction

Electron backscatter diffraction (EBSD) analysis was carried out by Dr. Colin Shaw and Dr. Cameron Hughes at Montana State University (Bozeman, Montana, USA). EBSD analysis utilized the scanning electron microscope (SEM) and was conducted at 20 Pa and 20-30kV. Oxford Instruments HKL Channel 5 Flamenco software (v.5.5) was used to collect Kikuchi-band diffraction patterns for quartz for 75 reflectors. The minimum grain size present using a petrographic microscope determined a range of step sizes from 1.5 to 5μm. Data collected from EBSD were used to create crystallographic preferred orientation plots, perform crystallographic vorticity axis analysis, oblique grain-shape analysis, and misorientation axes.

3.2 Quartz Crystallographic Preferred Orientation Plots

Quartz crystallographic preferred orientation (CPO) plots were generated for c-axes using collected EBSD data and the MTex toolbox for MATLAB, showing the orientation of the quartz c-axes for an analyzed thin section. Crystallographic preferred orientation plots were used as part of oblique grain-shape vorticity analysis as well as determining which quartz crystallographic slip systems were in place during deformation (Fig. 8).

3.3 Oblique Grain-Shape Method

Deformed quartz-rich rocks often exhibit inclined fabrics with some angle between quartz grains and the fabric foliation in the xz plane (Law, 1990). The angle between inclined quartz grains and the foliation is dictated by vorticity number and degree of finite strain (Platt and Behrmann, 1986). Studies have shown that oblique quartz fabrics form with their long axes (S_b) inclined to local kinematics during progressive deformation (Fig. 9b) (Wallis 1995; Xypolias, 2009). The oblique grain-shape method (oblique-grain-shape/quartz c-axis-fabric
Figure 8. Schematic diagram showing how c-axes and a-axes relate to slip systems with temperature and strain rate on crystallographic preferred orientation plots. From Passchier and Trouw (2005).
method of Xypolias, 2009) can be applied to rocks with a strong fabrics and crystallographic preferred orientation (CPO) data (Wallis, 1995). In deformed quartz-rich rocks, δ is equal to the maximum angle between the main foliation (SA) and the oblique fabric (SB) (e.g., Xypolias (2009) (Fig. 9b). It is approximately the angle between instantaneous stretching axis (ISA1) and principal finite strain axis X (e.g., Xypolias (2009). β is derived from the perpendicular to the crystallographic preferred orientation; CPO and main foliation (SA) (Fig. 9b and 9c) (Wallis, 1995; Xypolias, 2009). β provides information about the flow apophysis A1 (flow plane) and the principal finite strain axis X (Xypolias, 2009). Those values (δ and β) are significant because, if they are known, they can be used to calculate the mean kinematic vorticity number (Wm) using the equation from Wallis (1995):

\[ W_m = \sin 2\theta = \sin 2(\delta + \beta) \]  

Where θ is the angle between SB and A1.

Following the method of Johnson et al. (2009) all measured δ are plotted into histograms for each sample and then the mean and standard deviation of δ angle measurements are used to calculate a range of minimum and maximum Wm values (Fig. 10). Approximately 100 δ angle measurements are taken per thin section and the β angle for each sample is added to the calculated Wm value.

Traditionally, the oblique grain-shape method requires a quartz c-axis CPO plot to measure the angle between the flow plane and the foliation plane (β) as well as a well-developed oblique quartz fabric for determining the orientation of the ISA. Oblique grain shape-method is carried out by hand and this can lead to inaccurate measurements and Wm values.
Figure 9. Schematic illustration of oblique grain-shape vorticity analysis. (a) Relationship between the strain ellipse, ISA’s, $\Theta$, $\delta$, and $\beta$ angles in a dextral shear zone with the vorticity axis lying perpendicular to the inclined grain. $A_1$ represents the shear plane and horizontal flow apophyses, $A_2$ represents the oblique flow apophyses. (b) The long axes of quartz neoblasts with an oblique grain-shape fabric nucleate parallel to the maximum extensional Instantaneous Stretching Axis (ISA). $S_B$ represents the inclined grain axis, $S_A$ is the foliation plane, the angle between the two is the $\delta$ angle which represents the angle between ISA$_1$ and the principal maximum stretching axis. (c) Example calculation of the $\beta$ angle from a c-axes CPO plot where the $S_A$ and $A_1$ are not parallel. The $\beta$ angle represents the angle between the shear-zone boundary and the principal maximum stretching axis. From Xypolias (2009).
Figure 10. Example of the method proposed by Johnson et al. (2009) for calculating a range of $W_m$ values using Manual OGS Vorticity method. The frequency of angle between the quartz long axis and flow plane is displayed on the graph. The mean of angles and standard deviation are then calculated from the dataset to produce a range of $W_m$ values. From Langille et al. (2014).
Error in $W_m$ measurements related to manual oblique grain-shape method can stem from improper measurement of the angle of inclined grains. In addition, calculated values contain a certain amount of bias resulting from which areas of the thin section are used from angle measurements and the partitioning of phases throughout some thin sections. There is also possible room for error when measuring the $\beta$ angle where small changes in the measured angle can result in significant changes in the calculated $W_m$ value (Xypolias, 2010). In collaboration with Dr. Zachary Michels, here we developed a new method of oblique grain shape analysis that utilizes the MTEX toolbox in MATLAB and collected EBSD data. Oblique quartz grains are measured using commands in MATLAB (See Appendix A MATLAB Scripts). This eliminates bias associated with selecting regions of inclined quartz grains when using the traditional petrographic approach. Because all quartz grains are considered within a defined threshold using this new method, the $W_m$ values calculated using this method are considered more reliable.

Rather than using the inclined angle measurements of quartz grains to estimate $\delta$ in conjunction with the $\beta$ angle determined from a CPO plot that “records the angle between the flow apophysis A1 (flow plane) and the principal finite strain axis X” (Xypolias, 2009) this new method only considers the angle between the grain shape preferred orientation (SPO) and the flow apophyses A1 (Fig. 9a). Particles undergoing any degree of general shear are experiencing a degree of rotation and extension (Fig 9a) (Xypolias, 2009; Fossen, 2010). The paths particles take during deformation are divided by theoretical lines called flow apophyses, with one ($A_1$) parallel to the shear direction and another ($A_2$) representing the oblique flow (Fossen, 2010). The grain SPO (Figs. 9b, 12) is calculated using a created function “gSPO” in the MTEX toolbox in MATLAB (Appendix A) that defines a common orientation for the long axis of quartz grains. The orientation of $A_1$ is determined as the perpendicular to the central girdle of the quartz c-axis.
orientations. In both simple shear and monoclinic general shear geometries $A_1$ is expected to be perpendicular to the central girdle of quartz c-axis orientations (Fig. 12). (Platt and Behrmann, 1986; Law, 1990; Wallis, 1993; Johnson et al., 2009). When dealing with general shear, $A_1$ is parallel to the shear direction or more importantly the shear zone boundary (Fig. 11) (Johnson et al., 2009; Xypolias, 2009; Xypolias, 2010). In situations of high strain, $A_1$ can be near parallel to foliation, although this is not always the case, which calls for the need to determine the angle between $A_1$ and $S_a$ (Fig. 11) (Johnson et al., 2009). Because this new approach permits one to calculate the angle $\theta$ between SPO and $A_1$, measuring the $\beta$ angle by hand is not necessary and the new equation for mean kinematic vorticity number is:

$$W_m = \sin 2\Theta$$

(2),

where $\Theta$ is the angle between the grain SPO and $A_1$.

3.4 Crystallographic Vorticity Analysis

Crystallographic vorticity axis analysis is a relatively new method put forth by Michels et al. (2015) that isolates crystallographic orientations from individually deformed grains from using data collected from electron backscatter diffraction. Orientation statistics are used to determine the orientation of a best-fit crystallographic vorticity axis at the grain scale. As many grain-scale vectors are calculated as possible with multiple solutions per grain being necessary to calculate an accurate result (Fig. 13B). A bulk crystallographic vorticity vector is averaged at the specimen scale with the results from grain-scale analysis (Fig. 13C) (Michels et al., 2015). An assumption of CVA analysis is that bulk vorticity axes at the specimen scale record crystal-plastic deformation representative of kinematics operating at the macroscopic scale (Michels et al., 2015).
Figure 11. Diagram showing the quartz c-axis CPO plot placed in a shear zone context relative to the flow plane (Ap1) and fabric foliation. From Johnson et al. (2009).
Figure 12. Oblique grain-shape analysis of sample CB13-55c depicting the orientations of the central-girdle (C-girdle) of quartz c-axis, grain shape preferred orientation (SPO), the horizontal plane, and the flow apophyses (AP). Sample $W_m$ value shown in upper left corner. This plot was generated using the MTex toolbox in MATLAB. Plot contoured at 1 m.u.d. (multiple of uniform distribution) intervals with a 10° halfwidth.
Figure 13. Example of CVA analysis. A: Thin section SEM image containing grains capable of multiple vorticity axis solutions. Inset shows detail region containing the example grain (white outline). B: Isolated grain data colored by orientation relative to the x axis of the map; lower hemisphere projection of intragranular orientations showing the principal axes of the crystallographic unit cells (red, green, blue dots); and derived intragranular vorticity axis (black dot). Dashed arcs of small circles are projected from the calculated axis to show that rotation about the dispersion axis matches the spread of crystallographic orientations. C: Perspective spherical schematic illustrating the kinematic framework in the sample. CVA—crystallographic vorticity axis. From Michels et al. (2015).
When interpreting the kinematics of shear zones and plastically deformed rocks, it is important to view specimens in the plane perpendicular to the vorticity vector (Fig. 1). This is also known as the vorticity-normal surface. Often it is assumed that the vorticity-normal surface is perpendicular to fabric foliation and parallel to stretching lineation. This assumption is not always true and can lead to improper interpretations of kinematic indicators necessitating the need for fabric independent methods of determining the orientation of the vorticity axis. CVA analysis achieves this.

CVA analysis was performed on 21 thin sections using EBSD data and the MTEX toolbox for MATLAB. The number of calculated grain-scale vorticity axes varies for each thin section depending on the grains present and the degree of strain. From the individual grain-scale vorticity axes, a bulk vorticity vector is determined using a kernel density estimation and a 10-degree halfwidth (Michels et al., 2015; Kruckenberg et al., 2019). The vorticity axis at the grain scale represents the 3D rotation and distortion of an individual crystal lattice. Vorticity axes operate on much shorter timescales than other geologic features, thus the grain-scale vorticity axis represents a picture of “instantaneous” rotation recording the most recent geologic event affecting the grain (Kruckenberg et al., 2019). An assumption of CVA analysis is that the sum of many individual grain-scale vorticity axes is representative of the orientation of the vorticity vector at the specimen scale (Fig. 13, B-C). This can be scaled up to the mesoscopic scale and enable interpretations of things such as shear-zone kinematics and geometries (Kruckenberg et al, 2019). Since its first proposal, CVA analysis has been implemented by several researchers including Giorgis et al. (2016), Schmidt et al. (2016), and Kruckenberg et al. (2019). Michels et al., (2015) made available open-source code enabling the application of CVA analysis which was used when carrying out this research.
3.5 FABRICA Analysis

Following the approach of Kruckenberg et al. (2019) (Fig. 14), 3-D fabric elements (i.e., the foliation pole and stretching lineation) can be used to establish a common geographic reference frame for a sample. This can be used to rotate field-based measurements from the specimen reference frame to an overall geographic reference frame. Once the geographic frame is established, results of our CVA analyses (vorticity axes, ISA’s, and flow apophyses) were also rotated into this unifying reference frame (Fig. 14). The purpose of this step is to determine an overall bulk vorticity vector and determine the orientation of ISA’s and flow apophyses at the kinematic scale. To achieve this, we rotated the bulk vorticity axis for each sample into an established reference frame.

3.6 Plate Vector Modeling

The results of CVA and OGS vorticity analysis can be used to constrain the kinematic history of the CBSZ using the following equation:

\[ W_k \cos \alpha = \cos(90 - 2\theta) \]  \hspace{1cm} (3)

‘Where \( \alpha \) is the angle of inclination for an oblique-flow apophysis relative to the foliation plane, and \( \theta \) is the angle of inclination for ISA\(_1\), coincident with the direction of \( \sigma^3 \) of the principal stress ellipsoid, relative to the lineation direction’ (Fig. 15, A-C) (Fossen, 2010; Kruckenberg et al., 2019).

Knowing the orientation of the oblique flow apophyses is a critical step in untangling the kinematic history of a deformed region, because it is parallel to the convergence vector between two plates (Fossen, 2010). Because the oblique-flow apophysis is parallel to the convergence vector between two plates in a convergent setting, it can be used to determine the azimuthal
Figure 14. Example of rotating data from the sample frame into a common geographic reference frame using FABRICA analysis. Shown are equal-area, lower-hemisphere projections of quartz c-axis CPO plots with field lineation, poles to field foliation, and crystallographic vorticity axis plotted as well. Samples are plotted along the Burlington mylonite zone. From Kruckenberg et al. (2019).
orientation of the convergence vector. This can be done by subtracting the angle between flow apophyses (α) from the bulk foliation orientation as was the approach of Kruckenberg et al. (2019) and the approach used in this research. In addition, rotating flow apophyses orientation from the sample reference frame (Fig. 15, B-D) into a common geographic reference frame will yield an oblique flow apophysis parallel to the convergence vector (Fig. 15 H). Rotating data from the sample reference frame into a common geographic reference frame utilizes FABRICA in the MTEX toolbox in MATLAB and is described previously. The angle of convergence between the South American and Nazca Plates has been constant since at least the last 12 Ma at an azimuthal orientation of 082° (Fig. 3) (McNulty et al., 1998). Because of this, the theoretical orientations of oblique-flow apophyses and ISA`s from this research were used to calculate a plate motion vector for the Cordillera Blanca shear zone, thus calibrating a method proposed by Kruckenberg et al., 2019 who calculated a convergence vector for an ancient tectonic terrain (Fig. 15, A and H).

3.7 Slip System Analysis

Using a new approach developed in collaboration with Dr. Zachary Michels, slip systems active during progressive deformation are able to be analyzed using Intracranular Low-Angle (2-10°) Boundary Misorientation data. This approach utilizes the MTEX toolbox in MATLAB to plot low-angle boundary axes derived from collected EBSD data. In this method, the subgrain and inner boundaries are pulled from the grain set, which are then filtered for both the phase in question (quartz in this case) and then for boundaries between 2-10°. The quartz crystal orientations are computed along the boundaries of interest defining a crystallographic reference frame. This is then used to calculate an axis of misorientation, which is plotted in the specimen reference frame (Fig. 16). Published quartz c-axis CPO (Fig. 8) in the CBSZ indicated prism <a>
Figure 15. Diagram showing the approach of Kruckenberg et al. (2019) using the orientation of oblique flow apophyses (α), ISA’s (θ), and calculated $W_k$ values to determine the convergence vector for an ancient tectonic system. A) The relationship between α, θ, and $W_k$. The range of relative plate convergence angle is for the now inactive Burlington Mylonite Zone. B) How the minimum calculated $W_k$ value is related to a specific α and θ angle with the orientations of the oblique flow apophyses and ISA displayed. C) How the maximum calculated $W_k$ value is related to a specific α and θ angle with the orientations of the oblique flow apophyses and ISA displayed. D) Lower hemisphere projections showing the orientations of flow apophyses (black dots), ISA’s (red dots), and the sense of motion of the tectonic region in question. E-H) Fabric elements, bulk CVA axis, flow apophyses, ISA’s, and plate convergence vectors were rotated from the sample reference frame into a common geographic reference frame. From Kruckenberg et al. (2019).
and rhomb $\langle a \rangle$ slip, with two samples that recorded prism $\langle c \rangle$ slip (Hughes et al., 2019; 2020).

This new approach offers a chance to confirm previously reported results.
Figure 16. Diagram showing the relationship between low-angle boundary axes and slip system activity in quartz-dominated systems. From Zachary Michels, PhD.
Chapter 4:

Results

4.1 Quartz C-Axis Crystallographic Preferred Orientation Plots

Quartz c-axis CPO plots were generated (Fig. 17) for determining the angle between fabric foliation (β) and the flow plane for use with manual oblique grain-shape vorticity analysis. In addition, CPO plots can be used to determine dominant slip systems in deformation controlled by quartz. Hughes et al. (2019) determined that CPO patterns contain dominant prism <a> slip and subsidiary rhomb <a> slip in the Quebrada Gatay. All generated CPO plots show a similar pattern with c-axis orientations centered around a central girdle or point maximum. The presence of a central girdle indicates both rhomb <a> and prism <a> slip behavior, whereas a point maximum indicates dominant prism <a> slip (Fig. 8) (Passchier and Trouw, 2005). A few outliers to central girdle and point maxima plots include CB13-57a and CB13-55a. Hughes et al. (2019) found that at a significant depth below the detachment surface, samples displayed weak quartz c-axis CPO’s. This is the case for CB13-57a and CB13-55a that were collected from structural depths of 346 and 386 meters below the detachment surface. Quebrada Rajururi yielded CPO’s that range from rhomb <a> and prism <a> slip in the four samples from the upper 21 m to only prism <a> slip until 65 m. The deepest sample (MJCB11-29) displays a point maximum on the NE and SW quadrants in only prism <c> slip, supporting Hughes et al. (2020). Three samples from Quebrada Ishinca yielded a rhomb <a> and prism <a> slip at 42 and 46 m below the detachment. Sample CB13-09b was collected from a structural depth of 43 m below the detachment surface and the CPO plot is consistent with possible prism <c> slip and work done by Hughes et al. (2020). CPO’s from Quebrada Honda indicate predominate prism <a> and rhomb <a> slip from 4 meters to 53 m below the detachment.
4.2 Crystallographic Vorticity Analysis

Crystallographic vorticity axis analysis was performed on 21 samples using the methods of Michels et al., (2015) and the MTEX toolbox for MATLAB. Crystallographic vorticity axis analysis plots (Fig. 18) that display the orientation of the bulk vorticity axis centered a central point maximum indicating that the vorticity normal surface is parallel to the xz plane. For these samples the CBSZ exhibits a monoclinic shear zone geometry and accurate kinematic interpretations can be made from the surface perpendicular to foliation and parallel to the stretching lineation. Samples MJCB11-29 and CB13-09b display bulk CVA axes perpendicular to the xz plane coinciding with CPO plots possibly recording prism \(<c>\) slip due to significant depths below the detachment.

4.3 Oblique Grain-Shape Analysis

4.3.1 Manual Oblique Grain-Shape Analysis

Following Wallis (1995), oblique grain-shape analysis was carried out on quartz-rich samples with well defined, inclined fabrics. For each viable sample, a beta angle (\(\beta\)) was measured using the quartz c-axis CPO plot. Approximately 100 delta (\(\delta\)) angles were measured using the angle between inclined quartz grains and the foliation plane using Nikon Native Elements software. A \(W_m\) value for each sample was then calculated using the equation \(W_m=\sin 2(\beta+\delta)\). The range of \(W_m\) values for each sample is due to the standard deviation of measured \(\delta\) angles (Johnson et al., 2009; Langille et al., 2014). Four samples in the Quebrada Rajururi, \(W_m\) values range from 0.57-0.96 at structural depths of 10-340 m below the detachment surface indicating deformation that is more dominated by general shear. Three samples in the quebrada Gatay, \(W_m\) values range from 0.92-0.99 at structural depths of 164-386 m below the detachment surface indicating a heavy contribution of simple shear. In the quebrada Honda, \(W_m\) values range
from 0.71-0.99 at structural depths of 4-53 m below the detachment surface indicating a heavy contribution of simple shear. In the quebrada Ishinca, $W_m$ was calculated to be 0.97-0.99 at 42 m below the detachment surface indicating a region dominated by simple shear. Results of oblique grain shape vorticity analysis are displayed below (Fig. 19).

4.3.2 Oblique Grain-Shape Analysis Using MTEX

Oblique grain-shape vorticity analysis was also carried out on 16 samples using a new method. This method calculates a $W_m$ value based on the angle between the inclined quartz grains and the shear zone boundary using collected EBSD data and the MTEX toolbox for MATLAB. The orientations of the flow apophyses are inferred from EBSD data and the shear zone boundary is assumed to be represented by one of these flow apophyses. Figure 20 shows the calculated OGS plots and Table 4.1 displays the associated $W_m$ values. $W_m$ values from five samples in the quebrada Rajururi range from 0.10-0.92 over a structural thickness of 55 m. $W_m$ values from three samples in the Quebrada Gatay range from 0.81-0.99 over a structural thickness of 182 m. $W_m$ values from seven samples in the Quebrada Honda range from 0.21-0.86 over a structural thickness of 49 m. One $W_m$ value from the Quebrada Ishinca was calculated at 0.19 at a structural depth of 46 m. While there is a greater variation in $W_m$ values calculated using this method, the results generally agree with what was seen in the manual OGS calculations. Given the calculated $W_m$ values and associated structural thicknesses, larger ranges in calculated $W_m$ coincide with a greater structural thickness of collected samples.

4.4 Rotating to a Geographic Reference Frame

Samples found to contain foliation and stretching lineations were rotated from the specimen reference frame to an overall geographic reference frame using FABRICA analysis for use with the MTEX toolbox in MATLAB. Plots (Fig. 21) display a rotated CVA axis, rotated
Figure 17. Quartz c-axis (0001) crystallographic-preferred orientation plots. Equal-area, lower-hemisphere projections contoured at 1 m.u.d. (multiple uniform distribution) intervals with a 10-degree halfwidth. Quebradas are ordered north to south, and plots are arranged vertically with increasing structural depth. Structural depth shown on the right of each plot.
Figure 18. Lower-hemisphere, equal-area projections showing the orientation of the vorticity axis using crystallographic vorticity axis analysis. Black star indicates the orientation of bulk vorticity axis. Black great circle represents the orientation of the vorticity normal surface. Plots are contoured at 1 m.u.d. (multiple uniform distribution) intervals using a 10-degree halfwidth. Quebradas are ordered north to south, and samples are positioned vertically with increasing structural depth below the detachment surface.
a) Q. Rajururi:

Figure 19. Results of petrographic Oblique-Grain-Shape Vorticity Analysis. Each sample contains a histogram of the frequency of measured angles between the quartz long axis and the flow plane ($\theta$), the average of measured angles, standard deviation of angles, measured beta angle, calculated $W_m$ value, structural depth below the detachment surface, and associated c-axis CPO plot. Black lines on CPO plots represent measurement of $\beta$ angle. a) Results from Q. Rajururi, b) results from Q. Gatay, c) results from Q. Honda, d) results from Q. Ishinca. Quebradas are ordered north to south.
Figure 19 continued.

**MJCB11-17**

- $\Theta$: 29.9°
- StdDev: 6.15
- $\beta$: 0°
- $W_m$: 0.74-0.95
- Structural Depth: 32m
- $n = 101$

**MJCB11-25**

- $\Theta$: 27.64°
- StdDev: 9.22
- $\beta$: 0°
- $W_m$: 0.60-0.96
- Structural Depth: 65m
- $n = 101$
b) Q. Gatay:

**CB13-55c**

- $\Theta$: 30.27°
- StdDev: 6
- $\beta$: 10°
- $W_m$: 0.93-0.99
- Structural Depth: 164m

$n=99$

**CB13-59**

- $\Theta$: 23.23°
- StdDev: 6.54
- $\beta$: 17°
- $W_m$: 0.92-0.99
- Structural Depth: 319m

$n=100$

Figure 19 continued.
CB13-57c

Angle Between Quartz Long Axis and Flow Plane ($\Theta$)

\[ \Theta: 22.05^\circ \]
\[ \text{StdDev: 3.23} \]
\[ \beta: 16^\circ \]
\[ W_m: 0.94-0.99 \]
\[ \text{Structural Depth: 346m} \]
\[ n=101 \]

c) Q. Honda:

MJCB11-09

Angle Between Quartz Long Axis and Flow Plane ($\Theta$)

\[ \Theta: 27.5^\circ \]
\[ \text{StdDev: 8.48} \]
\[ \beta: 7^\circ \]
\[ W_m: 0.79-0.99 \]
\[ \text{Structural Depth: 13m} \]
\[ n=96 \]

Figure 19 continued.
Figure 19 continued.

For MJCB11-10:
- $\Theta$: 26.56°
- StdDev: 7.92
- $\beta$: 4°
- $W_m$: 0.71-0.95
- Structural Depth: 14m
- n= 75

For MJCB11-14:
- $\Theta$: 30.2°
- StdDev: 6.22
- $\beta$: 0°
- $W_m$: 0.74-0.96
- Structural Depth: 47m
- n= 88
d) Q. Ishinca:

CB13-09a

Angle Between Quartz Long Axis and Flow Plane (θ)

θ: 24.45°
StdDev: 6.61
β: 20°
W_N: 0.97-0.99
m = 101
Structural Depth: 42m

Figure 19 continued.
flow apophyses, a rotated shape preferred orientation of the inclined quartz grains, and the orientation of the foliation plane and stretching lineation. The shape-preferred orientation of inclined quartz grains is assumed to be parallel to one of the ISA$_1$. The orientation of ISA$_1$ in the geographic reference frame is parallel to the convergence vector in an oblique transpressional system (Fossen, 2010). Once rotated into the geographic reference, the quartz SPO can be used to determine the orientation of the convergence vector between the Nazca and South American Plates. The orientation of rotated CVA axes is generally the same for all samples and axes are orientated perpendicular to the direction of convergence.

### 4.5 Misorientation Data

Previous research by Hughes et al. (2019; 2020) used quartz c-axis CPO plots to interpret dominant slip systems during deformation. A new approach uses intragranular low-angle (2-10°) boundary misorientation to interpret dominant slip systems. This new method utilizes the MTEX toolbox in MATLAB. Figure 22, shows plots indicating deformation dominated by prism $<$a$>$ slip with contributions of romb $<$a$>$ slip. This is agrees with what Hughes et al. (2019), reported. However, two samples from Hughes et al (2020) recorded a contribution of prism $<$c$>$ slip. This new method did not show the expected plot for MJ11CB-29 (Figure 16).
a) Q. Rajururi:

Figure 20. Oblique grain-shape analysis plots displaying the quartz c-axis CPO as well as the orientation of the SPO (red line), flow apophyses (blue lines), and the central girdle (grey line). Plots are equal-area, lower-hemisphere projections contoured at 1 m.u.d. intervals with a 5-degree halfwidth. a) results from Q. Rajururi, b) results from Q. Gatay, c) results from Q. Honda, d) results from Q. Ishinca. Quebradas are ordered north to south.
b) Q. Gatay:

![CB13-55c](image1)

![CB13-59](image2)

![CB13-57c](image3)

c) Q. Honda:

![MJCB11-09](image4)

![MJCB11-10](image5)

![MJCB11-11](image6)

![MJCB11-12](image7)

![MJCB11-13](image8)

![MJCB11-14](image9)

![MJCB11-16](image10)

Figure 20 continued.
d) Q. Ishinca:

Figure 20 continued.
Table 4.1. Mean kinematic vorticity ($W_m$) values for MTEX OGS and manual OGS analysis. Quebradas are ordered north to south, and samples within quebradas are ordered with increasing structural depth.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quebrada</th>
<th>MTEX OGS $W_m$ Value</th>
<th>Manual OGS $W_m$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJCB11-23</td>
<td>Rajururi</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>MJCB11-21</td>
<td>Rajururi</td>
<td>0.31</td>
<td>0.56-0.83</td>
</tr>
<tr>
<td>MJCB11-20</td>
<td>Rajururi</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>MJCB11-17</td>
<td>Rajururi</td>
<td>0.14</td>
<td>0.74-0.95</td>
</tr>
<tr>
<td>MJCB11-25</td>
<td>Rajururi</td>
<td>0.90</td>
<td>0.60-0.96</td>
</tr>
<tr>
<td>CB13-55c</td>
<td>Gatay</td>
<td>0.99</td>
<td>0.93-0.99</td>
</tr>
<tr>
<td>CB13-59</td>
<td>Gatay</td>
<td>0.88</td>
<td>0.92-0.99</td>
</tr>
<tr>
<td>CB13-57c</td>
<td>Gatay</td>
<td>0.81</td>
<td>0.94-0.99</td>
</tr>
<tr>
<td>MJCB11-09</td>
<td>Honda</td>
<td>0.70</td>
<td>0.79-0.99</td>
</tr>
<tr>
<td>MJCB11-10</td>
<td>Honda</td>
<td>0.42</td>
<td>0.71-0.95</td>
</tr>
<tr>
<td>MJCB11-11</td>
<td>Honda</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>MJCB11-12</td>
<td>Honda</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>MJCB11-13</td>
<td>Honda</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>MJCB11-14</td>
<td>Honda</td>
<td>0.63</td>
<td>0.74-0.96</td>
</tr>
<tr>
<td>MJCB11-16</td>
<td>Honda</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>CB13-09a</td>
<td>Ishinca</td>
<td></td>
<td>0.97-0.99</td>
</tr>
<tr>
<td>CB13-10</td>
<td>Ishinca</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>
Figure 21. CVA plots rotated from the specimen reference frame to an overall geographic reference frame using fabric foliation and stretching lineation orientations. Samples are listed by quebrada. Plots contain the orientation of the Instantaneous Stretching Axis (red dot) and flow apophyses (blue lines). Modified from Hughes et al. (2020).
a) Q. Rajururi:

Figure 22. Plots showing intragranular, low-angle boundary misorientation data. Plots are contoured at 0.2 m.u.d. intervals with a 15 degree halfwidth. a) plots from Q. Rajururi, b) plots from Q. Gatay, c) plots from Q. Honda, d) plots from Q. Ishinca. Quebradas are ordered north to south.
b) Q. Gatay:

CB13-55c  CB13-59  CB13-57a

CB13-57c  CB13-55a


c) Q. Honda:

MJCB11-09  MJCB11-10  MJCB11-11  MJCB11-12

MJCB11-13  MJCB11-14  MJCB11-15  MJCB11-16

Figure 22 continued.
d) Q. Ishinca:

![Diagram]

CB13-10

Figure 22 continued.
Chapter 5:

Discussion

5.1 Quartz C-Axis CPO Plots

The results of quartz c-axis CPO plots are largely in agreement with results put forth by Hughes et al. (2019, 2020) that deformation in the CBSZ is dominated by prism <a> and rhomb <a> slip (Fig. 8). There are a few samples such as MJCB11-29 and CB13-09b that indicate the possibility of prism <c> slip (Fig. 8).

5.2 Crystallographic Vorticity-Axis Analysis

The results of CVA analysis display a strong central point maximum. Results indicate that the bulk vorticity axis is perpendicular to the xz plane or perpendicular to fabric foliation and parallel to the stretching lineation. Based on the orientation of the bulk vorticity axes, the majority of samples from the CBSZ exhibit a monoclinic shear zone geometry. Crystallographic preferred orientation data for MJCB11-29 records prism <c> slip that was also demonstrated by Hughes et al. (2020). The orientation of the bulk vorticity axis for the sample is located in the perimeter of the plot in the southwest quadrant, while the black great circle represents the orientation of the vorticity normal surface is nearly vertical. Records conditions at deeper positions. Another example of CVA plot deviating from the monoclinic system is CB13-09b. Crystallographic preferred orientation data from this study and Hughes et al. (2020) also records prism <c> slip. It is located at intermediate structural positions between two samples that record CVA indicative of monoclinic deformation. As with sample MJCB11-29 the bulk vorticity axis in located on the perimeter with orientation of the vorticity-normal surface steep. This permits for accurate kinematic interpretations to be made from viewing samples in the xz plane.

Crystallographic vorticity axis analysis is a relatively novel approach for locating the vorticity
normal surface and samples collected from the CBSZ produce well-defined and viable bulk vorticity axes. It can help to avoid samples such as CB13-09b and MJCB11-29 that deviated from monoclinic deformation. This is the first time this method of analysis has been applied to the Cordillera Blanca region.

5.3 Oblique Grain Shape Vorticity Analysis

Results of original manual method with EBSD and the new EBSD related Oblique Grain-Shape Vorticity Axis analysis vary slightly but display similar trends (Fig. 23). Differences in calculated \( W_m \) values are likely due to several factors. Samples that contained widely different results between the two OGS methods contained less pervasive inclined quartz fabrics as well as a high ratio of relict grains to recrystallized grains. In manual OGS analysis, regions of thin sections were selected for measurement based on the presence of inclined quartz grains. As many as 101 measurements were taken from an area of the thin section. A range of angles is predicted due to the known process where after a new quartz grain nucleates at the maximum angle, it then can rotate toward the foliation. The histogram permits \( W_m \) values for each viable sample to be obtained using a fairly robust approach laid out by Johnson et al. (2009). The angle \( \delta \) is the equivalent of the SPO using the MTEX method. This is more difficult to select for using the MTEX method of OGS analysis where a threshold of acceptable angles can be established for viable grains, but there is still room for inappropriate grains to be selected for measurement.

When performing manual OGS analysis, only thin sections with significant regions of inclined grains are viable for use. With the MTEX OGS analysis any thin section that is quartz rich with a shape-preferred orientation of inclined grains and has collected EBSD data can be used to calculate a \( W_m \) value. The MTEX OGS analysis also eliminates the need to measure a \( \beta \) angle as
the $W_m$ value is calculated from the angle between the inclined grain axis and the shear zone boundary. It would seem that there is less room for bias to manipulate results using this new method of OGS analysis but there is room for refining the procedure to produce more reliable results.

There is a variation of calculated vorticity values among the quebradas. For the Rajururi, Gatay, Ishinca and Honda transects using the MTE OGS analysis the $W_m$ values are 0.10-0.90, 0.81-0.99, 0.21-0.86, and 0.19 respectively. For the Rajururi, Gatay, Ishinca, and Honda transects using manual OGS analysis the $W_m$ values are 0.56-0.99, 0.81-0.99, 0.71-0.99, and 0.97-0.99. The Quebrada Gatay yielded results with the most agreement between OGS methods. Quebrada Rajururi displayed a different range of $W_m$ values between OGS analyses, but both methods showed deformation by both pure shear and simple shear dominated regimes. There was some disagreement between results of OGS methods in the Quebrada Honda, but this is likely due to the difference in number of viable samples between methods. Quebrada Ishinca had the largest disagreement of calculated $W_m$ values between methods likely due to the small number of viable samples. Variation in calculated $W_m$ values is likely attributed to the extent of inclined quartz shape preferred fabrics in a given sample and the ration of relict grains to recrystallized grains.

5.4 Intrgranular, Low-Angle Boundary Misorientation Analysis

Results of the low-angle, intragranular misorientation analysis indicate that deformation in the Quebrada Rajururi is dominated by prism $<a>$ slip. Sample MJCB11-23 shows contributions of basal $<a>$ and rhomb $<a>$ slip. Results from the Quebrada Gatay indicate predominantly prism $<a>$ slip with samples CB13-59 and CB13-57c showing a contribution from basal $<a>$ and
Figure 23. Comparison of OGS methods with samples that were viable for both methods of analysis. Results of MTEX OGS analysis shown by the blue line. Results of Manual OGS analysis shown by orange line.
rhomb $<a>$ slip. The data for sample CB13-57a indicate a weak quartz c- axis CPO due to deep structural levels as reported by Hughes et al. (2019). Data from the Quebrada Honda indicates predominant prism $<a>$ slip with most samples showing a contribution of basal $<a>$ and rhomb $<a>$ slip. The Quebrada Ishinca data show predominant prism $<a>$ slip. This agrees with what was reported by Hughes et al. (2020). Quartz c-axis CPO plots indicate prism $<c>$ slip was active in samples MJCB11-29 and CB13-09b in the Quebradas Rajururi and Ishinca. The intragranular, low-angle boundary misorientation plot for MJCB11-29 does not support this and sample CB13-09b was not viable for this method of analysis. Commonly slip systems are interpreted through quartz c-axis CPO plots and this approach offers a novel way of looking at slip systems using EBSD data.

5.5 Plate Vector Modeling

In convergent tectonic settings, such as the collision zone between the Nazca and South American Plates, the vector between two plates is parallel to the oblique flow apophyses (Fossen, 2010). Figure 15 shows the relationship between the angles between the two flow apophyses, the angle of inclination of the instantaneous stretching axes, and the calculated $W_k$ value. $W_k$ is assumed to be equal to $W_m$ in monoclinic shear zones (Kruckenberg et al., 2019). Once the $\alpha$ angle is determined using the above equation, the corresponding angle ($\alpha$) between $A_1$ and $A_2$ can be subtracted from the mean fabric foliation to determine the orientation of the convergence vector between the South America and Nazca plates.

Using eq (3) to calculate the convergence angle between the Nazca and South American Plates the following values are presented. In the Quebrada Gatay, the dominant foliation direction is 162º (Appendix B). Results from MTEX OGS analysis give $W_m$ values ranging from 0.81-0.99. This reveals a range of convergence angles from $137^\circ \pm 67^\circ$ to $160^\circ \pm 95^\circ$. In the
Quebrada Honda the dominant foliation direction is 119° (Appendix B). Results from MTEX OGS analysis yield $W_m$ values from 0.21-0.86 yielding possible convergence angles of $042° \pm 48°$ to $088° \pm 7°$. In the Quebrada Rajururi the dominant foliation direction is 118° (Appendix B). MTEX OGS analysis yield $W_m$ values from values from 0.10-0.92 yielding convergence angles from $033°$ to $095°$. In the Quebrada Ishinca the dominant foliation direction is 242° (Appendix B). MTEX OGS analysis calculated a $W_m$ value of 0.19 yielding a convergence vector of $163° \pm 98°$. The range of $W_m$ values from MTEX OGS analysis is 0.10-.99 and the mean field foliation of the detachment is 145° (Hughes et al., 2020). This yields a range of convergence angles from $061°-137°$ (Fig. 24). The average $W_m$ value from MTEX OGS analysis of all quebradas is 0.54. This yields a convergence vector of $088° \pm 7°$ which very closely matches the 082° convergence vector reported by McNulty (1998).
Figure 24. Chart showing calculated MTEX OGS $W_m$ values and associated convergence vector angles.
Chapter 6:

Conclusions

1) The Cordillera Blanca shear zone (CBSZ) is a recent (5 Ma-present) area of localized brittle-ductile deformation in the Peruvian Andes. Approximately 25 km of normal sense displacement on the roughly 200-km-long CBSZ has juxtaposed mylonitic rocks from the middle crust alongside cataclastic rocks at the surface.

2) New EBSD data confirm the published data of Hughes et al. (2020) indicating dominant prism $<a>$ to prism $<a>$ and rhomb $<a>$ slip, while two samples recorded prism $<c>$ slip. Low-angle, intragranular boundary misorientation analysis showed predominant prism $<a>$ slip in all samples with some samples showing a contribution of rhomb $<a>$ and possible prism $<c>$ slip.

3) Crystallographic vorticity axis analysis of samples from the CBSZ show that the xz plane is parallel to the vorticity normal surface, in many samples. This confirms the geometry of the CBSZ to be monoclinic in all but two samples. Because of the monoclinic geometry for most samples, the CBSZ $W_m$ is assumed to be equal to $W_k$.

4) Quartz-rich samples from the CBSZ proved viable for application of two methods of Oblique Grain Shape Vorticity analysis to determine kinematic vorticity values. The oblique grain-shape method was applied to thin section using petrography. Results yielded calculated $W_m$ values ranging from 0.56-0.99 indicating deformation by both general and simple shear in the CBSZ.

5) I propose a new method of oblique grain-shape vorticity analysis that utilizes collected EBSD data and the MTEX toolbox in MATLAB to calculate a mean kinematic vorticity ($W_m$) value as well as the orientation of flow apophyses and ISA’s. Results of the newly proposed
MTEX OGS vorticity analysis yielded $W_m$ values of 0.10-0.99 for the CBSZ which is a wider range of values than the manual OGS method but still shows deformation by both pure and simple shear. MTEX OGS analysis eliminates this bias by including all grains that fall within a defined threshold and can be performed readily on previously acquired EBSD data.

6) The output data ($W_m$ values, ISA and flow apophyses orientations) of MTEX OGS analysis determined that the convergence vector between the South America and Nazca plates ranges from $061^\circ$-$137^\circ$. An average MTEX $W_m$ value of 0.54 yields a convergence vector of $088^\circ \pm 7^\circ$. McNulty (1998) reported that the convergence vector between the South America and Nazca plates has been constant for the last 12 Ma is $082^\circ$. The use of this new method of vorticity analysis, in conjunction with plate vector modeling provides a calibration for future researchers looking at ancient tectonic systems and enables for unbiased, rapid vorticity analysis of deformed rock samples.
REFERENCES


Bonnot, D., 1984, Neotectonique et tectonique active de la Cordillere Blanche et du Callejon de Huaylans (Andes nord-péruviennes) [Ph.D. thesis]: Paris, University de Paris-Sud, 123 p


APPENDICES

Appendix A

MATLAB Scripts

Application of these scripts requires the use of CVA and FABRICA files available at https://github.com/zmichels

MTEX OGS Analysis

%% Plot the data after import
% figure,
% plot(ebsd)
% saveas(gcf,sprintf('%s_ebsd.png',sampleName))

%% compute some grain boundaries
[grains,ebsd.grainId,ebsd.mis2mean] =
calcGrains(ebsd,'tight','threshold',10*degree);

%% Filter the grain set
% by number of included solutions
grains = grains(grains.grainSize>=3);

%% recompute grains
% reset the ebsd variable
ebsd = ebsd (grains);
% recompute grain boundaries;
[grains,ebsd.grainId,ebsd.mis2mean] =
calcGrains(ebsd,'tight','threshold',10*degree);
grains = smooth(grains,5,'moveTriplePoints');

%% plot
figure,
plot(grains)
saveas(gcf,sprintf('%s_grains_filt.png',sampleName))

%% quartz orientations
% One mean orientation from each grain
o = grains('q').meanOrientation;

% crystal symmetry
cs = o.CS;
h = {Miller(0,0,0,1,'direction',cs),Miller(1,0,-
1,0,'direction',cs),Miller(1,1,-2,0,'direction',cs),Miller(1,0,-
1,1,'direction',cs),Miller(0,1,-1,1,'direction',cs)};

%% plot a CPO from mean orientations and contour/smooth/color
figure,
plotPDF(o,h,'antipodal','lower','smooth','halfwidth',10*degree,'colorrange','equal')
cb = mtexColorbar('Title','M.U.D.');
cb.Limits = [1 cb.Limits(2)];
saveas(gcf,sprintf('%s_CPO_meanOs.png',sampleName))

%% Compute an ODF
odf = calcDensity(o,'halfwidth',10*degree);

%% plot the ODF as a pole figure (looks the same as above)
figure,
plotPDF(odf,h,'antipodal','lower','smooth','colorrange','equal')
cb = mtexColorbar('Title','M.U.D.');
cb.Limits = [1 cb.Limits(2)];
saveas(gcf,sprintf('%s_CPO_meanOs_ODF.png',sampleName))

%% This Next part requires CVA scripts on your MATLAB path

%% Compute CVA results fro grains
% [gCVA, bulkVort] = grainsCVA(grains,ebsd);

%% Plot grain-scale CVA results
figure,
plot(gCVA.CVA,'antipodal','lower','smooth','halfwidth',10*degree)
cb = mtexColorbar('Title','M.U.D.');
cb.Limits = [1 cb.Limits(2)];
saveas(gcf,sprintf('%s_grains CVA.png',sampleName))

%% grid-based CVA
[eV,mags,bv,eId] = gridCVA(ebsd('q'));

%% Plot grid-based results
figure,
plot(eV(1,:), 'antipodal','lower','smooth','halfwidth',10*degree)
cb = mtexColorbar('Title','M.U.D.');
cb.Limits = [1 cb.Limits(2)];
saveas(gcf,sprintf('%s_grid CVA.png',sampleName))

%% SPO
[grains.prop.omega,grains.prop.a,grains.prop.b] = fitEllipse(grains);
gSPO = grains(grains.a./grains.b > 1.4);
[~,spoV] = max(calcDensity(rotate(vector3d.X,rotation('axis',vector3d.Z,'angle',gSPO('q').omega))));
spoV.z = 0;

% setup for proper rotation angle sign for 2nd AP
if spoV.x<0
    r = 1;
elseif spoV.x>0
    r=-1;
end

%% Perpendicular to quartz c-axes
% perpendicular vector
\[ c_{\text{Perp}} = \text{perp}(o \times h(1)) \];

% project onto great circle (z=0)
\[ c_{\text{PerpProj}} = \text{cross}(\text{cross}(c_{\text{Perp}}, z_{\text{vector}}), z_{\text{vector}}) \];

%% Vorticity number from oblique grain shape
% assume the grain shape is aligned with ISAs

% Alternatively, assume the c-axis-perpendicular vector/trace is SZ
\[ SZ = c_{\text{PerpProj}} \];

\[ \Theta = \text{angle}(\text{spoV}, SZ, '\text{antipodal}')/\text{degree} \];

% angle between flow apophyses
\[ \alpha_{\text{ap}} = 90 - 2*\Theta; \]
\[ \text{ap} = \text{rotate}(SZ, \text{rotation}(\text{axis}', z_{\text{vector}}, '\text{angle}', \alpha_{\text{ap}} \text{degree}) \);
\[ \text{apTraces} = \text{cross}(\text{ap}, \text{vector3d.Z}) \];

% vorticity number
\[ W_m = \cosd(\alpha_{\text{ap}}) \];

%% Some angles?
% angle between spo and x-axis (horizontal)
\[ \text{spoAng2X} = \text{angle}(\text{spoV, vector3d.X, 'antipodal'})/\text{degree} \];

% angle between c-axis-perp and x-axis (horizontal)
\[ \text{cPerpAng2X} = \text{angle}(\text{cPerpProj, vector3d.X, 'antipodal'})/\text{degree} \];

% angle between c-axis-perp and spo
\[ \text{cPerpAng2SPO} = \text{angle}(\text{cPerpProj, spoV, 'antipodal'})/\text{degree} \];

%% plot to show
figure,
% plot c-axes
\[ \text{plot}(o \times h(1), '\text{antipodal}', 'lower', 'smooth', 'halfwidth', 5*\text{degree}, '\text{figsize}', 'large') \]
hold on

% add c-axes "girdle" based on perpendicular-fit
\[ \text{plot}(\text{cPerpProj}, '\text{antipodal}', 'lower', 'plane', '\text{LineColor}', [.5 .5 .5], '\text{LineWidth}', 2, '\text{DisplayName}', 'c \text{ girdle}') \]

% add SPO direction, and plane
\[ \text{plot}([\text{spoV} - \text{spoV}], '\text{antipodal}', 'lower', '\text{MarkerFaceColor}', 'r', '\text{DisplayName}', '\text{grain spo}') \]
\[ \text{plot}(\text{cross}(\text{spoV, vector3d.Z}), '\text{antipodal}', 'lower', 'plane', '\text{LineColor}', 'r', '\text{LineWidth}', 2) \]

% add horizontal direction and trace
plot([vector3d.X - vector3d.X], 'antipodal', 'lower', 'MarkerFaceColor', 'k', 'DisplayName', 'horizontal')
plot(vector3d.Y, 'antipodal', 'lower', 'plane', 'LineColor', 'k', 'LineWidth', 2)

% add flow apophyses traces and directions
plot([ap - ap SZ - SZ], 'antipodal', 'lower', 'MarkerFaceColor', 'b', 'DisplayName', 'flow AP')
plot(cross([ap SZ], vector3d.Z), 'antipodal', 'lower', 'plane', 'LineColor', 'b', 'LineWidth', 2)

% add legend
legend show
hold on

% annotate with vorticity
annotation('textbox', [0.7 0.3], 'String', sprintf('W_m = %0.3f', Wm), 'FitBoxToText', 'on', 'FontSize', 12);
saveFigure(sprintf('%s_flow_Geometry.png', sampleName), '-bestfit')

CVA Analysis

%% compute grains from the ebsd dataset
[grains, ebsd.grainId, ebsd.mis2mean] = calcGrains(ebsd, 'angle', 10*degree, 'tight');

%% filter out potentially spurious grains
grains = grains(grains.grainSize>=3 & grains.GOS>0.1*degree);

%% filter ebsd data to match remaining grains
ebsd = ebsd(grains);

%% recompute grains
[grains, ebsd.grainId, ebsd.mis2mean] = calcGrains(ebsd, 'angle', 10*degree, 'tight');

%% RUN CVA ANALYSIS
[gCVA, bv] = grainsCVA(grains, ebsd);

%% Make a plot of the CVA results and add the "bulk" CVA vector
figure,
plot(gCVA.CVA, 'antipodal', 'lower', 'smooth', 'halfwidth', 10*degree)
hold on
plot(bv, 'antipodal', 'lower', 'Marker', '^', 'MarkerSize', 15, 'MarkerFaceColor', 'k', 'MarkerEdgeColor', 'w')
plot(bv, 'plane')
annotation('textbox', [0.7 0.3], 'String', sprintf('n = %i', length(gCVA)), 'FitBoxToText', 'on');
FABRICA Analysis

% assuming you already have some data computed that you want to rotate,
% such as orientations, vectors, ODFs, etc...

%% define the field fabric for the sample
strike  = 150;
dip     = 21;
trend   = 240;
plunge  = 21;

%% use geoFab()
linDir = -vector3d.X;
poleDir = vector3d.Y;

[fabOr, fabRot, strikeV, poleV, linV] = geoFab(strike, dip, trend, linDir, poleDir);

%% Use the variable 'fabRot' to rotate any data...

% for example... CVA results
% all cva vectors
cva = gCVA.CVA;
[~,bulkCVA] = max(calcDensity(cva));

% apply the rotation
cvaRot = fabRot*cva;
bulkCVARot = fabRot*bulkCVA;

% check for SZ variable
if exist('SZ')==0
    SZ = vector3d.X;
end

% normal to SZ for plane/great circle
apNormal = cross(SZ,vector3d.Z);

% check for oblique flow apophysis as variable 'ap'
if exist('ap') == 1
    apOblique = ap;
    apNormal = [apNormal; cross(apOblique,vector3d.Z)];
end

% apply the rotation to apophyses and ap-normals
apNormalRot = fabRot*apNormal;
szRot = fabRot*SZ;
apObliqueRot = fabRot*apOblique;
% ISA from spo
ISA = spoV;
isaRot = fabRot*ISA;

% or orientations
o = grains('q').meanOrientation;
% apply the rottion
oRot = fabRot*o;
% or an ODF...
odf = calcDensity(o);
odfRot = fabRot*odf;

cs = o.CS;
h = [Miller(0,0,0,1,'uvtw',cs),Miller(1,1,-2,0,'uvtw',cs)];

%% plot the rotated CVA
% CVA
figure,
plot(cvaRot,'antipodal','lower','smooth','halfwidth',10*degree,'figsize','large');
% add the field data
hold on
plot(poleV,'antipodal','lower','Marker','s','MarkerSize',12,'MarkerFaceColor','k','MarkerEdgeColor','w')
plot(poleV,'antipodal','plane','LineColor','k')
plot(linV,'antipodal','lower','Marker','o','MarkerSize',10,'MarkerFaceColor','w','MarkerEdgeColor','k')
plot(apNormalRot,'plane','antipodal','lower','LineColor','b','add2all')
plot(bulkCVARot,'antipodal','lower','Marker','^','MarkerSize',10,'MarkerFaceColor','k','MarkerEdgeColor','w','add2all')
plot([isaRot isaRot-isaRot],'antipodal','lower','MarkerFaceColor','r','DisplayName','grain spo')
annotation('textbox',[0 .7 0 .3],'String',sprintf('W_m = %0.3f',Wm),'FitBoxToText','on','FontSize',12);
saveFigure('example_rotated_CVA.png');

%% plot a rotated pole figure
figure,
plotPDF(oRot,h,'antipodal','lower','smooth','halfwidth',10*degree,'colorrange','equal','figsize','large')
% add the field data
hold on
plot(poleV,'antipodal','lower','Marker','s','MarkerSize',12,'MarkerFaceColor','k','MarkerEdgeColor','w','add2all')
plot(poleV,'antipodal','plane','LineColor','k','add2all')
plot(linV,'antipodal','lower','Marker','o','MarkerSize',10,'MarkerFaceColor','w','MarkerEdgeColor','k','add2all')
plot(apNormalRot,'plane','antipodal','lower','LineColor','b','add2all')
plot(bulkCVARot,'antipodal','lower','Marker','^','MarkerSize',10,'MarkerFaceColor','k','MarkerEdgeColor','w','add2all')
plot([isaRot -
isaRot],'antipodal','lower','MarkerFaceColor','r','DisplayName','grain
spo','add2all')
annotation('textbox',[0.7 0.3],'String',sprintf('W_m =
%0.3f',Wm),'FitBoxToText','on','FontSize',12);
saveFigure('example_rotated_CPO.png');

%% trend and plunge of the rotated CVA data
% this next function is new in the Fabrica toolbox, and you may not have it
% yet:
% all the CVA
[trend_CVA,plunge_CVA]=V2TP(cvaRot);
trend_CVA = trend_CVA(:);
plunge_CVA = plunge_CVA(:);

% bulk CVA
[trend_bulkCVA,plunge_bulkCVA]=V2TP(bulkCVARot);

% SZap
[trend_SZap,plunge_SZap]=V2TP(szRot);

% oblique apophysis
[trend_OBap,plunge_OBap]=V2TP(apObliqueRot);

% Make a table for exporting
T = table(trend_CVA,plunge_CVA);
% write table to an excel file format
writetable(T,'example_CVA_TP_export.xlsx')

Low-angle Intragranular Misorientation Analysis

% Assuming grains have already been calculated using a dual-angle
% segmentation approach that allows for computing intragranular boundaries
phase = 'q';
gq = grains(phase);

odfQ = calcDensity(gq.meanOrientation,'halfwidth',10*degree);
oMode = calcModes(odfQ);
cs = odfQ.CS;
h = [Miller(0,0,0,1,'uvtw',cs),Miller(1,1,-2,0,'uvtw',cs),Miller(-1,
1,0,0,'uvtw',cs),Miller(-1,1,0,1,'uvtw',cs)];

%% plot CPO just for reference
figure,
plotPDF(odfQ,h,'antipodal','lower','smooth','halfwidth',10*degree,'colorrange'
', 'equal')
%% Discrete low-angle (2⁻¹₁₀⁻∞) boundary misorientation analysis

% Note, the particular approach used here requires that you specify a
% second angle for inner-boundaries during grain reconstruction (as above)

% get all the subgrain/inner boundaries from the grainset
subB = gq.innerBoundary;

% boundaries of the phase of interest (forsterite in our example case)
subQ = subB(phase,phase);

% condition for only misorientations with angles of 2⁻¹₁₀⁻∞
condLAB = subQ.misorientation.angle>=1*degree &
subQ.misorientation.angle<10*degree;

% the "low-angle" boundaries of interest
labQ = subQ(condLAB);

% plot crystal reference frame
figure,
plotAxisDistribution(labQ.misorientation,'antipodal','lower','smooth','halfwidth',15*degree,'figSize','small')
mtexColorbar('Title','M.U.D.');
saveFigure(sprintf('%s_all_%s_LAB_axes_XTAL.png',sampleName,phase),'-bestfit')

% plot specimen/spatial reference frame
% first get all the crystal orientations along the boundaries
oLab = ebsd('id',labQ.ebsdId).orientations;

% compute the axis of rotation in specimen reference frame
misAx = axis(oLab(:,1),oLab(:,2));

% and angle
misAng = angle(oLab(:,1),oLab(:,2));

% plot specimen
figure,
plot(misAx,'antipodal','lower','smooth','halfwidth',15*degree)
mtexColorbar('Title','M.U.D.');</ns_all_%s_LAB_axes_SPEC.png',sampleName,phase),'-bestfit')

%% plots of LAB orientations
figure,
plotPDF(oLab,h,'antipodal','lower','smooth','colorrange','equal','halfwidth',10*degree)
cb = mtexColorbar('Title','M.U.D.');
setColorRange([0 max(cb.Limits)]);
saveFigure(sprintf('%s_LAB_ors.png',sampleName),'-bestfit')
## Appendix B

### Sample Locations, Orientations, and Types

#### Q. Rajururi:

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Average 242 35 16 247
VITA

Corey Flynn was born in Miami, Florida in October 1989 to Brian and Lisa Flynn. He attended Charlotte Catholic High School, graduating in 2008. He received a Bachelor of Arts degree in Geological Sciences from the University of Colorado at Boulder in December of 2018. Corey gave a presentation on in-situ electron microprobe dating of samples from the N. Madison range in Montana at the 2018 annual meeting for the American Geophysical Union. He received a GTA position in the Fall of 2019 from the Earth and Planetary Sciences Department at the University of Tennessee, Knoxville where he taught introductory geology courses.