Recrystallization fabrics of sheared quartz veins with a strong pre-existing crystallographic preferred orientation from a seismogenic shear zone

Nancy A. Price^{1*}, Won Joon Song¹, Scott E. Johnson¹, Christopher C. Gerbi¹, Rachel J. Beane², David P. West Jr.³

¹ *University of Maine, School of Earth and Climate Sciences, 5790 Bryand Global Sciences Center, Orono, Maine 04469-5790, USA*

² *Department of Earth and Oceanographic Science, Bowdoin College, 6800 College Station, Brunswick, ME 04011-8468, USA*

³ *Department of Geology, Middlebury College, McCardell Bicentennial Hall, 276 Bicentennial Way, Middlebury, Vermont 05753, USA*

*corresponding author

Email Address: naprice@pdx.edu

Present Address: *Department of Geology, Portland State University, P.O. Box 751, Portland, Oregon 97207-0751, USA*

Tel: +1 503 725 3398

Fax: +1 503 725 3025

Email addresses of other authors:

wonjoon.song@maine.edu

johnsons@maine.edu

christopher.gerbi@maine.edu

rbeane@bowdoin.edu

dwest@middlebury.edu

1. Introduction

Shear zones in the continental crust provide important natural laboratories for investigating mineral deformation mechanisms and their potential role in strain localization. Quartz deformation has been particularly well documented due to its common and widespread natural occurrence and the relative ease with which it can be experimentally deformed. These

29 studies have led to a broadly accepted understanding of how quartz recrystallization mechanisms and resulting
30 crystallographic preferred orientation (CPO) patterns relate to deformation conditions in shear zones. Experimental and
31 observational studies (Hirth and Tullis, 1992; Hobbs, 1968; Lloyd and Freeman, 1994; Stipp and Kunze, 2008; Stipp et al.,
32 2002a,b; White 1976) identified and described a progression of dynamic recrystallization quartz microstructures with
33 increasing temperature or decreasing strain rate in water present conditions (Stipp et al., 2002b): grain boundary bulging
34 (BLG; ~280-400°C for water present strain rates of 10^{-12} to 10^{-14} sec⁻¹), subgrain rotation (SGR; ~350-500°C for water
35 present strain rates of 10^{-12} to 10^{-14} sec⁻¹), and grain boundary migration (GBM; begins at the upper range of SGR around
36 ~400-500° for water present strain rates of 10^{-12} to 10^{-14} sec⁻¹). Quartz CPO patterns when plotted relative to the kinematic
37 reference frame (i.e. XY plane parallel to shear zone foliation, X is parallel to lineation direction, and Z is normal to foliation)
38 change with temperature through the temperature-dependent dominance of certain slip systems [basal <a> slip forming a c-
39 axis peak at the edge of the figure near the pole to the foliation (Z-axis), rhomb <a> slip plotting between the Y- and Z-axes,
40 prism <a> slip plotting at the Y-axis, and prism <c> slip plotting at the X-axis] that represent the slip directions with the
41 lowest critical resolved shear stress and the highest calculated Schmid factor (Baëta and Ashbee, 1969; Barth et al., 2010;
42 Hobbs, 1968; Law, 1990; Law et al., 1990; Lister and Dornsiepen, 1982; Lister and Hobbs, 1980; Lister et al., 1978; Lloyd et
43 al., 1992; 1997; Mainprice et al., 1986; Schmid and Casey, 1986; Toy et al., 2008; Tullis et al., 1973). Flow stress affects
44 the mean size of the recrystallized grains (Stipp and Tullis, 2003) and, at the lowest temperatures, may also affect
45 recrystallization mechanisms (Stipp et al., 2002b; Stipp and Tullis, 2003). Therefore, explanation of shear zone development
46 relies on an interpretation of the quartz microstructure and CPO patterns within the context of these progressions and
47 relationships.

48 The strength of a pre-existing fabric and the path of fabric development are among the factors that affect the type of
49 quartz microstructure and CPO that is produced by non-coaxial strain during shear deformation. The persistence of the host
50 rock CPO or parent grain orientation in the CPO of the recrystallized grains can lead to a pattern that is similar to, but more
51 diffuse than, the parent grain or host fabric (e.g. Halfpenny et al., 2006; Heilbronner and Tullis, 2006b; Menegon et al., 2008;
52 Michibayashi and Mainprice, 2004; Pauli et al., 1996; Stipp and Kunze, 2008; Stipp et al., 2002a; Webber et al., 2010).
53 Parent grain orientations and host rock fabrics persist in quartz even with static recrystallization and annealing (Heilbronner
54 and Tullis, 2006a; Kruhl and Peternell, 2002). Furthermore, a large proportion of parent grains may facilitate the
55 development of the new fabric and affect the mechanical evolution of the system if their orientations coincide with the
56 activity of slip systems that have the lowest critical resolved shear stress for the range of grain orientations present (e.g.
57 Michibayashi and Mainprice, 2004; Toy et al., 2008; Webber et al., 2010).

58 Various studies have also shown that quartz microstructure, CPO, and rheology evolve with strain as the parent grains
59 are completely recrystallized and as grains with “hard” orientations are progressively replaced by grains with “soft” or
60 “weak” orientations in the grain population of a quartz-rich sample (Heilbronner and Tullis, 2006b; Kruhl and Peternell,
61 2002; Takeshita et al., 1999). “Soft” refers to grains that, for given conditions of deformation (e.g. temperature, strain
62 geometry), would preferentially recrystallize via slip systems with the highest Schmid factor (e.g. Heilbronner and Tullis,
63 2006b, Law et al, 1990). For these “soft” orientations, the c-axis pole figure pattern changes from maxima at the periphery
64 (Z-axis) to paired maxima along the crossed girdle between the Y- and Z-axes and ultimately to a single peak at the center of
65 the pole figure (Y-axis) with increasing strain, indicating a transitional sequence of slip system dominance from basal $\langle a \rangle$ to
66 rhomb $\langle a \rangle$ to prism $\langle a \rangle$ slip with strain (Heilbronner and Tullis, 2006b; Kruhl and Peternell, 2002; Law et al, 1990; Lloyd
67 and Freeman, 1994; Lloyd et al., 1992; Takeshita et al., 1999). Lloyd and Freeman (1994) and Trimby et al. (1998) both
68 describe a change from SGR-dominant to GBM+SGR-dominant deformation with progressive strain. The quartz
69 microstructure under SGR recrystallization has also been described as progressing from ribbon grains with high aspect ratios
70 through core-mantle dominated microstructures towards complete replacement by new polygonal grains with layered grain
71 orientation domains (Halfpenny et al., 2004, 2006; Law, 1986; Law et al., 1984; Pauli et al., 1996; Trimby et al., 1998).
72 These and other studies collectively indicate that it is important to take into account all steps along the path of fabric
73 development when interpreting quartz microstructures, particularly from areas with complex or overprinting deformational
74 fabrics.

75 We examine the evolution of quartz microstructure and crystallographic orientation data for quartz-rich volumes
76 (referred to in this study collectively as quartz veins) in samples collected from within a shear zone exhumed from frictional-
77 to-viscous transition depths (~10-15km; Schmid and Handy, 1991) of a major crustal fault zone (Sandhill Corner shear zone
78 of the Norumbega fault system in Maine, USA; Price et al., 2012). The frictional-to-viscous transition is effectively
79 interchangeable with terms such as the brittle-ductile or brittle-plastic transition, but we prefer its use in the present
80 geological context (Handy et al, 2007). This study shows that: (1) the pre-existing host rock CPO (i.e. the wall rock that
81 hosts the shear zone) likely persisted in the CPO of the sheared samples and (2) the subsequent path of recrystallization, and
82 thus the resultant CPO, of the sheared samples was different between the inner- and outer-most parts of the shear zone. We
83 interpret the data based on the potential impact of transiently-elevated stresses and strain rates associated with the seismic
84 cycle on the differences in quartz fabrics from the inner- and outer-most parts of the shear zone.

85 86 2. Geologic setting

87 2.1. Regional geology

88 The eastern margin of the Appalachian orogen in Maine, USA is defined by northeast-striking lithotectonic belts that
89 preserve evidence for a complex orogenic history (Fig. 1; Gerbi and West, 2007; Hibbard et al., 2006; Hussey et al., 2010;
90 Tucker et al., 2001; van Staal et al., 2009). Siluro-Devonian subduction-related shortening led to early thrusts and recumbent
91 folds followed by later upright, isoclinal folds (Tucker et al., 2001). Crustal thickening and plutonism caused high-
92 temperature, low-pressure regional metamorphism and local contact metamorphism (Gerbi and West, 2007; Guidotti, 1989).
93 Peak metamorphic grade decreases across Maine from upper amphibolite facies in the southwest to greenschist and sub-
94 greenschist facies in the northeast, representing differential exhumation of an exposed estimated depth range of ~8-25km
95 along strike (Guidotti, 1989; Hubbard et al., 1995; Ludman and Gibbons, 1999; Swanson 1999a,b; Wang and Ludman, 2004;
96 West and Hubbard, 1997; West et al., 1993; West et al., 2008).

97 Following dominantly orthogonal convergence in the Late Silurian-Early Devonian (Bradley et al., 2000; Tucker et
98 al., 2001), a shift to west-directed, dextral transpressive shortening began in Middle-to-Late Devonian time (Gerbi and West,
99 2007; West et al., 2003), coincident with development of the Norumbega fault system. The primary structural evidence for
100 this shift to dextral transpression is the widespread and common occurrence of outcrop-scale, asymmetric folds of
101 compositional layering and quartz veins that indicate progressive dextral shearing (e.g., Short et al., 2006; Frieman et al.,
102 2013). Although the regional tectonic context of this dextral transpression is poorly constrained (e.g., Kuiper, 2016), it was
103 interpreted to have been syn- to post-metamorphic in south-central Maine but prior to regional cooling below muscovite
104 mineral closure temperatures (West and Lux, 1993).

105 The Norumbega fault system includes a 5-40km wide zone characterized by heterogeneously-distributed non-
106 coaxial, viscous, dextral deformation that occurred near peak (sillimanite grade) metamorphic conditions. Superimposed on
107 this early, higher-temperature history are narrow (≤ 2 km), near-vertical strands of highly-localized deformation that formed
108 parallel to the pre-existing compositional layering and higher-temperature foliation of the broader zone of non-coaxial dextral
109 shear. As a result of the differential exhumation noted above, the nature of this localized deformation depends on the along-
110 strike location within the fault system, with central and southern localities characterized by mylonites and ultramylonites, and
111 more northern localities characterized by phyllonites, cataclasites, and breccias (Hatheway, 1971; Ludman, 1998; Short and
112 Johnson, 2006; Short et al., 2011; Swanson, 1988, 1992, 1999b, 2006a,b; Wang and Ludman, 2004; West and Hubbard,
113 1997). Intense strain localization is thought to have occurred prior to or coincident with regional exhumation (West, 1999;
114 West and Hubbard, 1997). $^{40}\text{Ar}/^{39}\text{Ar}$, U-Pb zircon, and monazite ages (Ludman et al., 1999; West and Hubbard, 1997)
115 constrain the timing of dextral shearing and faulting to between Middle Devonian and Early Permian time, although it is not

clear if dextral deformation was continuous or episodic for this ~80-100 my span (West, 1999). Piercing points and calculated shear strain values estimate total right-lateral displacement in the range of ~25-300km (e.g. Hubbard, 1999; Swanson, 1992; Wang and Ludman, 2004).

2.2. Sandhill Corner shear zone

The Sandhill Corner shear zone in south-central Maine is the longest continuous strand of localized deformation in the Norumbega fault system. It is a ~300-500m wide, northeast-striking, subvertical, mylonitic shear zone that is located along the contact of two lithologic units (i.e. a schist unit and a quartzofeldspathic unit) in the study area (Fig. 1; Grover and Fernandes, 2003; Pankiwskyj, 1976; Price et al., 2012; West and Peterman, 2004). The shear zone contains mylonite and ultramylonite derived largely from the quartz- and feldspar-rich rocks of the Cape Elizabeth Formation and to a lesser extent sheared schistose rocks derived from the adjacent Crummett Mountain Formation (West and Peterman, 2004, aka Scarboro Fm. of Grover and Fernandes, 2003). For the purposes of this paper, we henceforth refer to these rocks and their sheared equivalents simply as the quartzofeldspathic unit (i.e. QF host rock, QF protomylonite and mylonite transition zone, QF mylonite) and the schist unit (i.e. schist host rock, sheared schist). The Cape Elizabeth Formation is a metasedimentary rock unit that was partially migmatized and metamorphosed to upper amphibolite facies at a time prior to the development of the later, lower-temperature mylonitic shear zones (biotite + quartz + plagioclase $\pm$ muscovite $\pm$ garnet $\pm$ sillimanite $\pm$ tourmaline; Grover and Fernandes, 2003; West and Peterman, 2004). The Crummett Mountain Formation is a graphite-rich, pelitic schist (quartz + plagioclase + muscovite + biotite + garnet + andalusite $\pm$ sillimanite with abundant andalusite-bearing quartz veins) that is host to complexly-folded and boudinaged lenses of layered calc-silicate granofels (quartz + plagioclase + actinolite $\pm$ calcite $\pm$ biotite; calc-silicate granofels unit of Fig. 1).

Price et al. (2012) describe an across-strike, west-to-east traverse of the Sandhill Corner shear zone in the southern part of the study area (Fig. 1) as containing: (1) a protomylonite to mylonite transition zone up to 100m in width, (2) a ~100-300m wide mylonite banded with layers of ultramylonite that originated as deformed pseudotachylyte, (3) a < 5m shear zone core of ultramylonite and phyllonite, (4) a ~5-10m wide zone of intensely sheared schist, and (5) up to a ~250m zone of heterogeneously-sheared schist. The core of the shear zone is located at the contact between the quartzofeldspathic and schist units. In the QF mylonite and shear zone core, pseudotachylyte and mylonite are mutually-overprinting, indicating coeval frictional and viscous deformation consistent with deformation at frictional-to-viscous transition depths within a major crustal seismogenic fault (Handy et al., 2007; Price et al., 2012).

144 As shown in the equal-area plots in Fig. 1, the Sandhill Corner shear zone has a subvertical foliation (mean
 145 037°/88°NW), a subhorizontal mineral (stretching) lineation (mean 5°→037°), and consistently dextral kinematics associated
 146 with highly non-coaxial strain (kinematic vorticity number 0.97 +/- 0.03 from the quartz method; Johnson et al., 2009). As
 147 noted above, the shear zone is superimposed on, and is parallel to, the earlier higher-temperature shear fabric.
 148 Quartzofeldspathic mylonites are fine-grained with feldspar and mica porphyroclasts that define the mineral lineation (West
 149 and Hubbard, 1997). Thin sections cut perpendicular to the shear zone foliation and parallel to the mineral lineation show
 150 kinematics unambiguously consistent with dextral shear (e.g. shear bands, muscovite fish, sigma and delta feldspar clasts; see
 151 Johnson et al. [2009] and West and Hubbard [1997] for a more detailed discussion of the mylonites and kinematic
 152 indicators). Quartz dynamic recrystallization microstructures and a Type II crossed girdle c-axis CPO pattern (in the
 153 macroscopic foliation plane at right angles to the mineral lineation, Johnson et al., 2009) within the Sandhill Corner shear
 154 zone indicate deformation dominated by dislocation creep, whereas feldspar porphyroclasts deformed by fracture (Johnson et
 155 al., 2009; Price et al., 2012; West and Hubbard, 1997). These microstructures and the mineral assemblage are consistent with
 156 a temperature of mylonitization within the range of 350°C to 450-500°C (Stipp et al., 2002a,b). This temperature range
 157 extends below the minimum temperature for the peak metamorphic conditions of the host rock (sillimanite grade, ≥500°C;
 158 e.g. Hodges and Spears, 1982), indicating that localization post-dated peak metamorphism, possibly coincident with
 159 exhumation (West, 1999; West and Hubbard, 1997). There is little evidence to indicate that the Sandhill Corner shear zone
 160 experienced later, lower-temperature reactivation or overprint in the study area following strain localization (e.g. a lack of
 161 post-deformational growth of new quartz grains, chlorite retrogression, or thermobarometric discontinuities; Johnson et al.,
 162 2009; Price et al., 2012; West and Hubbard, 1997; West et al., 2008).

163

164 3. Field observations

165 Quartz veins within the schist and quartzofeldspathic unit host rock are asymmetrically-folded quartz-rich volumes
 166 (Fig. 2). These folds, in addition to folds of compositional layering, are widespread and common, particularly in the schist,
 167 and correlate with the regionally extensive, outcrop-scale asymmetric folds described in Section 2.1. These folds formed by
 168 progressive shearing during the earlier, higher-temperature history of the Norumbega fault system. As is typical for folds
 169 arising from progressive shearing, many stages of fold rotation can commonly be seen at any outcrop with abundant quartz
 170 veins, from folds at early stages of initiation with local axial surface foliation at a high angle (30-45°) to the shear plane to
 171 others at later stages that are either (a) rotated into concordance with the subvertical shear zone foliation (mean strike:
 172 ~037°), flattened, and thinned (Fig. 2e) or (b) attenuated and imbricated (Fig. 2c,d). At the later stages of fold evolution, the

association among the parts of a given fold (i.e. “upper” and “lower” limbs of a fold) is typically lost (Fig. 2e,f), and the thinned quartz veins are further disrupted by shear banding and asymmetric boudinage. Folds in the early stages of development typically plunge moderately to steeply to the north-northeast (example fold hinge trend and plunge of $\sim 35^{\circ} \rightarrow 025^{\circ}$), verge to the north, and are associated with a fold-specific, variably but moderate-to-steeply dipping axial surface foliation (example strike and dip of $\sim 005^{\circ}/50^{\circ}\text{SE}$) (Fig. 2a,b). The thickness of the veins ranges from several centimeters to a millimeter or less, with vein thickness decreasing with proximity to the shear zone core. The transition zone from quartzofeldspathic host rock to mylonite (Fig 3) is not as well exposed as the schist transition, but the quartz veins within the mylonite are also thinned (mm-scale) and parallel to the subvertical shear zone foliation. Given that the quartz veins had been progressively deformed by folding and shearing, crosscutting relationships that might indicate an origin for the veins have been lost. However, it is likely that they represent mineralized fractures and/or quartz-rich veins of pegmatite origin that formed during peak metamorphism prior to the asymmetric folding and shearing associated with the onset of dextral kinematics.

4. Analytical Methods

A suite of oriented samples were collected from an across-strike transect of Sandhill Corner shear zone (Fig. 1 and Table 1). This study is based on analyses of over 50 thin sections, with a subset of the most representative samples highlighted in the paper. Samples described in this paper were largely collected within the southern part of the field area, where the shear zone comprises only the quartzofeldspathic and schist units, and were cut perpendicular to local foliations and parallel to local lineations, all of which are consistent with the mean lineation and foliation of the shear zone (Fig. 1). Several host rock fold samples were cut perpendicular to the mean shear zone foliation and parallel to the mean mineral lineation (noting north/northeast) as well as perpendicular to the fold hinge as observed in hand sample (noting down-plunge and northeast directions, see Fig. 7). Thin sections were made from multi-grain, quartz-rich volumes oriented sub-parallel to the shear zone foliation and far from porphyroclasts; no matrix quartz was analyzed for this study.

Quartz CPO and misorientation plots are based on quartz mineral orientation maps created using electron backscatter diffraction (EBSD) on polished sections of quartz veins (Nowell and Wright, 2004; Prior et al., 1999). Polished sections were mechanically polished to 0.3 μm grit and chemically polished with a colloidal silica suspension (Lloyd, 1987). Electron dispersive spectroscopy (EDS) was coupled with EBSD to create mineral-specific orientation maps using the VEGA-XMU Scanning Electron Microscope at the University of Maine with TSL-OIM Data Collection and EDAX Genesis software. Operating parameters during EBSD data collection on uncoated samples oriented at a 70° tilt at high vacuum included an

202 accelerating voltage of 20kV, a working distance of 25mm, and a probe current of 10nA, corresponding to a spot size of ~1
203 μm . Data acquisition parameters for the EBSD were set in the TSL-OIM software with a square grid at 2×2 binning, high
204 gain, a binned pattern size of 160, a theta step size of 0.5° , 8 bands, and 11 reflector families for quartz. The step size for
205 mineral orientation maps varied between $2\mu\text{m}$ and $\sim 10\mu\text{m}$ depending on grain size of the sample. The raw indexing rates of
206 quartz ranged from 97% to 100%.

207 Quartz EBSD data filtered by chemistry were processed and plotted with the TSL-OIM post-processing software. Post-
208 processing (a cleanup routine) of quartz data points based on confidence index (CI) and neighboring orientations included the
209 replacement of non- and poor-indexed points ($\text{CI} < 0.1$) with well-indexed neighboring points of $\text{CI} > 0.1$ (“neighbor CI and
210 orientation correlations”; grain tolerance angle 10° , minimum CI of 0.1, clean up level 2). The well-indexed points ranged
211 between 72 to 90% of the raw quartz maps for most samples. The confidence index is a parameter used by the processing
212 software to determine pattern indexing accuracy based on a voting system in which each pattern solution is compared to the
213 next best solution and then ranked. To remove suspicious grains smaller than 4 pixels (collection points), the EBSD data
214 were cleaned via a one or two times iterative routine (“grain dilation”; grain tolerance angle 10° , minimum grain size 4
215 pixels), where the orientation of points that do not belong to a grain are changed to match that of neighboring grains if the
216 majority of those neighbors belong to the same grain. Grains in post-processing are defined by an internal misorientation
217 $< 10^\circ$ and a minimum grain size of 4 pixels. The data sets were used to plot misorientation angle histogram profiles, rotation
218 angle boundary maps, and inverse pole figures. All mineral orientation maps were focused on quartz within individual veins;
219 if a map captured data from matrix quartz, the map was cropped so that only the data from the quartz grains in the vein were
220 used.

221 Pole figures are equal area, lower hemisphere projections with linear contouring. For samples plotted in the kinematic
222 reference frame of the shear zone (i.e. perpendicular to the subvertical shear zone foliation, parallel to the subhorizontal
223 lineation), the XY plane of the pole figure is parallel to the shear zone foliation, X is parallel to the lineation direction, and Z
224 is normal to the foliation. For the fold sample cut within the shear zone kinematic reference frame (i.e. perpendicular to the
225 mean shear zone foliation and parallel to the mean mineral lineation), the right side of the pole figure corresponds to the
226 northeast compass direction (see Fig. 7a). For the fold sample cut within the fold reference frame, the pole figure is plotted
227 and labeled so that the XZ plane is perpendicular to the fold hinge, the Y direction is parallel to the fold hinge, and the east
228 compass direction is highlighted on the pole figure (see Fig. 7b). Misorientations were measured from each pixel; pole
229 figures were plotted from cleaned mineral orientation maps using one average orientation per grain. Quartz misorientation
230 plots were limited to rotation angles between 5 - 104.5° with 5° bin, following symmetry constraints and recommendations of

231 Prior (1999). Where the quartz mineral orientation maps are used to show quartz grain types, the data were processed to
232 show one average orientation per grain and to remove Dauphiné twins. Additional analyses, including quartz grain size, will
233 be included in a separate, follow-up paper that will focus in more detail on the spatial distribution of quartz data along and
234 across strike and the implications for the architecture and microstructural evolution of a seismogenic shear zone at frictional-
235 to-viscous transition depths.

236

237 5. Quartz microstructures

238 Three quartz grain types dominate the recrystallized quartz veins in rocks of the Sandhill Corner shear zone: (1) large,
239 amoeboid, low aspect ratio grains; (2) large, high aspect ratio grains; and (3) small, low aspect ratio grains. These grain types
240 are found independently within some veins as well as in combination within other veins. In this section and in Figs. 1, 3, and
241 4, we describe the observed quartz microstructures in terms of the grain types and where in the shear zone the microstructures
242 are found, including uncommon microstructures; an interpretation of the deformation mechanisms follows in the discussion
243 (Section 8.1).

244

245 5.1. Grain Type 1- large, amoeboid, low aspect ratio grains

246 Asymmetrically-folded quartz veins within the schist and quartzofeldspathic host rock display large ($>100\mu\text{m}$),
247 irregularly-shaped grains with lobate grain boundaries, some local undulatory extinction, and smaller island grains (Figs. 3
248 and 4a). Although the aspect ratio of the grains is relatively low ($<\sim 5$), the grains form a shape-preferred orientation that is
249 parallel to the axial surface of the asymmetric quartz folds.

250

251 5.2. Grain Type 2- large, high aspect ratio grains

252 Straight quartz veins parallel to the shear zone foliation within the mylonite, sheared schist, and locally in the
253 protomylonite contain long, thin grains with high aspect ratios (~ 5 -20) that are aligned parallel to the shear zone foliation
254 (Figs. 3 and 4a). The size of the large, high aspect ratio grains is typically $>100\mu\text{m}$ in equivalent diameter, with some veins
255 containing smaller, very highly elongate grains (aspect ratio >20). Where asymmetric quartz folds have been rotated towards
256 the foliation, these elongate grains may locally define a shape preferred orientation axial surface to the rotated fold, whether
257 or not the fold has been rotated into complete alignment with the shear zone foliation. The grains display broad undulatory
258 extinction, and smaller elongate island grains are present. The boundaries of these grains are lobate, particularly where they
259 interfinger, but otherwise have a straight appearance along their length. The grain boundaries may locally have a high-

frequency, serrated appearance in places where a few smaller, low aspect ratio grains are present along the boundary. Veins that contain only Type 2 grains do not show significant evidence for polygonal subgrains. Large, high aspect ratio grains that display the core-mantle microstructure and that contain subgrains are described below as a combination microstructure.

5.3 Grain Type 3- small, low aspect ratio grains

Quartz veins in the quartzofeldspathic mylonite, the shear zone core, and sheared schist closest to the shear zone core display grains that have relatively low aspect ratios (<4) and that are smaller ($\sim 5\sim 80\mu\text{m}$) than either of the other two grain types (Figs. 3 and 4a). Type 3 grains are a mixture of irregularly shaped grains with weakly lobate grain boundaries and more polygonal grains with straighter grain boundaries; in only a few rare samples are the small grains all polygonal in shape. The more elongate of the small, irregularly-shaped grains define a shape-preferred orientation at an angle to the shear zone foliation that varies in strength among samples. Extinction patterns in crossed polarized light in many samples show layers of elongate grain orientation domains (groupings of small grains with similar orientations) that are parallel to the shear zone foliation. The layering is more pronounced in some veins than in others (typically in the quartzofeldspathic mylonite samples), and not all veins with only Type 3 grains display this layering.

5.4 Combinations of grain types

Grain type combinations are dominated by a mixture of large and small grains: (a) Types 1 and 3, or (b) Types 2 and 3 (Fig. 4b). The first combination (a) of the large, low aspect ratio, amoeboid-shaped grains (Type 1) and smaller, low aspect ratio grains (Type 3) is only found in the schist host rock, the quartzofeldspathic host rock, and the QF protomylonite at the edges of the shear zone (Fig. 3). Type 3 grains, which are polygonal in shape, are typically found along the boundaries between the larger Type 1 grains giving them a serrated appearance. Type 1 grains may display patchy extinction patterns and contain subgrains, particularly with increased proximity to grain boundaries. A rare example of cataclasite in the protomylonite (205; Fig. 5) is associated with this combination of grains, with local replacement of Type 1 by Type 3 grains where this shear fracture occurs.

The second combination (b) of large, high aspect ratio grains (Type 2) and smaller, low aspect ratio grains (Type 3) is present in the QF protomylonite and mylonite transition zone, and common in the QF mylonite (Fig. 3). The Type 3 grains surround the larger Type 2 grains creating a core-mantle microstructure (Fig. 4b). The Type 2 grains display patchy extinction and contain subgrains, most prominently at their boundaries. Smaller Type 3 grains are both polygonal and irregular in shape. The proportion of Type 2 to Type 3 grains is variable and is not directly associated with proximity to the

shear zone core. In veins with a larger proportion of smaller Type 3 grains, the smaller grains commonly display layered grain orientation domains, particularly veins from the QF mylonite samples.

Quartz veins containing all three grain types (Fig. 4b) are predominantly found in the sheared schist where the folded veins are variably transposed, imbricated, and attenuated. Limbs that have been thinned show large, high aspect ratio grains (Type 2) that are aligned parallel to the limb edge and the shear zone foliation, whereas the limbs that have been rotated and/or imbricated with little thinning display amoeboid, low aspect ratio grains (Type 1) that maintain the fold-related shape-preferred orientation at an angle to the shear zone foliation. The large grains (Type 1 and 2) locally contain subgrains and smaller, low aspect ratio grains (Type 3) along grain boundaries but do not show a well-developed core-mantle microstructure. Clusters of small Type 3 grains are found at the edges of quartz veins that have large grains at the center.

5.5. Uncommon quartz microstructures.

Some quartz veins display uncommon extinction patterns and uncommon relationships between grains that do not fit into the grain type groups listed above (Fig. 6). Rare, particularly large grains ($>1\text{-}2\text{cm}$) within quartz veins of the QF mylonite are cut by discontinuous strings of small polygonal grains (Fig. 6a). These strings are at most a few grains in width, are dominantly foliation parallel, and do not cut across the entire host grain. The host grain displays patchy extinction but is not pervasively subgrained. Where these host grains are surrounded by the core-mantle microstructure (Type 2 + 3 grains), the large host grain and the Type 3 grains surrounding it have the same extinction point in crossed polarized light. Also, a few quartz veins display irregularly blocky and patchy extinction patterns that are associated with heterogeneous subgrain distributions (Fig. 6b-d). These veins are spatially associated with pseudotachylyte and deformed pseudotachylyte veins, and have a low proportion of indexed points when mapped for crystal orientation with the SEM-EBSD.

6. Quartz CPO patterns

6.1. Host rock CPO

The quartz veins in the schist and quartzofeldspathic host rock are asymmetrically-folded, and folds at a relatively early stage of development and progressive rotation show an associated CPO (Fig. 7). Plotted in the fold kinematic reference frame as labeled in Fig. 7b (i.e. XZ plane perpendicular to the fold hinge, Y direction parallel to the fold hinge), the CPO of these folds appears as a broad c-axis maximum overlapping the right and left edges of the pole figure perpendicular to the fold hinge and an a-axis girdle within the XY plane. C-axis pole figures for individual fold limbs and c-axis figures from sections around the fold do not show significant, reproducible differences in CPO patterns (e.g. Hongn and Hippertt, 2001).

318 Within the reference frame of the shear zone (i.e. the XY plane is parallel to the subvertical shear zone foliation, $\sim 37^\circ$ strike;
319 X is parallel to the lineation; Z is normal to the foliation; and the right side of the pole figure to the northeast), the c-axis
320 maximum of the host rock fold plots in the upper left quadrant of the pole figure and the a-axis plots as a girdle that extends
321 from the upper right to the lower left quadrant $\sim 30^\circ$ from the edge of the pole figure (Fig. 7a). In the host rock fold samples
322 studied, the strength of the host rock CPO and the exact location of the c-axis maximum within the upper left quadrant of the
323 pole figure varies from sample to sample, as might be expected for folds formed by progressive shearing.

324

325 6.2. Shear fabric CPO

326 Fig. 8 shows representative CPO pole figures produced from quartz veins of the sheared schist unit, the QF
327 mylonite, and the QF protomylonite and mylonite transition zone. The c-axis patterns observed (plotted with the XY plane
328 parallel to the subvertical shear zone foliation; X is parallel to the lineation; and Z is normal to the foliation) can be grouped
329 into a number of types: (a) single maximum (58, Fig 8); (b) paired maxima mirrored on either side of the XY plane (56, Fig
330 8); and (c) an elongate crossed girdle perpendicular to the XY plane (67, NFS2, Fig 8). These c-axis pattern types are
331 observed in samples collected from all the rock units deformed within the shear zone. However, the crossed girdle patterns
332 (c) are more commonly found in quartz veins from the highly-sheared schist and the QF protomylonite and mylonite
333 transition zone, whereas the single and paired maxima (a, b) are more commonly found in veins from the QF mylonite.

334 In samples that display a single c-axis maximum, the cluster of poles is typically located either in one quadrant or in
335 the center of one half of the pole figure (58, Fig. 8). Only one sample displays a c-axis maximum at the center of the pole
336 figure (264, Fig. 8); this sample was collected from an unfolded sheared pegmatite of the QF transition zone. In samples that
337 show paired maxima in locations mirrored on either side of the XY plane, one maximum is typically stronger (i.e. contains a
338 higher concentration of poles) (41, Fig. 8). The spread of poles around these maxima may define a weak crossed girdle
339 pattern, connecting the maxima across the center of the pole figure perpendicular to the XY plane (51, 56, Fig. 8). Where the
340 c-axis patterns display a well-developed crossed girdle, the crossed girdles are nearly perpendicular to the left-right equator
341 of the pole figure (i.e. the flow plane is nearly parallel or at a small angle to the foliation; NFS2, Fig. 8). Many crossed girdle
342 patterns display an asymmetry about the XY plane, where one half of the girdle contains a stronger cluster of poles than the
343 other half of the girdle (67, Fig. 8). The crossed girdle pattern may (67, Fig. 8) or may not (61, Fig. 8) display tails, typically
344 weaker than the rest of the crossed girdle. In the few samples where these tails are better developed, the tails show an
345 asymmetry about the YZ plane, consistent with right-lateral deformation (67, Fig. 8).

346

6.3. CPO patterns and quartz microstructures

A comparison between the CPO patterns of the large and small Types 2 and 3 grains from samples of mixed grain types (e.g. core-mantle microstructure) shows little difference in the location of poles in the c-axis pole figures (Fig. 9). In samples that show a crossed girdle pattern, the large and small grains will both display the same pattern shape. The patterns between the large and small grains do differ in the clustering of the poles, which is a result of the fact that there are a greater number of smaller grains in a given map over larger grains. There is no clear correlation between the presence of tails in the c-axis pole figure and grain size; where a sample displays a crossed girdle pattern with tails (Fig. 9), the figure of the large and small grains both display tails.

Veins containing only the small Type 3 grains typically display single or paired maxima rather than well-developed crossed girdles, particularly within the veins of QF mylonite and samples from the shear zone core. In samples where these veins display alternating layers of elongate grain orientation domains, the paired c-axis maxima reflect the orientations of the grain domains. For example, Fig. 10 shows that one maximum (Fig. 10a) is associated with one fabric domain and that the other maximum (Fig. 10b) is associated with the second fabric domain.

7. Misorientation Analysis

7.1. Misorientation rotation angle profiles

Figs. 10 and 11 show a selection of representative misorientation rotation angle profiles based on the shapes of the neighbor-pair profiles (red) relative to the random-pair (blue) and random (green) profiles (Wheeler et al., 2001). The nearest-neighbor misorientation, as plotted on a histogram, describes the angle of rotation between two adjacent pixels (collection points), providing the misorientation across grain boundaries, whereas the random-pair misorientation describes the misorientation profile of the entire population of pixels. The differences between histograms plotting these two misorientation types can reflect interactions between neighboring grains and/or reflect orientation inheritance from a parent grain (Neumann, 2000). In all samples, the neighbor-pair profiles (red) are dominated by a peak at 60° that deviates from the random-pair profiles (blue), which is consistent with observations of samples containing Dauphiné twins (e.g. Lloyd, 2004).

In one population of quartz veins, the neighbor-pair profiles (28 and 264, Fig. 11) show a higher number fraction at 5° , a decrease between 5 - 10° , relatively constant number fraction from 10 to 50° , an increase to the asymmetric peak at 60° , and a decrease at higher angles. In one quartz vein within a sheared, unfolded pegmatite, the decrease in neighbor-pair number fraction after 60° is abrupt (264, Fig. 11). In most quartz veins, this transition is gradual, with the neighbor-pair number

fraction steadily decreasing with increasing misorientation up to $\sim 90^\circ$ (28, 70, Fig. 11). The random-pair profile (blue) in the latter patterns (70, Fig. 11) typically increases gradually from the low and high angle ends of the profile to a less pronounced peak around 60° ; quartz veins with these misorientation profiles commonly have well-developed crossed girdle c-axis pattern.

In contrast, a different population of quartz veins displays a flat neighbor-pair profile (red), where the number fraction is roughly the same from 10° to 90° (53, Fig. 11; 93, Fig. 10). The only significant variation in the flat neighbor-pair profile is the peak at 60° . The random-pair profile (blue) in this group of samples is more variable, displaying a broad peak around 60° (51, Fig. 11), a flatter profile (53, Fig. 11), or a skewed profile with greater number fractions with higher misorientation angles (93, Fig. 10, 12). Quartz veins with a CPO of a single or paired c-axis maxima display the flat neighbor-pair misorientation profiles, particularly in those samples from the QF mylonite and the shear zone core dominated by Type 3 grains. Veins within this group with misorientation profiles that vary from the flat neighbor-pair misorientation profile (51, Fig. 11 vs. 93, Fig. 10, 12) display a decrease in the number fraction at higher misorientation angles, suggesting transitional states between the veins that display the flat neighbor-pair profile (53, Fig. 10) and veins that display the profiles described in the preceding paragraph (264, Fig. 10).

7.2. Inverse pole figures

Inverse pole figure (IPF) plots of the orientation of misorientation rotation axes show a clustering of axes plotting near the c-axis for misorientations in or less than the $60\text{--}70^\circ$ rotation interval (Fig. 12). In all samples, the strongest c-axis clustering is found within the $50\text{--}60^\circ$ rotation interval, and presence and/or strength of c-axis clustering in other rotation angles intervals varies by sample. For misorientation rotations greater than $\sim 70^\circ$, points cluster at the edge of the forbidden zone (i.e. areas on the IPF plots where rotations do not plot because of geometric constraints resulting from symmetry in quartz; Grimmer, 1980; Mackenzie, 1964; Wheeler et al., 2001). Many samples also show clustering at the sides of the pole figure in the $70\text{--}80^\circ$, $80\text{--}90^\circ$, and/or $90\text{--}100^\circ$ intervals and about the rhombohedral (0-111) and (1-101) orientations; this clustering is strongest in samples that do not show a flat nearest-neighbor misorientation rotation angle profile (28 and 264 vs. 93, Fig. 12). Diffuse clustering around the prism (0-110) and (1-100) orientations or a-axis occurs in only a few rare samples.

7.3. Grain boundary maps and relationship to grain types

404 The grain boundary maps show the correlation between misorientation angle at grain boundaries and grain
405 microstructure (Fig. 11). Where there is a combination of large and small grain types, the highest misorientation angles, $>70^\circ$
406 and $50-70^\circ$, are at the boundaries of the large grains (e.g. blue and black colored boundaries of 28, 70, Fig. 11).

407 The connection between misorientation angle and grain types is most apparent in veins that contain only small Type
408 3 grains and alternating layering of grain orientation domains; the orientation domains display different misorientation
409 profiles (Fig. 10). The grain domains that are associated with the stronger, c-axis maximum (Fig. 10a) have a stepped
410 neighbor-pair misorientation profile, with $10-50^\circ$ rotations displaying a higher number fraction than $70-100^\circ$ rotations. The
411 random-pair profile for these domains mirrors the neighbor-pair profile, with more low angle boundaries ($<50^\circ$) and fewer
412 high angle boundaries ($>70^\circ$). The grain domains that are associated with the weaker c-axis maximum (Fig. 10b), have a
413 stepped to flat neighbor-pair profile that has slightly more boundaries with high angles ($>70^\circ$). The random-pair profile for
414 these domains is similar to the random profile. In total, with both domains included, the quartz vein shows a flat neighbor-
415 pair profile with a near random random-pair profile dominated by greater number fractions at higher misorientation angles.

416

417 8. Discussion

418 The majority of the quartz veins in the Sandhill Corner shear zone represent recrystallization of existing,
419 asymmetrically-folded veins present in the host rocks, the transposition and thinning of which in the schist can be traced from
420 the edges of the shear zone inward towards the shear zone core. The origin of quartz veins in the QF mylonite is less clear,
421 particularly samples nearest the shear zone core where the veins are thinner ($<1\text{ mm}$) and where mineralized intergranular
422 fractures in feldspar are filled with quartz (Johnson et al., 2009). Multi-grain, quartz-rich volumes, oriented sub-parallel to
423 the shear zone foliation and far from porphyroclasts were preferentially chosen to reduce the likelihood of analyzing a sample
424 that formed later in the history of the shear zone as a mineralized fracture, that might not have reached steady-state, or that
425 preserves evidence for strain within a localized kinematic reference frame different from that of the larger shear zone. The
426 consistency of microstructural observations and data among spatially-associated samples (e.g. inner-most vs. outer-most parts
427 of the shear zone) suggest that the majority of the samples did not originate later in the shear zone history. Therefore,
428 although the timing and origin of all quartz veins cannot be unambiguously determined, the data are presented and
429 interpreted under the assumption that the majority of quartz veins analyzed originated from the asymmetrically-folded veins
430 present in the host rock.

431

432 8.1. Interpretation of quartz microstructures

433 The large, low aspect ratio, amoeboid Type 1 grains are characteristic of the host rock fabric. The island grains and
434 lobate grain boundaries of Type 1 grains reflect deformation by GBM recrystallization (Hirth and Tullis, 1992; Stipp et al.,
435 2002a,b). At the edges of the shear zone, particularly within the sheared schist, the folded asymmetric quartz veins of the
436 host rock were transposed with minor internal recrystallization (Figs. 2 and 3), the rotation being partly or largely
437 accommodated by deformation in the biotite-rich matrix; these fold limbs still display the SPO that had been coincident with
438 the axial surface of the associated asymmetric fold (Fig. 7).

439 At the edge of the shear zone in the sheared schist and in the QF protomylonite (Figs. 3 and 4), the Type 1 grains of
440 the host rock are overprinted along grain boundaries by Type 3 grains. The serrated Type 1 grain boundaries and the
441 presence of subgrains near the grain boundaries indicate that these Type 3 grains formed from SGR recrystallization
442 mechanisms (Hobbs, 1968; Lloyd and Freeman, 1994; Stipp and Kunze, 2008; Stipp et al., 2002a,b; White 1976). These
443 microstructures may indicate deformation at lower temperatures, assuming a constant strain rate. The association of the Type
444 3 grains with the one sample that shows cataclasite in the protomylonite (205, Fig. 5) suggests that SGR recrystallization was
445 contemporaneous with seismic slip in the Sandhill Corner shear zone, as is consistent with the mutually-overprinting nature
446 of pseudotachylyte and mylonite in these rocks (Price et al., 2012).

447 Within the shear zone, the majority of the small Type 3 grains display microstructures that are consistent with both
448 SGR and GBM recrystallization (Figs. 3 and 4). The SGR-dominant recrystallization is interpreted from the polygonal grain
449 shape and from the core-mantle microstructure with subgrained parent grains, whereas the GBM processes are recorded by
450 the irregular, weakly lobate shapes of the daughter grains (Hobbs, 1968; Hirth and Tullis, 1992; Stipp et al., 2002a,b). Many
451 daughter grains are larger than the subgrain size in the parent grains. Combinations of Type 2 and 3 grains in the core-mantle
452 microstructure are more prevalent near the center of the shear zone (i.e. in the highly-sheared schist, the QF mylonite, and
453 parts of the QF mylonite transition zone; Fig. 3), and veins that comprise only Type 3 grains are found within or closest to the
454 shear zone core, indicating a greater degree of recrystallization nearest the core (Fig. 3). Where only Type 3 grains are
455 present, the grain orientation domains reflect the orientations of the Type 2 parent grains (Fig. 10; Pauli et al., 1996;
456 Halfpenny et al., 2004, 2006).

457 Veins containing only Type 2 grains are found in the QF protomylonite, the QF mylonite, and the sheared schist.
458 The spatial distribution (Figs. 1, 3; Table 1) of these veins (relative to veins with only Type 3 or Type 2+3 grains) suggests
459 that veins with only Type 2 grains represent either (a) a spatially-transitional microstructure reflecting a greater degree of
460 recrystallization with proximity to the shear zone core or (b) an overprint relationship where the veins with only Type 2
461 grains preserve a slightly earlier stage of deformation not affected by the overprint of Type 3 grains (Fig. 3). Considering the

462 former interpretation, Type 2-style ribbon grains have been associated in the literature with the activity of SGR
463 recrystallization mechanisms as an early stage in the path-dependent evolution of the core-mantle microstructure (e.g. ribbon
464 grains form prior to subgrains during the accumulation of strain at SGR/GBM conditions; Lloyd and Freeman, 1994; Trimby
465 et al., 1998). However, the island grains and lobate grain boundaries of Type 2 grains are consistent with deformation by
466 GBM-dominant recrystallization mechanisms, and they are commonly found in the Sandhill Corner shear zone without
467 evidence for subgrains or Type 3-style new grains. Given the overprint interpretation, Type 2 grains may reflect an early
468 period of recrystallization by GBM-dominant mechanisms (i.e. “stretched” versions of Type 1 grains) at comparatively
469 higher temperatures and/or lower strain rates followed by the shift to SGR-dominant recrystallization mechanisms.

470 Quartz displaying a mixture of all three grain types is found in transposed and recrystallized folded quartz veins of
471 the sheared schist where some fold limbs have been attenuated and where strain was accommodated by dynamic
472 recrystallization in addition to matrix-accommodated rotation. In these cases, the microstructure represents the
473 heterogeneous distribution of strain where the host rock Type 1 grains of the fold limbs that have experienced less dynamic
474 recrystallization are juxtaposed next to thinned limbs with Type 2 grains that have experienced a greater degree of
475 recrystallization (Fig. 4). Type 3 new grains are present at grain boundaries along with subgrains in these Type 1 and 2
476 grains, consistent with the interpretation that Type 3 grains represent an overprint.

477 Evidence for damage and recrystallization associated with coseismic slip and postseismic creep in the seismic cycle
478 may be preserved in the uncommon microstructures found in the Sandhill Corner shear zone. This connection is supported
479 by the spatial association of the uncommon microstructures with pseudotachylyte and deformed pseudotachylyte. Quartz
480 veins that display irregular, blocky and patchy extinction patterns (Fig. 6b-d) may represent the best evidence for quartz
481 microstructures that formed during elevated and/or rapidly decaying strain rates (Ellis and Stöckert, 2004; Kohlstedt and
482 Weathers, 1980; Küster and Stöckert, 1999; Rolandone et al., 2004; Trepmann and Stöckert, 2003). As Kim et al. (2010),
483 Bestmann et al. (2012), and DePaola et al. (2015) show, new quartz grains and a “mylonitic” microstructure can both be
484 produced during coseismic slip. The anomalously low proportion of indexed points during SEM-EBSD mapping supports
485 the possibility that veins with abnormal extinction patterns have lattice-scale defects like microfractures or a particularly high
486 dislocation density (Schwartz et al., 2009). Large quartz grains cut by dominantly foliation-parallel fractures (Fig. 6a) form
487 discontinuous strings of small new grains along fractures (Vernooij et al., 2006b) that may have resulted from transiently
488 high coseismic/postseismic strain rates (Ellis and Stöckert, 2004a; Kohlstedt and Weathers, 1980; Rolandone et al., 2004;
489 Trepmann and Stöckert, 2013). With continued strain, these foliation parallel fractures produce Type 2 grain-style slivers
490 that are ultimately surrounded by smaller grains forming a core-mantle microstructure unrelated to the host rock quartz

491 fabric. Because all of these microstructures are rare features in the quartz veins of the Sandhill Corner shear zone, they are
492 unlikely to have resulted from interseismic, steady-state conditions.

494 8.2. The pre-existing CPO in recrystallized quartz CPO patterns

495 Sheared quartz veins in the Sandhill Corner shear zone typically display c-axis CPO patterns that are asymmetric
496 across the foliation line (XY plane), with one hemisphere containing a higher number of clustered points than the other. This
497 suggests that the shear zone CPO is influenced by a CPO fabric inherited from the earlier, higher-temperature history of
498 shearing in the Norumbega system. The CPOs of asymmetric folds at early to moderate stages of development are typically a
499 single c-axis maximum in the one quadrant of the pole figure (i.e. between the XY and YZ planes) when plotted in the shear
500 zone kinematic reference frame (Fig. 7). This suggests that the CPO associated with these asymmetric folds, which formed
501 during the earlier, higher-temperature history of the Norumbega system, may have been inherited from the host rock, causing
502 an asymmetry about the XY plane in the CPO of the later mylonitic shear fabric. However, few samples from within the
503 Sandhill Corner shear zone show a c-axis maximum in one quadrant of the pole figure (e.g. 58, Fig. 8); most samples show a
504 stronger cluster of points or a single maximum near the center of one hemisphere within the YZ plane (e.g. 41, 208, 67, 305,
505 Fig. 8). Matrix-accommodated rotation of the limbs of the asymmetric folds during shearing could account for this difference
506 in the placement of the c-axis maximum, in the shear zone reference frame, between the host rock and sheared samples.
507 Field and microstructural observations (Figs. 2 and 4b; Types 1+2+3) show that the asymmetric folds experienced some
508 component of matrix-accommodated rotation. When considered in the shear zone kinematic reference frame (Fig. 13), the
509 fold limbs would rotate toward the flow apophysis AP₁, leading to a change in fold limb orientation relative to the foliation.
510 Such a rotation would place the observed c-axis maximum CPO of host rock folds in an orientation within or near the YZ
511 plane (Fig. 13), and coincident with recrystallization dominated by rhomb <a> and/or basal <a> slip. If we make the
512 assumption that the limbs of host rock quartz veins at intermediate stages of development were passively rotated into
513 alignment with the shear-zone foliation, then a rotation of approximately 30° might be expected, broadly consistent with a
514 comparison between the sample in Fig. 7 and pole figures in Fig. 8.

515 In addition to matrix-accommodated rotation, most quartz veins are dynamically recrystallized. At the temperature
516 conditions indicated by dislocation creep primarily via SGR and GBM, the operation of the expected basal <a>, rhomb <a>,
517 and prism <a> dominant slip should spread out the c-axis pattern to form the typical crossed girdle pattern. A well-developed
518 crossed girdle pattern is present in some samples (NFS2, 67, Fig. 8), whereas a significant population of samples display an
519 incomplete girdle pattern (305, 51, Fig. 8). Of those displaying an incomplete girdle, the most common is the pattern

containing paired maxima, one near the center of each half of the pole figure on either side of the XY plane, in an orientation coincident with recrystallization dominated by rhomb $\langle a \rangle$ slip (56, Fig. 8). Where alternating grain orientation domains are present (e.g. all Type 3 grains or core-mantle microstructure of Type 2 + Type 3), each maximum of this CPO pattern is associated with one dominant grain orientation (Fig. 10; Halfpenny et al., 2004, 2006; Heilbronner and Tullis, 2006b; Pauli et al., 1996).

Paired c-axis maxima have been observed in progressively recrystallized samples (e.g. Heilbronner and Tullis, 2006b). The paired maxima of the quartz veins of the Sandhill Corner shear zone may be a result of such fabric evolution. However, the CPO patterns of veins from the Sandhill Corner shear zone with the core-mantle microstructure that display paired maxima on either side of the XY plane still show a stronger asymmetric clustering of points in one maximum relative to the other. We attribute this asymmetry about the XY plane to the persistence of the inherited host rock CPO pattern in the recrystallized samples of the shear zone. The inherited fabric would yield one c-axis maximum and account for the greater number of points in one hemisphere about the XY plane. A paired maxima suggests that the second maximum reflects the orientation of quartz grains that formed during recrystallization. Webber et al. (2010) documented double maxima in olivine CPO patterns from sheared dunites and similarly proposed that the strong maximum was inherited from the host rock CPO and the second, weaker maximum developed by recrystallization during shear zone deformation.

8.3. Quartz CPO data and IPF plots of misorientation rotation axes

Inverse pole figure (IPF) plots of the misorientation rotation axes are dominated by diffuse clustering around the c-axis (Fig. 12), with the strongest c-axis clustering around the 50-60° rotation interval. While Dauphiné twins in these plots may not be positively identified without the detailed demonstration of rotation about the c-axis from the misorientation of neighbor pairs, strong clustering around the c-axis in the 50-60° rotation interval is consistent with IPF plots showing rotation around the c-axis due to Dauphiné twins (Lloyd, 2004).

Clustering in the IPF figures around the c-axis in other rotation angle intervals (e.g. 40-50° interval) as well as clustering around other crystallographic directions should reflect recrystallization via a dominant slip system (Neumann, 2000; Lloyd et al., 1997; Wheeler et al., 2001). The crossed girdle c-axis CPO patterns within quartz veins of the Sandhill Corner shear zone suggest dislocation creep dominated by slip in the prism $\langle a \rangle$ and rhomb $\langle a \rangle$ directions as well as in the basal $\langle a \rangle$ direction in samples that display tails. There are weak associations between the dominant slip system predicted by the CPO patterns and the direction of the rotation axes of the IPF plots. For example: (a) the c-axis clustering outside of the 50-60° rotation interval could be explained by recrystallization via dominant prism $\langle a \rangle$ slip; (b) clustering around the

549 rhombohedral orientations in the IPF plots primarily found in the higher rotation angle intervals (i.e. 70-100°) may be a result
550 of rhomb $\langle a \rangle$ dominant slip; and (c) c-axis crossed girdle patterns with well-developed tails do have corresponding clusters
551 in the basal $\langle a \rangle$ corners of the IPF plots. Clustering in the IPF plots of many samples is not particularly strong, especially
552 those samples that show a flat nearest-neighbor misorientation angle histogram profile (e.g. 93, Fig. 12), suggesting that other
553 factors may be influencing the orientation of the rotation angles; such as the activity of multiple or paired slip systems,
554 changes caused by GBM mechanisms, and/or a component of grain size sensitive flow (e.g. grain boundary sliding; Rutter
555 and Brodie, 2004).

556 557 8.4. Misorientation rotation angles

558 Rotation angle histogram profile patterns of the nearest-neighbor pair (red line, Fig. 11) typically lie between two
559 “end member” types. The first type has a relatively constant number fraction from 10 to 50°, an increase to the peak at 60°,
560 and then a drop off at high angles (e.g. 28 and 264, Fig. 11). While Dauphiné twins may not be conclusively identified in
561 these histogram plots without the detailed demonstration of rotation within a grain map, the peak at 60° is consistent with
562 published observations of samples containing identified Dauphiné twins (e.g. Lloyd, 2004). A high number fraction at 10° is
563 consistent with the observations of misorientation profiles related to the formation of new grains via SGR recrystallization
564 (neighbor-pair > random-pair), and the progressive rotation of subgrains and new grains could lead to an increase in the
565 number fraction of rotation angles between 20 and 50° (e.g. Lloyd, 2004; Lloyd and Freeman, 1994; Neumann, 2000; Stipp
566 and Kunze, 2008; Trimby et al., 1998; Wheeler et al., 2001). Boundaries with misorientation angles greater than 60° may
567 form via SGR if multiple slip systems were active (Wheeler et al., 2001) or through GBM recrystallization, the inheritance
568 from host grain boundaries (e.g. Jiang et al., 2000), and the growth of new grains in fractures and microcracks (Hippertt and
569 Egydio-Silva, 1996; Vernooij et al., 2006a,b). We interpret the “flattening” of the histogram profile between 10-50° to
570 represent the influence of the GBM mechanisms, as both SGR and GBM processes are active.

571 The second neighbor-pair profile type is best described as a flat neighbor-pair profile from 10° to 95° (53, Fig. 11).
572 Although Dauphiné twins have not been conclusively documented as discussed previously, the peak at 60° in this flattened
573 profile is consistent with observations of samples containing identified Dauphiné twins; this peak reflects a lower number
574 fraction around 60° relative to the first neighbor-pair profile type. The flattened misorientation profile is most common in
575 samples with poorly-developed (53, Fig. 11) and paired maxima crossed girdle CPO c-axis patterns (e.g. 56, Fig. 8), and
576 suggests either different or additional mechanisms, such as grain size sensitive processes (e.g. Fliervoet, et al., 1997, 1999;

577 Jiang et al., 2000; Law, 1990), are operating in these samples relative to those displaying the first type of neighbor-pair
578 profile.

579   Rotation angle histogram profile patterns of the random-pair (blue line, Fig. 11) show three general trends: (1) the
580 random-pair profiles mimic the neighbor-pair (red) profiles for angles above 20°, (2) the random-pair line displays a broad
581 peak around 60°, or (3) the random-pair profiles display a relatively higher number fraction of misorientation angles greater
582 than 60°. In samples where the random-pair profile approximately mimics the neighbor-pair profile (264, 28, Fig. 11), the
583 neighbor-pair profile displays a peak above the random-pair line at 60° (potentially related to Dauphiné twins) and shows a
584 higher number fraction at low angles of 5-20° consistent with parent-daughter relationships via SGR recrystallization, which
585 is typical of patterns published in other studies (e.g. Wheeler et al, 2001; Lloyd, 2004; Lloyd and Freeman, 1994; Neumann,
586 2000). The other two random pair patterns are not common in the literature. Where the random-pair profile shows a broad
587 peak centered around 60° (70, Fig. 11), the neighbor-pair profile also displays a peak in that range. Samples with this
588 random-pair profile typically have well-developed c-axis crossed girdle patterns (70, Fig. 11), a correlation that suggests that
589 mechanisms forming this peak also facilitate the formation of the crossed girdle pattern. Finally, the random-pair profiles
590 that display a relatively higher number fraction of misorientation angles greater than 60° (51, 53, Fig. 11) would indicate
591 some mechanism to either increase the high angle rotations and decrease the low angle rotations (e.g. activation of additional
592 slip systems), or to mix the grains such that the angles between any two grains would be closer to the statistical random
593 profile (e.g. grain size sensitive processes). Samples that show this near random random-pair histogram profile also typically
594 have a flat neighbor-pair profile, Type 3 grains, and a poorly developed c-axis crossed girdle pattern, paired maxima, or no
595 crossed girdle pattern- all of which support a conclusion that other or additional mechanisms influenced the formation of the
596 quartz microstructure in these samples (e.g. grain size sensitive processes).

597   A more detailed misorientation analysis of a sample containing Type 3 grains with layered grain orientation domains
598 shows different CPOs and misorientation profiles for each of the grain orientation domains (Fig. 10). The domain that plots
599 as a single, stronger c-axis maximum in one half of the pole figure (potentially coincident with the location of the inherited
600 CPO) shows a neighbor-pair misorientation angle profile with a higher number fraction in the 10-50° range and a stepped
601 random-pair profile with higher number fractions with angles less than 60° (Fig. 10a). The other orientation domain that
602 plots as the second c-axis maximum shows the flatter neighbor-pair misorientation angle profile with a greater number
603 fraction in higher misorientation angles (>60) (Fig. 10b). These differences suggest that each orientation domain may be
604 deforming via different slip systems or mechanisms (e.g. dislocation creep in Fig. 10a vs. grain size sensitive processes in
605 Fig. 10b). Given that one domain with the stronger maximum fabric (Fig. 10a) may reflect the inherited CPO and may have

once had a core-mantle relationship via SGR, it is possible that the grains in the weaker maximum domain (Fig. 10b) may have experienced a higher component of grain boundary sliding that mixed the mantle grains following rotation recrystallization (e.g. Halfpenny et al., 2006). The high degree of grain boundary sliding could have influenced the misorientation relationships between grains, leading to a "flattened" neighbor-pair profile (red) and random-pair profile (blue) that is closer to theoretical random (green line) in the misorientation angle histogram (Fig. 10b).

8.5. Associations among sample location, rock type, and quartz fabric data

Combining observations of the quartz microstructure, CPO data, and misorientation data with the spatial distribution of samples across the shear zone (Fig. 14) distinguishes two categories of quartz fabrics: (1) veins with a mixture of grain types, crossed girdle c-axis patterns, and low angle dominated neighbor-pair misorientation angle profiles; and (2) veins with layered Type 2 grains, Type 2+3 grains in a core-mantle relationship, or Type 3 grain orientation domains that have poorly-developed CPO patterns; and flat neighbor-pair misorientation angle profiles. The first fabric type is dominantly found in the sheared schist and the QF protomylonite and mylonite transition zone (i.e. the outer part of the shear zone) whereas the second fabric type is more commonly found within the most highly sheared schist and the QF mylonite in the inner part of the shear zone. As described in the sections above, the dominance of different deformation mechanisms and/or active slip systems may have led to the different fabric types, which could be a result of a sample's location within the shear zone, suggesting across-strike variations in deformation conditions (see Section 8.6 for a more detailed discussion as related to shear zone evolution and deformation with the seismic cycle).

8.6. Factors affecting quartz fabric development

8.6.1. Conditions of deformation during localization

The across-strike transition of microstructures from those consistent with GBM recrystallization the edge of the shear zone to those consistent with SGR nearest the core suggests a shift in deformation conditions as the shear zone narrowed during localization. This transition in activity of recrystallization mechanism is typically associated with a decrease in temperature or an increase in strain rate. At a constant flow stress, an increase in strain rate may be associated with localization. However, observations of the Norumbega fault system (e.g. Ludman et al., 1999; West, 1999; West and Hubbard, 1997), including mineral cooling ages, are consistent with a shift to lower temperatures during localization, possibly due to exhumation. A shift in material properties may also have affected the evolution of the shear zone. In the Sandhill Corner shear zone, the quartz veins are contained within a mica-rich polymineralic matrix (largely derived from

635 recrystallized and deformed pseudotachylyte; see Price et al., 2012), and a decrease in matrix grain size may have caused a
636 shift to a grain size sensitive creep within the inner-most parts of the shear zone (Price et al., 2012; Wallis et al., 2013, 2015),
637 a weaker rheology. Overall, given the current lack of constraints on the time-dependent relationships among flow stress,
638 strain rate, and temperature in the Sandhill Corner shear zone, the shift in recrystallization mechanisms may not be
639 definitively attributed to increasing temperature or strain rate. However, considering the evidence for a time-dependent
640 decrease in temperature within the larger Norumbega fault system, we interpret the shift from GBM recrystallization to SGR
641 recrystallization to more likely reflect a temperature decrease as the shear zone localized.

642

643 8.6.2. Fabric evolution with recrystallization

644 Observed cross-strike variations of the quartz fabrics of the Sandhill Corner shear zone may also be associated with
645 the degree of recrystallization of the quartz veins, particularly with proximity to the shear zone core. The shift from GBM to
646 SGR+GBM may reflect stages in the microstructural and fabric evolution of the quartz veins, stages that were preserved as
647 the shear zone localized. Quartz microstructures of the Sandhill Corner shear zone could be interpreted to reflect a
648 progression under SGR recrystallization from ribbon grains to a core-mantle microstructure to complete replacement by new
649 polygonal grains displaying layered orientation domains (Halfpenny et al., 2004, 2006; Law, 1986; Law et al., 1984; Pauli et
650 al., 1996; Trimby et al., 1998), with the inner-most parts of the shear zone containing veins with the greatest degree of
651 recrystallization. Alternatively, this same progression could represent a shift from GBM-dominant to SGR-dominant
652 recrystallization over time as the shear zone localized. Type 2, ribbon grains with no subgrains or new grains related to the
653 core-mantle microstructure may instead be an early, higher temperature microstructure formed by GBM recrystallization that
654 is overprinted by later lower-temperature SGR recrystallization rather than an early stage in a progressive sequence of SGR
655 recrystallization.

656 The shift in dominance of slip systems with the degree of recrystallization of the quartz veins following geometric
657 constraints (Heilbronner and Tullis, 2006b; Kruhl and Peternell, 2002; Law et al, 1990; Lloyd and Freeman, 1994; Lloyd et
658 al., 1992; Takeshita et al., 1999) affects the c-axis pole figure pattern. In this case, there would be an observed shift from
659 maxima at the periphery (Z-axis) to paired maxima along the crossed girdle between the Y- and Z-axes and ultimately to a
660 single peak at the center of the pole figure (Y-axis) with progressive recrystallization. If the degree of recrystallization is
661 greater nearest the core, which might be expected as the Sandhill Corner shear zone localized, then the strongest and most
662 well defined CPO patterns should be found nearest the core. Instead, the strongest and most well defined CPO patterns are
663 found in the outer-most parts of the shear zone, indicating either (a) the quartz fabrics of the inner part of the shear zone

664 never developed a well-defined crossed girdle pattern, or (b) additional mechanisms operating only in the inner part of the
665 shear zone continued to change the CPO away from a crossed girdle pattern.

666

667 8.6.3. Influence of the inherited fabric

668 If the majority of quartz veins in the Sandhill Corner shear zone originated as asymmetrically folded veins in the
669 host rock in an orientation broadly consistent with the example shown in Fig. 7, then the quartz veins would have started with
670 a strong pre-existing fabric as the mylonitic shear zone initially localized. For host rock folds in early to intermediate stages
671 of development, this inherited fabric is a single maximum in one quadrant of the pole figure in the kinematic reference frame
672 of the shear zone (Fig. 7a). If the limbs of the asymmetric folds were rotated as presented in Fig. 13, then the inherited c-axis
673 cluster would have been rotated into an orientation within or near a plane normal to the foliation, an orientation that typically
674 is achieved by recrystallization via rhomb $\langle a \rangle$ dominant slip.

675 A quartz grain will recrystallize through slip systems with the lowest critical resolved shear stress and the highest
676 Schmid factor. Under non-coaxial strain, these slip systems are dominated by prism $\langle a \rangle$, rhomb $\langle a \rangle$, and basal $\langle a \rangle$,
677 depending on temperature and progression of recrystallization. If rhomb $\langle a \rangle$ was the slip system that was dominantly active
678 under the lowest critical resolved shear stress as the Sandhill Corner shear zone was localized (as indicated by the crossed
679 girdle pattern of the pole figures and the clustering of the misorientation rotation axes in the IPF plots), then a population of
680 grains placed in an orientation where this slip system had the highest Schmid factor would have been the weakest in flow and
681 have readily recrystallized. If the inherited c-axis maximum was rotated into an orientation coincident with rhomb $\langle a \rangle$
682 dominant slip, then it would have been a weak orientation and the inherited maximum would likely persist in the CPO as the
683 sample was progressively recrystallized (Heilbronner and Tullis, 2006b; Neumann, 2000; Takeshita et al., 1999). This
684 interpretation is supported by the distinctly different c-axis pattern of a sheared quartz vein from an unfolded, sheared
685 pegmatite vein in the QF transition zone. In this sample, the well-developed c-axis CPO maximum is located at the center of
686 the pole figure rather than either side of the XY plane (264, Fig. 8). If the c-axis maximum coincident with rhomb $\langle a \rangle$ slip
687 reflects the influence of an inherited CPO, then the c-axis maximum around the Y-axis of the figure of the quartz vein from
688 the sheared but unfolded pegmatite vein (264, Fig. 11) may represent a type of CPO pattern that could have been produced if
689 such an inherited fabric was not present.

690

691 8.6.4. Deformation associated with the seismic cycle

692 Deformation associated with the seismic cycle influenced the development of rock fabrics in the Sandhill Corner
693 shear zone (e.g. Price et al. 2012; Handy et al. 2007). Consistent with co- and post-seismic deformation, documented effects
694 of transiently elevated stresses and strain rates on quartz fabrics include grain size reduction driven by recovery after
695 microfracturing (e.g. Kim et al., 2010), twinning induced by transiently high stresses (Springer et al., 2009; Wenk et al.,
696 2011), and variable quartz new grain sizes formed in transiently high and then rapidly decaying strain rates (e.g. Trepmann
697 and Stöckert, 2003). We suggest that the uncommon microstructures described in Section 5.5 reflect the transient stresses
698 and strain rates associated with the seismic cycle. Examples include discontinuous strings of small polygonal grains in large
699 single-crystal quartz grains that may have formed under transiently high stresses (Fig. 6a; e.g. Trepmann and Stöckert, 2013)
700 and the heterogeneous distribution of sub/new grains that may have formed during rapidly decaying strain rates associated
701 with post-seismic relaxation (Fig. 6b-d; e.g. Rolandone et al., 2004; Trepmann and Stöckert, 2003).

702 Because any quartz microstructures formed by coseismic slip and post-seismic creep in the Sandhill Corner shear
703 zone were cyclically overprinted by interseismic viscous deformation (e.g. Price et al., 2012), the effects of coseismic
704 damage on quartz fabric development is likely to be variably obscured. However, the spatial distribution of quartz
705 microstructures suggests that the seismic cycle may have played an important role. As discussed in Section 8.5, samples with
706 poorly-developed CPO patterns and flat neighbor-pair misorientation angle profiles are most commonly found in the inner
707 parts of the shear zone. The mechanism preventing the development of a well-developed crossed girdle and promoting the
708 development of the flat nearest-neighbor profile would have to have been operating preferentially within the inner-most parts
709 of the shear zone, the area where evidence for coseismic damage is most prevalent.

710 Observations from upper crustal faults show significant fracturing within the core of the fault zones (e.g. Chester et
711 al., 1993; Faulkner et al., 2003; Jefferies et al., 2006a,b; Wibberley and Shimamoto, 2003). Samples from Sandhill Corner
712 shear zone also show pseudotachylite and other indicators of increased fractures (Price et al., 2012) with proximity to the
713 shear zone core. Microfracturing is a coseismic process that could have decreased the grain size in quartz (e.g. Anders et al.,
714 2014). Although the occurrence of widespread microfracturing in these samples cannot be shown unequivocally, if
715 microfracturing were a major factor affecting quartz fabrics in the innermost part of the shear zone, then it may have
716 decreased the quartz grain size prior to recrystallization, the pole figure would not have developed a strong fabric (e.g.
717 Trepmann and Stöckert, 2009), and grain size sensitive processes (e.g. grain boundary sliding) would have been more likely
718 (e.g. Hippertt, 1994), potentially leading to the flat neighbor-pair misorientation angle profiles also observed in those samples
719 (Fliervoet, et al., 1997, 1999; Jiang et al., 2000). An increased prevalence of Dauphiné twinning has also been associated
720 with the elevated transient stresses during pseudotachylite formation (Springer et al., 2009; Wenk et al., 2011). Finally,

pervasive fracturing may have led to the preferential formation of quartz mineralized fractures within the inner-most parts of the shear zone. A new quartz-filled fracture that formed later in the shear zone history may not have recrystallized to the same degree as the older veins and, thus, would have a comparatively weaker crossed girdle CPO. Because the quartz data from the inner parts of the shear zone are similar, mineralized fractures of varying age are not favored as explanation for the difference between the inner- and outer-most parts of the shear zone.

As more studies build our understanding of the effect of co- and post-seismic elevated stresses and strain rates on interseismic deformation (e.g. Trepmann and Stöckert, 2013), it may be possible to identify the features of quartz fabric development that serve as lasting evidence for seismic damage in quartz after more obvious microstructures have been lost through recrystallization and grain growth (e.g. Trepmann et al., 2007).

9. Conclusions

Based on the data presented in this paper, we suggest that the development of quartz fabrics of the Sandhill Corner shear zone was influenced by: (1) the inherited fabric CPO, (2) the SGR-dominated recrystallization mechanisms expected for the conditions of deformation, and (3) spatial variation in deformation conditions and mechanisms between the inner- and outer-most parts of the shear zone (Fig. 14). The starting microstructure and grain orientations of the quartz veins would have been controlled by the inherited fabric of veins that were asymmetrically folded during the earlier, higher-temperature history of the Norumbega fault system. Matrix accommodated rotation of the fold limbs would have placed the inherited CPO within or near the XY plane. Given that rhomb $\langle a \rangle$ slip or basal $\langle a \rangle$ slip may have been the slip system with the highest Schmid factor at the conditions of deformation, the concentration of poles on one side of the XY plane may have persisted accounting for the asymmetry in the crossed girdle patterns observed in the Sandhill Corner shear zone. The quartz veins were recrystallized by GBM dominant mechanisms at higher temperatures followed by SGR-dominant mechanisms at lower temperatures.

The quartz data from the Sandhill Corner shear zone differ between the inner- and outer-most parts of the shear zone, suggesting that spatial variations in deformation conditions or recrystallization mechanisms led to distinct changes in the quartz fabrics. The outer-most parts of the shear zone shows a progression of quartz data consistent with deformation with localization in the shear zone (i.e. the well-developed CPO crossed girdle patterns and misorientation angle histogram profiles that agree with microstructures that indicate SGR-dominant recrystallization with GBM), whereas the inner-most parts of the shear zone do not show a similar progression. Quartz veins from the inner-most parts of the shear zone show poorly developed CPO patterns and misorientation angle histogram profiles that are not consistent with SGR+GBM or SGR

dominant recrystallization. Conditions within the inner-most part of the shear zone may have prevented the formation of the crossed girdle pattern in this high strain zone, such as transiently elevated stresses and strain rates associated with the seismic cycle. Although grain size reduction by dynamic recrystallization (via SGR) was certainly an important process in these rocks, other recrystallization processes may have also played a role. An increase in grain size sensitive processes, such as grain boundary sliding, over other recrystallization mechanisms could have led to a relatively underdeveloped crossed girdle c-axis CPO pattern and changed the misorientation rotation angles to higher values creating the observed flat nearest-neighbor misorientation profile.

We conclude that the across-strike differences in quartz fabric development reflect initial localization with decreasing temperatures followed by diverging paths of fabric evolution due to differences in deformation conditions and recrystallization mechanisms within different parts of the shear zone (Fig. 14). Different deformation conditions affected the rocks of the inner-most parts of the shear zone, conditions that would have promoted a significant decrease in grain size, an increase in grain size sensitive processes over other recrystallization mechanisms, a relatively underdeveloped crossed girdle c-axis CPO pattern, and flat neighbor-pair misorientation rotation angle histogram profiles. Considering the widespread occurrence of deformed and undeformed pseudotachylyte in the shear zone, one possible explanation is that these rocks may have experienced transiently high stresses associated with the seismic cycle, leading to microfracturing and a decrease in quartz grain sizes closer to the center of the shear zone (DePaola et al., 2015; Springer et al., 2009; Wenk et al., 2011).

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Figure Captions

Figure 1. Geologic map of the study area within the Norumbega fault system (NFS). The Sandhill Corner shear zone (SCSZ) is located along the contact between the quartzofeldspathic (QF) and schist units: the Cape Elizabeth Formation and Crummett Mountain Formation, respectively. Regional geology is after Osberg et al. (1985), and local geology and designation of shear zone boundaries follow Grover and Fernandes (2003), West and Peterman (2004), and Price et al. (2012). Equal-area nets of the shear fabric plot data from this study, Grover and Fernandes (2003), and West and Peterman (2004); mean foliation of $037^{\circ}/88^{\circ}\text{NW}$; mean lineation of $5^{\circ}\rightarrow 037^{\circ}$. Quartz veins described in this paper were largely collected within the area outlined by the polygon in the local map, showing sample numbers and locations. Example fold hinge orientations of host rock samples are plotted on an equal-area net; mean $35^{\circ}\rightarrow 025^{\circ}$. The detailed rock type map shows the distribution of the dominant quartz grain types; see Figs. 3, 4 and Section 5 for descriptions. The across-strike sequence and widths of the rock units in the cross section (A-B) are representative of the southern part of the shear zone and are derived from Price et al. (2012).

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1064

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1066 grains (Type 1) by smaller, low aspect ratio grains (Type 3) in quartz veins (a) is more prevalent around rare cataclasite (c,d).
1067 (a, b)- plane-polarized (ppl); (c,d)- cross-polarized photomicrographs (xpl); bt-biotite, fsp-feldspar, ms-muscovite, and qtz-
1068 quartz; S-shear zone foliation, C'- shear band cleavage. Sample numbers are presented, and arrows in photomicrographs
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1072 Discontinuous fractures are decorated by strings of small polygonal grains that cut rare, particularly large grains leading to a
1073 core-mantle style microstructure. (b-d) A few quartz veins display irregular, blocky and patchy extinction patterns that are
1074 associated with heterogeneous subgrain distributions. All images are cross-polarized photomicrographs and show quartz
1075 unless otherwise labeled; tur -tourmaline. Sample numbers are presented.

1076

1077 **Figure 7.** The microstructure and CPO of an example asymmetrically-folded quartz vein from the host rock, representative
1078 of the veins at the early/intermediate stages of folding. In the shear zone kinematic reference frame (a), the same sample was
1079 cut relative to the regional shear zone foliation and lineation (XY-foliation, mean of $037^{\circ}/88^{\circ}\text{NW}$; X-lineation, mean
1080 lineation of $5^{\circ}\rightarrow 037^{\circ}$; right side of the pole figure to the northeast), and shows the fold-specific shape preferred orientation
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1082 specific fold reference frame (b; as labeled: XY is axial surface to the fold; fold hinge in the Y direction, hinge: $35^{\circ}\rightarrow 025^{\circ}$;
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1087 microstructure is presented as a SEM-EBSD produced grain orientation map; colors in the orientation map corresponded to
1088 the inverse pole figure (IPF) key provided. Geographic orientation of the grain maps correspond to the respective pole
1089 figures. The scale for each c-axis (0001) and a-axis (11-20) pole figure with multiples of uniform density is shown; n-
1090 number of grains plotted. Sample number is presented.

1091

Figure 8. A suite of c-axis (0001) and a-axis (11-20) pole figures showing crystallographic preferred orientation (CPO) patterns typical of quartz veins found within the Sandhill Corner shear zone. The samples are arranged in order away from the shear zone core. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. A schematic pole figure shows the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation. Mean foliation: 037°/88°NW; mean lineation: 5°→037°. Sample numbers are presented.

Figure 9. Quartz crystallographic preferred orientation (CPO) patterns for different grain size fractions of a deformed quartz vein sample (38). Orientation maps and c-axis (0001) and a-axis (11-20) pole figures show (a) all sizes, (b) >80 μm, and (c) <30 μm (equivalent diameter). Colors in the orientation map corresponded to the inverse pole figure (IPF) key provided, and grain boundaries are outlined in black. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. (a) shows the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation.

Figure 10. Fine-grained quartz vein sample (93) with layered grain orientation domains shows different crystallographic preferred orientation (CPO) patterns and misorientation rotation angle histogram profiles for each of the grain domains. Data for the entire sample are shown at left, and data for outlined grain domains a and b are shown at right. The histogram plots show the random (green), random-pair (blue), and neighbor-pair (red) profiles. The scale for each c-axis (0001) and a-axis (11-20) pole figure with multiples of uniform density is shown; n-number of grains plotted. The pole figures at left show the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation. Colors in the orientation map (left) correspond to the inverse pole figure (IPF) key provided, and Dauphiné twins are presented as a white line. Colors in the misorientation angle boundary maps (GB Map) show the ranges provided in the key.

Figure 11. Misorientation rotation angle histogram plots, misorientation angle boundary maps (GB Map), mineral orientation maps (IPF Map), and c-axis (0001) and a-axis (11-20) pole figures of selected quartz vein samples (264, 70, 51, 53 and 28) from the Sandhill Corner shear zone. The histogram plots show the random (green), random-pair (blue), and neighbor-pair (red) profiles. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. Colors in the orientation map corresponded to the inverse pole figure (IPF) key provided, and Dauphiné twins are presented by white line in IPF Maps. Colors in the grain boundary map correspond to the misorientation angle ranges shown in the key. The samples are arranged in order away from the shear zone core.

1121

1122 **Figure 12.** Misorientation data for four selected quartz vein samples (28, 51, 264, and 93) from the Sandhill Corner shear
1123 zone. Misorientation rotation axes are plotted on inverse pole figures for rotation angle ranges from 5-104.5°.
1124 Misorientation rotation angle histogram profiles show the random, random-pair, and neighbor-pair profiles as seen in Figs. 10
1125 and 11. Sample numbers are presented.

1126

1127 **Figure 13.** A conceptual diagram showing how the matrix-accommodated rotation of folded quartz veins of the host rock
1128 might change the location of the inherited crystallographic preferred orientation (CPO) in quartz veins of the Sandhill Corner
1129 shear zone. The style and degree of rotation varies from sample to sample. The orientation of the host rock folds (example
1130 fold hinge: 35°→025°) and placement of the inherited CPO in one quadrant of the pole figure in the shear zone kinematic
1131 reference frame (mean foliation: 037°/88°NW, mean lineation: 5°→037°) is approximate following the observations of
1132 asymmetric host-rock folds at early to intermediate stages of development. AP1, AP2- flow apophyses; AP1 is the flow
1133 plane.

1134

1135

1136 **Figure 14.** A conceptual diagram summarizing the deformation history of quartz veins from the Sandhill Corner shear zone
1137 and outlining the inferred path of fabric development for the rocks from the inner and outer parts of the shear zone. SPO-
1138 shape preferred orientation; CPO- crystallographic preferred orientation; SGR- subgrain rotation; GBM- grain boundary
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(a) Primary Quartz Grain Types:

(b) Grain Type Combinations:

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Figure 7. The microstructure and CPO of an example asymmetrically-folded quartz vein from the host rock, representative of the veins at the early/intermediate stages of folding. In the shear zone kinematic reference frame (a), the same sample was cut relative to the regional shear zone foliation and lineation (XY-foliation, mean of $037^\circ/88^\circ \text{NW}$; X-lineation, mean lineation of $5^\circ \rightarrow 037^\circ$; right side of the pole figure to the northeast), and shows the fold-specific shape preferred orientation (SPO) at an angle to the shear zone foliation and a single c-axis maximum in one quadrant of the pole figure. In the sample-specific fold reference frame (b; as labeled: XY is axial surface to the fold; fold hinge in the Y direction, hinge: $35^\circ \rightarrow 025^\circ$; right side of the pole figure to the east), the quartz grains define a SPO axial surface to the fold and a crystallographic preferred orientation (CPO) of a single c-axis maximum at the periphery of the pole figure near normal to the fold limbs. This CPO is an example of the “pre-existing” fabric of this sample and has been observed from several other folds of the host rock from the field area. Maps are derived from two cuts of different orientations from the same sample. Quartz microstructure is presented as a SEM-EBSD produced grain orientation map; colors in the orientation map corresponded to the inverse pole figure (IPF) key provided. Geographic orientation of the grain maps correspond to the respective pole figures. The scale for each c-axis (0001) and a-axis (11-20) pole figure with multiples of uniform density is shown; n-number of grains plotted. Sample number is presented.

Figure 8. A suite of c-axis (0001) and a-axis (11-20) pole figures showing crystallographic preferred orientation (CPO) patterns typical of quartz veins found within the Sandhill Corner shear zone. The samples are arranged in order away from the shear zone core. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. A schematic pole figure shows the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation. Mean foliation: 037°/88°NW; mean lineation: 5°→037°. Sample numbers are presented.

Figure 9. Quartz crystallographic preferred orientation (CPO) patterns for different grain size fractions of a deformed quartz vein sample (38). Orientation maps and c-axis (0001) and a-axis (11-20) pole figures show (a) all sizes, (b) $>80\ \mu\text{m}$, and (c) $<30\ \mu\text{m}$ (equivalent diameter). Colors in the orientation map corresponded to the inverse pole figure (IPF) key provided, and grain boundaries are outlined in black. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. (a) shows the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation.

Figure 10. Fine-grained quartz vein sample (93) with layered grain orientation domains shows different crystallographic preferred orientation (CPO) patterns and misorientation rotation angle histogram profiles for each of the grain domains. Data for the entire sample are shown at left, and data for outlined grain domains a and b are shown at right. The histogram plots show the random (green), random-pair (blue), and neighbor-pair (red) profiles. The scale for each c-axis (0001) and a-axis (11-20) pole figure with multiples of uniform density is shown; n-number of grains plotted. The pole figures at left show the relationship between the pole figures and the kinematic reference frame of the shear zone: XY-foliation, X-lineation. Colors in the orientation map (left) correspond to the inverse pole figure (IPF) key provided, and Dauphiné twins are presented as a white line. Colors in the misorientation angle boundary maps (GB Map) show the ranges provided in the key.

Figure 11. Misorientation rotation angle histogram plots, misorientation angle boundary maps (GB Map), mineral orientation maps (IPF Map), and c-axis (0001) and a-axis (11-20) pole figures of selected quartz vein samples (264, 70, 51, 53 and 28) from the Sandhill Corner shear zone. The histogram plots show the random (green), random-pair (blue), and neighbor-pair (red) profiles. The scale for each pole figure with multiples of uniform density is shown; n-number of grains plotted. Colors in the orientation map corresponded to the inverse pole figure (IPF) key provided, and Dauphiné twins are presented by white line in IPF Maps. Colors in the grain boundary map correspond to the misorientation angle ranges shown in the key. The samples are arranged in order away from the shear zone core.

Figure 12. Misorientation data for four selected quartz vein samples (28, 51, 264, and 93) from the Sandhill Corner shear zone. Misorientation rotation axes are plotted on inverse pole figures for rotation angle ranges from 5-104.5°.

Misorientation rotation angle histogram profiles show the random, random-pair, and neighbor-pair profiles as seen in Figs. 10 and 11. Sample numbers are presented.

Figure 13. A conceptual diagram showing how the matrix-accommodated rotation of folded quartz veins of the host rock might change the location of the inherited crystallographic preferred orientation (CPO) in quartz veins of the Sandhill Corner shear zone. The style and degree of rotation varies from sample to sample. The orientation of the host rock folds (example fold hinge: 35°→025°) and placement of the inherited CPO in one quadrant of the pole figure in the shear zone kinematic reference frame (mean foliation: 037°/88°NW, mean lineation: 5°→037°) is approximate following the observations of asymmetric host-rock folds at early to intermediate stages of development. AP1, AP2- flow apophyses; AP1 is the flow plane.

Figure 14. A conceptual diagram summarizing the deformation history of quartz veins from the Sandhill Corner shear zone and outlining the inferred path of fabric development for the rocks from the inner and outer parts of the shear zone. SPO- shape preferred orientation; CPO- crystallographic preferred orientation; SGR- subgrain rotation; GBM- grain boundary migration; QF-quartzofeldspathic.

Table 1. Location and grain type data for samples reported in this study

Sample	Distance from shear zone core [m] ^a	Rock Type	Dominant Quartz Grain Type ^b
60	227.25	QF host rock	Type 1
205	202.06	QF protomylonite and mylonite transition zone	Type 1+3
61	201.01		Type 1+3
208	120.44		Type 2+3
82	111.88		Type 1+3
264	90.28		Type 1+3
70	89.44	QF mylonite	Type 2+3
NFS2	77.31		Type 2+3 &
58	64.89		Type 2+3 &
56	62.98		Type 1+3
260	45.14		Type 2+3
51	38.65		Type 2+3
57	34.86		Type 3
53	29.53		Type 3
93	18.27		Type 3
41	0	Shear zone core	Type 3
305	-5.46	Highly sheared schist	Type 2+3
28	-9.01		Type 1+2+3
21	-16.57		Type 1+3
25	-19.20		Type 2+3
14	-22.51		Type 1+2+3
67	-25.35		Type 2+3
10	-25.87	Schist host rock	Type 1
11	-26.45		Type 1
303	-36.90		Type 1
38	-82.57	Heterogenously sheared schist	Type 2

^aDistance of each sample from shear zone core was measured perpendicular to the strike of the core. Positive and negative distances indicate the orientation toward NW and SE, respectively, from shear zone core. For sample locations, see Fig. 1.

^bEach grain type of quartz is described in Fig. 3.