Microstructures of a deformed kyanite–quartz vein of the Raft River Mountains in northwest Utah, USA

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Abstract

Deformed kyanite-quartz veins in the Miocene detachment fault zone of the Raft River metamorphic core complex, Utah, may provide information about P-T-fluid-deformation conditions prior to or during core complex development. Boudinaged 2-50 cm thick kyanite-quartz veins are hosted in a distinctive muscovite-rich quartzite horizon and can be followed over 4 km along Clear Creek. Deformation of kyanite and quartz is also observed at the microstructural scale, with many kyante crystals kinked, bent or broken.

Electron backscatter diffraction (EBSD) analysis of a bent kyanite crystal shows no internal grain boundaries with misorientations of \( >10^\circ \), but a consistent orientation shift along the crystal producing a cumulative misorientation of \( 45^\circ \) between the extremes of the crystal. EBSD analysis of a kinked kyanite displayed seven different orientation bands across the length of the 0.5 mm crystal. A pole figure from the kinked crystal displays a uniform orientation for the \( <010> \) pole, but the orientation of the \( <100> \) and \( <001> \) axes are spread out along an arc, indicating rotation around the \( <010> \) pole. Rotation about \( <010> \) is consistent with the known easy glide system of kyanite.

Quartz microstructures indicate that deformation occurred along the Raft River Shear Zone under greenschist facies (350°-480°C) conditions. Pole figures of quartz orientations, measured through EBSD, provide strain geometry information; with Type I cross girdles indication prevailing plain strain deformation. One pole figure is dextrally asymmetrical, indicating top-to-the-east shear, in conjunction with plain strain deformation. Kyanite grains do not show a shape preferred orientation or a crystal preferred orientation, despite showing both brittle and ductile crystal deformation features. Based on these results, it is unlikely kyanite can be used as a kinematic indicator in shear zone deformation at low to medium metamorphic grade.

Keywords: kyanite, deformation, quartz, microstructure, detachment faults
INTRODUCTION

Microstructural characteristics of naturally deformed, well studied minerals such as quartz provide insight into temperature, shear sense, and strain rate. Deformation features and mechanisms in quartz are well-constrained (Lister and Hobbs, 1980; Mancktelow, 1987; Hirth and Tullis, 1992; Lenze et al., 2005; Passchier and Trouw, 2005; Menegon et al., 2008). However, the deformation of the Al₂SiO₅ polymorphs has not been as well studied (Raleigh, 1965; Hirth and Tullis, 1992; Lenze et al., 2005; Beane and Field, 2007), compelling an investigation of kyanite deformation characteristics. The Raft River Metamorphic Core Complex in Utah provides an environment to study deformed kyanite in the context of pressure, temperature, and fluid conditions as determined through microstructure analysis of the surrounding deformed quartzite. The adjacent mylonitic quartzite exhibits a previously described fabric (Compton et al., 1977; Wells et al., 2000; Gottardi et al., 2008; Sullivan, 2008), providing an opportunity to compare the constrained quartz fabric to any present kyanite fabrics.

Microstructural analysis of quartz and calcite is currently well described as a deformation indicator through both laboratory and experimental analysis (Lister and Hobbs, 1980; Mancktelow, 1987; e.g., Hirth and Tullis, 1992). While previous research has looked at kyanite deformation (Raleigh, 1965; Lenze et al., 2005; e.g., Beane and Field, 2007), its deformation is still less understood. Microstructure assemblages in quartz are dependent of temperature, pressure, strain-rate, and fluid pressure, and have been used previously to help constrain deformation conditions for naturally deformed quartz (e.g., Mancktelow, 1987; Stipp et al., 2002; Menegon et al., 2008). Additionally, progressive deformation of quartz can lead to the development of a c-axis crystal preferred orientation, the expression of which is dependent on strain geometry, and shear
sense (Passchier and Trouw, 2005; Menegon et al., 2008). When crystal orientation measurements are plotted on a stereonet, the resulting pattern depends on strain geometry (Lister and Hobbs, 1980; Passchier and Trouw, 2005).

Crystal plastic deformation is controlled by the mechanism of dislocation glide with climb of dislocations, also known as dislocation creep. The active slip system in deformation describes both the slip plane and the direction of slip. Continued intracrystalline deformation leads to the development of a crystallographic preferred orientation (CPO). Quartz deformation can be categorized into five temperature ranges, with different deformation expressions depending on the slip system active. The active slip system is primarily dependent on temperature, but additionally influenced by pore fluid pressure, pressure, and strain rate. In low temperature deformation (<300°C) brittle fracturing, kink bands, and undulose extinction occur through pressure solution. Quartz under low-grade metamorphic deformation(300-400°C) exhibits sweeping undulose extinction, deformation lamellae, dynamic recrystallization forming core and mantle structures, formed through dislocation glide and creep, mainly on the basal glide plane <a>. Quartz deformed under medium metamorphic conditions (400-500°C) exhibits flattened parent crystals, and significant to complete recrystallization through sub grain rotation, with prism <a> slip becoming dominant. At temperatures 500-700°C quartz deformation is dominated by prism <c> slip (Passchier and Trouw, 2005).

Raleigh (1965) experimentally deformed kyanite, and determined the easy glide system within the crystal structure to a (100)[001] slip system. Research on ultra-high-pressure rocks in the Alps (Lenze et al., 2005) found naturally deformed kyanite grains, and through U-stage measurement found a <010> rotation axis for kink band geometry,
consistent with easy glide (100)[001]. Crystal orientation measurements sterographically projected did not display a CPO for kyanite; however, no CPO was found in the surrounding quartz either (Lenze et al., 2005). Beane and Field (2007) mapped individual kyanite crystals with EBSD techniques to determine crystallographic deformation orientation, examining plastically deformed kyanite crystals within an ultra-high pressure shear zone in Kazakhstan. They found that naturally deformed kyanite crystals agree with Raleigh’s (1965) experimentally determined glide system, with grain rotation around <010> pole, consistent with a (100)[001] slip system (Beane and Field, 2007). Beane and Field (2007) examine two distinct expressions of kyanite deformation, undulatory and kinked crystal forms, finding both to utilize the same deformation slip system. The unpublished finding of deformed kyanite in Raft River shear zone by Gottardi in 2007 prompted this study, with the goal to compare the plastic deformation of the kyanite with the surrounding quartzite.

Metamorphic core complexes, like the Raft River Mountains, are a product of extensional tectonics and expose orogenic crust that was exhumed in part by low-angle normal faults (detachments). The initial orientation of low angle faults is difficult to constrain because of a lack of seismicity on present low angle normal faults, and the lack of preservation due to a rapid unroofing of footwall (Wells, 2001). In the North American Cordillera, typical detachment zone rocks are quartzite and quartzofeldspathic gneiss that have been little studied for their pressure-temperature-fluid history during core complex formation, although recent studies of other core complexes have used stable isotope geochemistry to document temperature and fluid conditions during extension (Mulch, 2006, 2007).
Deformed kyanite-quartz veins in the shear zone from the Clear Creek section of the Raft River Metamorphic Core Complex, Utah, may provide information about conditions during core complex development. The deformed kyanite-quartz veins may link P-T, fluid, and deformation histories through determination of the conditions of vein formation and deformation.

For this study, I looked at the field expression of a kyanite-quartz vein in Clear Creek section of the Raft River shear zone, and examined with a petrographic microscope the deformation characteristics of kyanite and quartz from within the vein. Additionally, I mapped both quartz and kyanite with the EBSD technique to quantitatively measure crystallographic orientation to look for a crystal preferred orientation of each mineral. EBSD was also used to determine the orientation of kyanite deformation relative to its crystal structure.

GEOLOGIC SETTING

The Raft River Mountains form a N80°E trending 40km elongate doubly plunging antiform, and are spatially associated with the Albion and Grouse Creek Mountains (Fig. 1). The Raft River Mountains formed during Miocene extension, creating the Raft River shear zone (RRSZ) and Raft River Detachment fault (RRDF) (Compton et al., 1977; Wells et al., 2000; Wells, 2001; Sullivan, 2008). The Raft River metamorphic core complex, shear zone, and detachment fault provide unique opportunities to study the formation and deformation of a metamorphic core complex though the preservation of the entire rock sequence, including the footwall, shear zone, detachment fault, and hanging wall. Careful mapping of the region (Compton et al., 1977), and previous research provides a thermo-chronology, a model for shear zone development, microstructural
Figure 1: Map of the western North America, with schematic tectonic features. Black regions are known metamorphic core complexes. Raft River, Albion, Grouse Creek Mountains are highlighted in red. Inset shows general geologic map. Modified from Sullivan (2008), and Wells (2001)
The Raft River Mountains contain Archean to Permian rocks that were deeply buried during the late Mesozoic Sevier orogeny (Wells, 2001). Exhumation occurred through the formation of two separate Cenozoic detachment faults. The older detachment fault occurred in the western portion of the region with Albion and Grouse Creek mountains striking N-S and exhibiting a top-to-the-WNW shear sense resulting from Eocene-Oligocene extension. The Raft River Mountains strike E-W, and exhibit a top-to-the-east shear sense resulting from Miocene extension (Wells, 2000).

The Raft River Mountains expose greenschist facies basement and metasedimentary rocks. Unconformably overlying the 2.5 Ga Green Creek Archaean monzogranite basement is a Proterozoic, Mississippian to Permian, sedimentary sequence of quartzite and schist (Fig. 2; Compton et al., 1977; Wells et al., 2000). The Raft River shear zone is confined to a 100-300m thick region within the Proterozoic metasedimentary sequence and the top few to 10s of meters of underlying Archaean basement (Wells et al., 2000). The detachment overlies the schist member of the Elba Quartzite in eastern Raft River Mountains and stratigraphically equivalent Schist of Upper Narrows in the west, separating a hanging wall of Proterozoic and Paleozoic from Proterozoic metasedimentary rocks and Archaean basement (Wells et al., 2000). An exceptional metaconglomerate occurs at the base of the Elba quartzite in the Clear Creek section.
Figure 2: Generalized Stratigraphic column of the Clear Creek section of the Raft River Mountains. Modified from Gottardi (2008)
providing an outcrop scale visual record of the extent of shearing and direction of
extension with the quartzite (Fig. 3). The metaconglomerate displays stretched cobbles
with aspect ratios of 20-50 parallel to lineation (Sullivan, 2008).

The Raft River detachment fault displaces rocks as young as Miocene, as seen
though well bore logs, indicating that the Raft River shear zone and detachment fault was
active during Miocene extension (Wells et al., 2000). Wells (2000) identifies quartz
microstructures within the mylonitic quartzite that show characteristics of 300° – 400° C
deformation conditions, including sub grain formation, undulatory extinction, and
deformation lamellae. Samples from six locations along strike of the Raft River
Mountains record muscovite \(^{40}\text{Ar}/^{39}\text{Ar}\) dates from 47.4±0.14 Ma in west to 14.7±0.17 Ma
in east, with two data points around 45 Ma, and four in 22-14 Ma ranges (Fig. 4). East of
the two western-most sample locations, Wells notes a 23 Ma change in 4km. In Century
Hollow (Fig. 4), the differential cooling temperatures of muscovite and apatite, \(~350° C\)
and \(~150°C\) respectively, record a rapid cooling rate of approximately 20°C/Ma, while
Dunn Creek (Fig. 4) records a cooling rate of approximately 85°C/Ma. Dating provides
an apparent slip rate for the migration of leading edge of the domal uplift of \(~7\text{mm/yr}\)
from 13.5-7.4 Ma (Wells et al., 2000).

The shear zone and detachment fault is localized with the quartzite directly above
the basement unconformity, which Wells (2001) attributes as a major rheological
boundary at deformation temperatures. The orientation of the initial shear zone, as
described by Wells, does not
Figure 3: Field photograph of basal metaconglomerate. Streched pebbles provide excellent strain indicators.
Figure 4: Geologic map of Raft River Mountains. Core complex detachment fault is in black. Box shows the extent of the Clear Creek Section. Muscovite Ar$^{40}$/Ar$^{39}$ ages are plotted from Wells (2000). Modified from Sullivan (2008), and Wells (2001, 2000).
conform to normal Mohr-Coloumb failure orientation, but instead utilizes the rheologically weak quartzite. Wells interprets the initial average dip of the quartzite as 7° to 30°, with the dip of the unconformity resulting from unroofing and flexure related to the uplift of the Grouse Creek and Albion Mountains. The Raft River shear zone orientation with respect to the footwall indicate that the lower shear zone boundary developed parallel to the basement unconformity rather than forming oblique to flat lying stratigraphy, and progressively rotating to a low angle (Wells, 2001).

Sullivan (2007) systematically investigated micro-fabrics and strain along the Clear Creek section of the Raft River Mountains (Fig. 4), which strikes roughly parallel to shear direction, and found that deformation generally increases down plunge to the east. Published pole figures show a weakly asymmetric type I cross-girdle, indicating regime II deformation that is mostly coaxial (Sullivan, 2008). Few samples in the eastern most sampled region show more asymmetric cross girdles indicative of more non-coaxial deformation. Sullivan concludes that the extreme constrictional deformation within the basal metaconglomerate is rheologically driven through strain-path partitioning and moderate constrictional deformation. Sullivan identifies a shear fault at the basal contact, parallel to transport, focused within the biotite schist where phyllites adjacent to the conglomerate absorbed more of the non-coaxial shear, providing an explanation for observing significant constrictional deformation within a localized region (Sullivan, 2008).

Recent work in the Raft River Mountains has continued to focus on the well-exposed Clear Creek section, with systematic analysis of microfabrics and stable isotopes for five vertical transects through the exposed shear zone (Gottardi et al., 2008). Gottardi
(2008) finds the Elba quartzite generally displays regime II microstructures, with recrystallized grain sizes between 35 and 40 microns. Quartz CPO measured using EBSD show symmetrical cross-girdles (Gottardi et al., 2008) indicative of dominant pure shear (coaxial) (Lister & Hobbs, 1980; Law, 1990), with a general trend of more non coaxial fabric at the base, grading into more coaxial fabrics upward (Gottardi et al., 2008)

Oxygen isotope thermometry through quartz-muscovite isotope exchange indicates a 140°C linear temperature gradient over the 100 m section, from 485°C at the conglomerate-quartzite contact to 345°C in the microconglomerate (Gottardi et al., 2008).

Muscovite δD values reported at -120 to -125 ‰ indicate that mica interacted at high T with meteoric fluid (Gottardi et al., 2008). The dramatic temperature change up section through the shear zone would imply an increase in strain rate by two orders of magnitude from top to bottom; however, finite strain is generally constant through the quartzite, possibly suggesting that deformation was diachronous (Gottardi et al., 2008).

**PETROGRAPHY OF THE VEIN**

**Outcrop and Sampling**

Thirty-four oriented samples of a kyanite bearing quartz vein were collected along the 4 km Clear Creek outcrop (Figs 4, 5). The vein region is characterized by increased phyllosilicate abundance along with kyanite and coarse textured quartz in comparison to the homogeneous, granular textured quartzite above and below (Fig. 5). The vein is discontinuous within a distinctive phyllosilicate-rich quartzite horizon, ranging from 2-50cm thick (Fig. 5d). An observational correlation between the vein and sub-vertical normal faults (Fig. 5c) that crosscut the quartzite was noted, but not thoroughly investigated. Kyanite bearing quartz veins have not been found at other outcrops.
Figure 5: Outcrop photos from the Clear Creek Section of the Raft River Mountains. a. View of typical section along clear creek outcrop. Red quartzite bed is highly visible near the top. The schistose region containing the kyanite quartz vein is approximately 2m above the person. b. View of eastern most section of Clear Creek section. General top-to-the-east plunge visible. c. High-angle, low-displacement normal fault. d. Schistose, phylosillicate rich region containing the kyanite quartz vein. e. Boudin structures at two levels within the highly schistose region. f. Detail of kyanite quartz. Blocky texture of overlying quartzite is distinct compared to vein quartz.
around the Raft River Mountains. Both kyanite and quartz are present as boudins (Fig. 5e), with occasionally additional kyanite horizons visible through up to a meter of section (Fig. 5f). Thin sections are cut parallel to lineation, and perpendicular to foliation.

**Mineralogy**

Quartz dominates the vein, but most thin sections are not representative because they chosen to preferentially include kyanite. The majority of the quartz grains are <1mm, while some larger ribbon grains are formed parallel to foliation. Additionally some quartz grains resist recrystallization and are bent significantly (Fig. 6a). Kyanite makes up 20-45% in thin section, with most grains around 250µm in the largest dimension. Most thin sections include trace amounts of muscovite, primarily along shear bands (Fig 6b) and filling kyanite pull-apart fractures (Fig 6c); however, the eastern most sample includes ~40% muscovite. Trace minerals include small (<50µm) rutile grains (~2%) clustered along kyanite-quartz matrix boundaries, zoned tourmaline grains (<2%) generally adjacent to the rutile, and zircon (<1%) (Fig 7). One trace mineral found using the EDS system on the Carleton College SEM was identified in two different thin sections, containing yttrium (29% normalized for oxygen) and iridium (54% normalized for oxygen); however, the iridium peak may be an interference peak and actually correspond to phosphorus (Fig 8), which would indicate the phase is a monazite.
Figure 6: Photomicrographs a. Cross-polarized light (CPL) image of sample RR-07-11. Large bent quartz crystal seen among recrystallized quartz grains. b. CPL image of shear band through kyanite matrix filled with muscovite. c. Pulled apart kyanite crystals filled with muscovite.
Figure 7: Plain polarized light photomicrograph of sample RR-07-11. Green zoned tourmaline grains are in the center of the image. Rutile is the dark yellow-brown mineral with high relief. Small nearly elear needles are an unknown phase.
Figure: a. Back scatter image of unknown mineral phase. b. Energy Dispersive Spectroscopy (EDS) semiquantitative data regarding the atomic composition of the unknown phase. Percent compound values are normalized to exclude oxygen content.
KYANITE AND QUARTZ MICROSTRUCTURES

Typical samples of the quartz-kyanite vein show undulatory extinction, ribbon shaped quartz grains and moderate to high levels of recrystallization (Fig. 9a). The deformed quartz grains form a well developed crystal preferred orientation, qualitatively observed through use of a gypsum plate with cross polarizing light on a petrographic microscope. Sweeping extinction, visible subgrains, and deformation lamellae characterize typical samples, and are consistent with Hirth and Tullis regime II (Fig. 9b,c,d; Hirth and Tullis, 1992). Sutured and lobate grain boundaries are additional deformation features (Fig. 9e).

Samples show thin-section scale deformation features that include s-folds, shear-bands, and smaller pull-apart fractures in crystals with new mineral growth. S-shaped folds made of fine-grained kyanite are seen within a recrystallized quartz matrix (Fig. 10a). Shear-bands (Figs. 6b, 10b) generally show normal, top-to-the-east displacement, consistent with the general shear sense of deformation. Pull-apart fractures generally occur within medium to large kyanite crystals oriented parallel to lineation. Fractures are perpendicular to the long-axis of the crystals, and generally filled with fine, fibrous white mica (Fig. 6c). Ribbon shaped quartz grains are nearly all parallel to lineation, while larger kyanite grains do not display any sort of shape-preferred orientation, and in fact display a starburst pattern in places.

In addition to thin-section scale deformation, individual kyanite crystals show varying levels of deformation. Crystals show both the sweeping extinction of bent crystal structure, in along with the banded of extinction of a kinked crystal structure (Fig. 11). Generally crystals will either show one deformational response, but one exceptional
Figure 9: CPL photomicrographs of quartz micro-structures. 

a. Sweeping extinction in ribbon quartz grains, surrounded by core and mantle structures of recrystallized quartz grains. 

b. Deformation lamellae within a quartz grain. 

c. and d. Views of the same heavily recrystallized region of quartz. c. Recrystallized fabric is highly visible, with core and mantel structures giving way to full recrystallization. d. Original grain shape is more visible through similar extinction. 

e. A quartz grain shows a bulging grain boundary.
Figure 10: Thin section scans oriented top right to the east. 

**a.** Thin section scale fold of kyanite rich layer within a quartz matrix. 

**b.** Shear band filled with muscovite. (Check original orientation and shear sense)
Figure 11: Photomicrograph with cross polarized light of deformed kyanite. Kyanite grain A exhibits a bent crystal form, while kyanite grain B exhibits a highly kinked crystal form.
crystal shows sweeping extinction with a single kink in middle of the crystal (Fig. 12).

**Electron backscatter diffraction analysis**

To be able to further investigate the microstructures in a more quantitative way, electron backscatter diffraction (EBSD) was used to acquire crystallographic orientations of quartz and kyanite. Developed for geologic analysis by Prior (1999), EBSD utilizes a sensor that detects diffraction bands that are the result of the crystal structure and are unique to each mineral and dependent on orientation. Samples were analyzed at the University of Minnesota Characterization Facility on a JSM-6500f SEM and HKL Channel 5 software. Samples were prepared by polishing with 1µm diamond abrasive before a Syton colloidal silicon polish for 30-60 minutes. The EBSD technique creates a map of indexed points, each with crystallographic orientation information. These data, when plotted on a stereonet, create unique patterns that correlate to experimentally constrained strain geometries.

Large-scale and small-scale orientation maps provide different levels of analysis, with large-scale maps to identify a crystal preferred orientation, while detailed maps constrain crystal scale deformation. Quartz orientation data from a region of ribbon-textured quartzite (Fig. 13a) when plotted as a pole figure shows a well developed, weakly asymmetrical, type I cross girdle; (Fig. 13b,c; Passchier and Trouw, 2005). Prior to plotting the data, the data were corrected by first extrapolating zero solutions with 8, and 7 neighbors. Then wild spikes were eliminated, followed by additional extrapolation of zero solutions.

A stripe across a thin section was mapped recording crystal orientation of both kyanite and quartz, to be able to directly compare representative pole figures of each
Figure 12: Photomicrograph of a kyanite grain rotated within a muscovite rich matrix. Sweeping undulatory extinction can be seen beginning at the ends of the crystal and grading towards the center. A kink band within the crystal has been highlighted with dashed red lines.
Figure 13: a. Backscatter image of mapped region of quartz with indexed points colored according to Euler angle. Non indexed points extrapolated using 8, 7, and 6 neighbors, then wild spikes were removed. b. Stereonet of quartz orientations data within the mapped region showing a type I cross girdle. c. Contoured pole figure data showing strong central type I girdle.
phase from across an entire thin section (Fig. 14a). Quartz pole figures show a type I
cross girdle that is weakly asymmetric (Fig. 14b) Kyanite data from the same mapped
region do not show the same spatial organization as quartz data (Fig. 14c). There is no
CPO identifiable for kyanite within the area mapped.

While no general CPO of kyanite was found, individual kyanite crystals were
mapped for crystal orientation to examine the crystal scale deformation. One distinctive
pair of adjacent crystals displayed both kinking and bending crystal deformation (Fig.
15a). Looking at the kinked kyanite crystal, orientation block diagrams were created in
HKL Channel software for each section between kink boundaries, showing consistent
orientation of the <010> axis (green) as <100> and <001> axis (blue and red) rotate (Fig.
15a). A pole figure of a single kinked kyanite crystal shows the <010> axis as stationary,
and the <100> and <001> axes sweeping, indicating a consistent rotation about the
<010> axis across kink band boundaries (Fig. 15b). A second kyanite grain, directly
adjacent to the mentioned kinked crystal, shows a bent crystal structure with sweeping
extinction. A transect through the crystal shows a progressive misorientation with few
point-to-point changes of greater the 2° and none greater the 10°; however, combined
these slight changes in orientation create a cumulative misorientation of 42° along the
transect (Fig. 15a,c).

One kyanite crystal displayed the undulatory extinction of a bent crystal structure,
along with a distinct kink band across the center of the crystal (Figs. 12, 16). Looking at
the crystal orientation in a transect across the crystal, there is a gradual change to just
over 25° rotated compared to the initial orientation before the kink band, jumping to ~38°
misoriented within the kink band region. Across the second kink band boundary,
Figure 13: a. Backscatter image of mapped region with indexed points colored according to Euler angle. Wild spikes were removed, and non indexed points extrapolated using 8, 7, and 6 neighbors. b. Polefigure of quartz orientations within the mapped region showing a weak type I cross girdle. c. Polefigure showing orientation data for kyanite. No significant patterns are visible.
Figure 14: a. Backscatter image of mapped region with indexed points colored according to Euler angle. Blue crystal shows kinked deformation, while the pink crystal shows sweeping extinction in CPL and exhibits a bent crystal form. Red lines represent a misorientation of greater than 10° (defined as a grain boundary), while yellow lines are misorientations of >2° (defined as a subgrain boundary). White numbers show relative misorientation across a specific boundary. Crystal block diagrams show three dimensional orientation of specific points within the kinked kyanite crystal. Wild spikes were removed, and non indexed points extrapolated using 8, 7, and 6 neighbors. b. Polefigure of kyanite orientations within the upper portion of the kinked kyanite crystal. the <010> pole is consistent while the other two poles show sweeping orientations indicating rotation about the <010> pole across the kink bands. c. Misorientation profile from A to A’ (a. pink crystal) along undulatory kyanite grain relative to first point. Data are not plotted for points which could not be indexed or misindexed.
Figure 16: a. Backscatter image of distinctive kinked and bent kyanite crystal. b. Mapped region with indexed points colored according to Euler angle. Note high level of misindexing, which is primarily systematic a 180° rotation error. c. Misorientation profile from A to A’ along undulatory and kinked kyanite grain relative to first point. Data are not plotted for points which could not be indexed. Orientation profile data were modified to correct likely misindexed data by rotating erroneous data 180°. Near 0 values were removed.
the misorientation returns to 25° rotated and gradually returning to less than 5° rotated compared to the initial point orientation (Fig. 16).

**DISCUSSION**

The kyanite-quartz-phyllosilicate containing layer is attributed to be of vein origin because of textural and contextual information. However, another possible interpretation would be that kyanite formed from concentrated aluminum, due to an original clay-rich depositional layer within the quartzite sequence. Throughout the entire quartzite sequence, muscovite is found in lower concentrations, and the schistose nature of the kyanite bearing region could be due to the dissolution and removal of SiO₂, concentrating less soluble phyllosilicates. Additionally, the general morphology and coarse quartz texture of the kyanite-quartz layer leads to the vein classification when compared to the morphology of the surrounding homogeneous, granular textured quartzite. Kyanite-quartz veins, and other quartz-aluminosilicate veins, are repeatedly described in previously published work (Sauniac and Touret, 1983; Whitney and Dilek, 2000; Sepahi et al., 2004; Beitter et al., 2008; Wagner et al., 2009). Further analysis of the vein, like muscovite oxygen isotope analysis, could confirm the vein genetic interpretation.

The quartz microstructures generally resemble those described by Hirth and Tullis (1992) as regime II. These structures include ribbon shaped grains, deformation lamellae, sweeping extinction, and core and mantle structures. Kyanite deformation features include bent and kinked crystals, as well as pull-apart fractured grains. Elongate quartz grains generally show a shape-preferred orientation parallel to lineation, while kyanite grains do not show any shape-preferred orientation. EBSD analysis shows a well-developed CPO of quartz, with a type I cross girdle in one sample, and a slightly
asymmetric type I cross girdle in a second sample. Kyanite pole figures do not show the
development of any significant CPO. EBSD analysis of individual deformed kyanite
grains finds that both modes of crystal deformation rely on the same slip system, a
rotation about <010> pole (e.g. Fig 14).

Previous research in the Raft River Mountains has also found comparable
deformation features, and strain geometries as indicated by quartz pole figures (Wells et
al., 2000; Wells, 2001; Gottardi et al., 2008; Sullivan, 2008). Regime II deformation
provides a rough constraint on temperature, pressure and strain rate; however the
presence of fluids can drastically reduce the necessary temperature for certain
experimentally formed regime II microstructures at 800°C, 10^-6 S^-1, 1.5 GPa, at 30%
strain; however, Stipp et al. (2002) compared well-constrained, naturally-deformed,
quartz veins to Hirth and Tullis’ (1992) experimental work, attributing regime II
structures to 350° to 480°C as a result of significantly lower natural strain rates. Stipp
(2002) calculated strain rate using flow law data, as temperature was well known within
the field zone through mineral reaction isograds. Stipp’s (2002) deformation temperature
range for regime II microstructures of 350°-480°C is consistent with Gottardi’s (2008)
deformation temperature of 345° to 485°C for quartzite deformation in the Raft River
shear zone as calculated through quartz-muscovite oxygen stable isotope thermometry.

EBSD measured orientations of a section of recrystallized ribbon quartz, plotted
on a stereonet form a Type I cross girdle (Lister and Hobbs, 1980; Passchier and Trouw,
2005) indicative of plane strain, or coaxial deformation. Coaxial deformation would
imply a significant thinning of the quartzite. A second pole figure from a region of mixed
quartz and kyanite shows a dextrally asymmetrical Type I cross girdle indicative of plane strain with a component of top-to-the-east shear (Lister and Hobbs, 1980; Passchier and Trouw, 2005). The Type I cross girdle correlates to deformation activity primarily on the basal $<a>$ slip system, and a little on the rhomb $<a>$ slip system, but did not utilize the prism slip system, which would indicate higher temperature deformation (Passchier and Trouw, 2005).

Only one EBSD map was performed to look for a kyanite CPO, but the region was selected to cover a significant range of kyanite crystals. There is no significant kyanite CPO present within the mapped area, while a weak quartz CPO is present. The presence of only a quartz fabric, despite intermixed kyanite and quartz, makes it unlikely that kyanite can be used as a strain geometry marker to indicate strain rate, or shear direction. Because of the highly deformed nature of many of the kyanite crystals, there was hope that deformation would be orientation dependent, and lead to a CPO. No shape preferred orientation was observable either within the thin sections, precluding any hope to treat the kyanite grains as ridged bodies for kinematic vorticity strain calculations.

CONCLUSIONS

Quartz microstructures within a kyanite-quartz vein in the Clear Creek section of the Raft River Mountains indicate deformation under greenschist facies (350°-480°C.) conditions. Pole figures of quartz CPO, measured through EBSD, have Type I cross girdles indicating plain strain deformation. One CPO is dextrally asymmetric, indicating top-to-the-east shear, along with plain strain deformation.

Kyanite grains do not show either a shape preferred orientation or a crystal preferred orientation, despite showing both brittle and plastic crystal deformation.
features, suggesting it is unlikely to be a useful marker for strain rate, shear direction, or
Future research could look at the orientation of individual kink boundaries; however, many bent and kinked crystals form startburst and other not systematic patterns.
Investigation of the mechanisms behind some crystals deforming through the formation of kink bands, while other exhibit a bent crystal structure could be the focus of a new study. Additionally, researchers can look for deformed kyanite in an area where there are strong independent controls on temp, pressure, and strain rate for greater constrains on deformation conditions. Other research that could help generally constrain the formation conditions of the vein includes muscovite-quartz oxygen stable isotope analysis, quartz-rutile thermometry, and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ dating.
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REFERENCES


