Quartz c-axis orientation patterns in fracture cement as a measure of fracture opening rate and a validation tool for fracture pattern models

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ABSTRACT

We evaluate a published model for crystal growth patterns in quartz cement in sandstone fractures by comparing crystal fracture-spanning predictions to quartz c-axis orientation distributions measured by electron backscatter diffraction (EBSD) of spanning quartz deposits. Samples from eight subvertical opening-mode fractures in four sandstone formations, the Jurassic–Cretaceous Nikanassin Formation, northwestern Alberta Foothills (Canada), Cretaceous Mesaverde Group (USA; Cozzette Sandstone Member of the Iles Formation), Piceance Basin, Colorado (USA), and upper Jurassic–lower Cretaceous Cotton Valley Group (Taylor sandstone) and overlying Travis Peak Formation, east Texas, have similar quartzose composition and grain size but contain fractures with different temperature histories and opening rates based on fluid inclusion assemblages and burial history. Spherical statistical analysis shows that, in agreement with model predictions, bridging crystals have a preferred orientation with c-axis orientations at a high angle to fracture walls. The second form of validation is for spanning potential that depends on the size of cut substrate grains. Using measured cut substrate grain sizes and c-axis orientations of spanning bridges, we calculated the required orientation for the smallest cut grain to span the maximum gap size and the required orientation of the crystal with the least spanning potential to form overgrowths that span across maximum measured gap sizes. We find that within a 10° error all spanning crystals conform to model predictions. Using crystals with the lowest spanning potential based on crystallographic orientation (c-axis parallel to fracture wall) and a temperature range for fracture opening measured from fluid inclusion assemblages, we calculate maximum fracture opening rates that allow crystals to span. These rates are comparable to those derived independently from fracture temperature histories based on burial history and multiple sequential fluid inclusion assemblages. Results support the R. Lander and S. Laubach model, which predicts that for quartz deposited synchronously with fracture opening, spanning potential, or likelihood of quartz deposits that are thick enough to span between fracture walls, depends on temperature history, fracture opening rate, size of opening increments, and size, mineralogy, and crystallographic orientation of substrates in the fracture wall (transected grains). Results suggest that EBSD maps, which can be more rapidly acquired than measurement of tens to hundreds of fluid inclusion assemblages, can provide a useful measure of relative opening rates within populations of quartz-filled fractures formed under sedimentary basin conditions. Such data are useful for evaluating fracture pattern development models.

1. INTRODUCTION

Networks of naturally open fractures in rock provide conduits for fluid flow, and may influence hydrocarbon recovery, hydrogeology, and underground fluid storage (Committee on Fracture Characterization and Fluid Flow et al., 1996). Fracture networks are challenging to measure in subsurface rocks, in part because they may comprise fractures of differing age, size, and degree of mineral fill. Differences in network patterns can have profound effects on a wide range of engineering operations (Aguilera, 1980; Philip et al., 2005; Weng et al., 2011), so considerable effort has been made to build process-based models to predict fracture network growth and resulting patterns (Olson, 1993, 2004; Renshaw and Pollard, 1994; Maerten et al., 2006; Borghi et al., 2015). Although such models predict rates of fracture growth, a significant challenge for validating such models is the extremely limited capacity of geologic methods to independently measure age, rates, or duration of fracture growth.

Unmineralized fractures have remained difficult to interpret due to a lack of a means by which to record the fracture opening history. However, fractures at depth in sandstone are commonly filled, at least to some degree, by authigenic quartz as well as other phases (Laubach, 2003, and references therein). Fractures with crack-seal texture may preserve a record of the opening history of the fracture, as each crack-seal increment is usually marked by a band of fluid inclusions that were trapped by crystal growth during fracture opening. Fluid inclusion thermometry can be used to estimate the temperature at which quartz precipitation occurred during each incremental growth. More-
over, temperatures from fluid inclusion assemblages tied to burial and thermal histories can be used to estimate fracture opening rates (Becker et al., 2010; Fall et al., 2012, 2015). Analysis of geologic evidence indicates that fracture networks can form over a wide range of geological time scales of millions of years (Olson et al., 2009; Laubach et al., 2009; Becker et al., 2010; Fall et al., 2015), in accordance with rates predicted by diverse numerical models (e.g., Olson, 1993, 2004; Renshaw and Pollard, 1994; Olson et al., 2009). Fluid inclusion–based thermochronologic analyses give independent measures of timing and opening rates and allow us to validate models, but these types of data are tedious and time consuming to collect, and the applicability of the method is restricted to appropriate samples that contain relatively large two-phase aqueous fluid inclusions.

Characteristic features of some deep-seated fractures are localized, fracture-spanning cement deposits in otherwise open fractures, called bridges (Laubach, 1988; Laubach et al., 2004b). Fractures with bridges typically lack textures of competitive crystal growth common in metamorphic veins (Bons et al., 2012). The Lander and Laubach (2015) model accounts for crystal growth patterns in quartz cement in sandstone fractures, and predicts that for quartz deposited synchronously with fracture opening, the spanning potential, or likelihood of quartz deposits sufficiently thick to span between fracture walls, depends on (1) temperature, (2) the size of the opening increment, (3) the size of the quartz substrate in the fracture wall (transected grains), (4) the quartz c-axis preferred orientation of the substrate, and (5) the fracture opening rate (Fig. 1).

\[
\text{spanning potential} = \frac{2 \times \text{growth rate}}{\text{fracture opening rate}}.
\]

When the fracture opening rate is fast and quartz growth is slow (low spanning potential), only crystals with favorable orientations can form spanning bridges, implying that a crystallographic preferred orientation (CPO) of spanning crystals whose fast-growing c-axis are oriented at a high angle to the fracture wall should develop. Similarly, crystals with small grain sizes would be the least likely to form spanning bridges due to the tendency for smaller grains to grow into slow-growing euhedral crystals compared to larger cut grains, where fast growth on anhedral faces is maintained longer. Because of the dependence of the spanning potential on fracture opening rate and crystallographic orientation of the substrate, if temperature can be estimated

Figure 1. (A) The effect of crystallographic orientation in the development of quartz bridges during active fracture opening (after Lander et al., 2008). (B) Preferred crystallographic orientation of quartz crystals with c-axis at a high angle to fracture walls as a result of growth competition during passive growth into fractures (after Bons et al., 2012; Lander and Laubach, 2015).
independently, this model could be used to calculate fracture opening rates by knowing the crystallographic orientation. Crystallographic orientations of quartz can be assessed rapidly for a large number of substrate grains using scanning electron microscope (SEM) based electron backscatter diffraction (EBSD). To test these predictions, we document textures of quartz cement and crystallographic orientations in eight opening-mode fractures in four sandstone formations, the Jurassic-Cretaceous Nikanassin Formation, northwestern Alberta foothills (Canada), the Cretaceous Iles Formation, Mesaverde Group, Piceance Basin, Colorado (USA), and the upper Jurassic sandstone of the Cotton Valley Group and overlying Cretaceous Travis Peak Formation, east Texas (USA), using cathodoluminescence (SEM-CL) and EBSD. Fractures in these sandstones formed under different temperatures and in different structural settings, but similar (but not identical) quartzose composition and grain size simplify comparison of cement patterns. We statistically evaluate the presence of CPOs of c-axis with respect to fracture walls using a new routine to quantify three-dimensional (3D) crystal orientation relative to a 2D fracture wall. Our results agree with Lander and Laubach (2015) model predictions. We show that with evidence of the temperature of fracturing (measured or inferred), the crystallographic orientations of crystals with the lowest spanning potential can be used to estimate maximum fracture opening rates. Minimum opening rates can be calculated based on the crystallographic orientation of failed bridges that did not span incremental opening gaps. Calculated fracture opening rates are comparable to those calculated using fluid inclusions for the same samples. This new approach using crystallographic orientations provides an independent and efficient method to estimate fracture opening rates.

2. METHODS

We analyzed eight opening-mode fractures from four formations. Although the fracture population we tested is small, quartz cement patterns closely resemble those found in a wide range of sandstones and are representative of fractures from a wide range of basinal settings (Laubach et al., 2004b). All fractures we analyzed are from fracture populations having a wide range of kinematic aperture size in which narrow fractures tend to be fully sealed with quartz, but wide fractures may only have inconspicuous quartz deposits over most of the fracture surface, interspersed with isolated quartz bridges that span between fracture walls (Figs. 1 and 2). For such fracture arrays the terms joint (barren fracture) and vein (filled fracture) are inconvenient. Thin sections were cut parallel to bedding and perpendicular to the fractures, except for sample TP-1, which was cut perpendicular to bedding and parallel to the length of the fracture. In thin section, textures in fracture quartz were imaged using transmitted light microscopy and SEM-CL. SEM-CL images reveal quartz textures that result from differences in trace element composition and mineral structure and crystallographic orientations (e.g., Pagel et al., 2000) and provide information about microstructures and cement textures in sandstones and fractures that are not readily discernible using conventional optical methods alone (Milliken and Laubach, 2000). Samples were carbon coated, and CL images were obtained using a Philips XL30 SEM equipped with an Oxford Instruments MonoCL system at 15 kV and a Zeiss Sigma high vacuum field emission SEM with an Oxford X-Max 50 silicon drift detector (SDD) and a Gatan MonoCL4 operated at 5 kV. Grayscale CL (panchromatic) images were obtained using a blue filter; color images were obtained by stacking three grayscale images collected using blue, red, and green filters. CL images were assembled into contiguous mosaics and microstructural features were mapped using a consistent procedure (Gomez and Laubach, 2006).

Although universal stage techniques can be used to measure the c-axis orientation in quartz, EBSD analysis is increasingly common, primarily because it allows more data to be collected in less time, and multiple crystal axes as well as multiple phases can be analyzed simultaneously (Prior et al., 1999). Thus, EBSD is the method of choice to measure crystallographic orientations of quartz cement in fractures.

Following CL imaging, samples were chemically-mechanically polished for 5–6 h using a VibroMet vibratory polisher and a colloidal silica solution. EBSD maps were obtained with an Oxford Instruments Nordlys detector attached to a Philips XL30 environmental scanning electron microscope. EBSD patterns were acquired at low vacuum on rectangular grids by moving the electron beam at regular step sizes between 5 μm and 10 μm, with an electron accelerating voltage of 30 kV, and a working distance of 21.5 mm. The overall indexing in the EBSD maps exceeded 70%. EBSD patterns were indexed and postprocessed using CHANNEL 5 software (Oxford Instruments, 2007). For all eight fractures, All-Euler maps (Euler, 1776; see Maitland and Sitzman, 2007) showing crystal orientation at each data point were superimposed on band contrast maps. Based on orientation, a grain selection was performed during which misorientations of <10° were ignored, and crystals related by Dauphiné twin symmetry were considered part of the same grain. Inverse pole figure (IPF) maps were constructed to highlight the orientation of each grain relative to the orientation of the fracture walls using HKL Tango (Oxford Instruments, 2007). IPF maps were superimposed on SEM-CL maps in order to identify the crystallographic orientation of different generations of fracture cements and to distinguish them from the host rock. A statistical analysis of the distribution of the orientation of c-axis was performed using pole figure plots and analytical tools in HKL Mambo (Oxford Instruments, 2007).

SEM-based backscattered electron diffraction or EBSD (for reviews, see Prior et al., 1999; Zaefferer, 2011) analysis can be used to map at the micrometer scale the spatial distribution of the crystallographic orientation of quartz deposits within a fracture, and the pattern of deposits relative to grains on the fracture wall. Combining SEM-CL and EBSD analysis delineates complex patterns of fractures and zoning in quartz deposits. IPF maps indicate the crystal orientation at each point. For ease of visualization the orientation of c-crystallographic axis is plotted using pole figures, and quartz bridges are color coded based on relative orientation of c-axis with respect to fracture walls.

The c-axis orientation patterns were analyzed with a stereological procedure we devised that compares measurements to a uniform probability distri-
Fluid inclusion microthermometry results used in this study were conducted at the Bureau of Economic Geology, University of Texas at Austin, using a Fluid, Inc.–adapted, U.S. Geological Survey–type, gas-flow heating-freezing stage mounted on an Olympus BX51 microscope. Details of these studies were reported elsewhere (Becker et al., 2010; Fall et al., 2012, 2015; A. Fall, 2014, written commun.). For each fluid inclusion assemblage, several individual fluid inclusions were measured. Liquid-vapor homogenization temperatures were determined to ±0.05 °C by thermal cycling using temperature steps of 0.1 °C (Goldstein and Reynolds, 1994). Fluid inclusion homogenization temperatures were sequentially rearranged using crosscutting and overlapping relationships observed in SEM-CL images (see Laubach et al., 2004b). Temperature range and trend records were correlated with published burial history curves for each study area and an absolute time of fracture opening and cementation was calculated. Average fracture opening rates were calculated by dividing final kinematic aperture (the distance between original fracture walls, regardless whether cement or porosity lay between) by total opening duration.

Figure 2. Examples of studied fractures in hand sample. All fractures are at a high angle to bedding. (A) Nikanassin Formation sample NK-1 in the steep limb of an anticline (box shows location of B). (B) Sample NK-1. X-y axes indicate the orientation of the cut thin section with respect to the reference frame shown in Figure 6. (C) Travis Peak Formation sample TP-1 in core. This fracture (F) is nearly vertical. (D) Travis Peak Formation sample TP-2 showing several vertical, partially filled fractures.
3. GEOLOGIC SETTING OF SAMPLED FRAC TURES

3.1 Nikanassin Formation, Alberta Foothills, Canada

The Late Jurassic to Early Cretaceous Nikanassin Formation was deposited in the rapidly subsiding foredeep of the Western Canada Sedimentary Basin (Fig. 3). This unit was subsequently uplifted in a series of folds and reverse thrust faults during the Late Jurassic to Eocene (Fermor, 1999). Nikanassin strata in this area underwent continuous burial to depths of >6 km and were exhumed to their present surface position during the Eocene (Kalkreuth and McMechan, 1996). Four fractures from three Nikanassin Formation samples were analyzed. Opening-mode fractures are aligned at high angles to beds (vertical in flat-lying beds) and graphic restoration aligns fracture poles in opposite limbs, suggesting that fractures predate folding, although opening during folding cannot be ruled out. Two samples (NK-1 and NK-2) are from outcrop exposures near the town of Grande Cache and one is in core from a well ~100 km north of Grande Cache (NK-3) (Figs. 2 and 3).

Nikanassin Formation sandstones are fine to medium litharenites (Miles et al., 2012; Raines, 2011). Reported permeability in core ranges from 0.05 to 1 mD (Hayes, 2009; Solano et al., 2011; Zambrano et al., 2014). Nikanassin Formation litharenites that we analyzed are fine, poorly sorted, and highly compacted (intergranular volume 12%–22%), composed primarily of quartz (~30%–40%), carbonate minerals (~7%–25%), and sedimentary rock fragments (~50%–60%), including chert (as much as ~15% of the total rock volume). They are tightly bound with quartz (~5%–10%) and carbonate cement (to 5%), and have trace porosity (<0.5%) (Table 1). Kinematic apertures of subvertical opening-mode fractures analyzed are between 0.1 and 3 mm for outcrop samples, and between 0.2 and 0.3 mm for the core sample (Table 2). The lengths of cut grains along fracture margins can have an effect on quartz accumulation (Lander and Laubach, 2015): they range between 0.05 and 0.95 mm in outcrop samples, and between 0.09 and 0.35 mm for the core sample (Table 2). Fluid inclusion analyses indicate that fractures in outcrop samples from near Grande Cache opened at temperatures of between 120 °C and 170 °C. Correlation of these trapping temperatures with the burial and thermal history suggests that they probably formed between 60 and 50 Ma, at average opening rates as fast as ~70 m/m.y. (Table 2). Thus in the Iles Formation, fracture opening rates are similar to those found in the tectonically quiescent East Texas Basin, and about three times slower than those that formed in the Alberta fold-thrust belt (Table 2).

3.2 Iles Formation, Piceance Basin, Colorado

The Piceance Basin is an elongate, northwest-southeast–trending asymmetric intermontane basin in northwestern Colorado, formed during the Late Cretaceous and Paleogene (Johnson and Nuccio, 1986; Cumella, 2009). Near vertical opening-mode fractures formed regionally in nearly flat-lying rocks (Lorenz and Hill, 1994), most likely as a result of protracted gas generation in adjacent strata (Fall et al., 2015). The Mesaverde Group core sample we analyzed (I-1) is from the Iles Formation in the SHCT1 well (Lorenz and Hill, 1994; Hooker et al., 2009) from 2410 m depth (Fig. 4).

The Cozzette Sandstone Member of the Iles Formation comprises very fine to fine marine litharenites (Lorenz, 1983; Dutton et al., 1993; Ozkan et al., 2011). Reported porosity and permeability for Cozzette Sandstone Member in core samples from a nearby well (Grand Valley; Fig. 4) range from 4% to 7% and 0.002 to 0.003 mD, respectively (Ozkan et al., 2011). The Iles Formation sample that we analyzed is fine to medium, poorly sorted, and highly compacted (intergranular volume ~12%). The sample is composed primarily of quartz (~40%) and sedimentary rock fragments (~60%), including chert (~10%), and is tightly cemented with quartz (10%), contains authigenic mica and chlorite, and has trace porosity (<0.5%) (Table 1). The kinematic aperture of the fracture analyzed is between 0.6 and 0.7 mm, and lengths of cut grains along fracture margins range between 0.14 and 0.25 mm (Table 2).

Correlation of the sequence of fluid inclusion assemblage trapping temperatures with burial and thermal history indicates that fractures in a sample from the SHCT1 core at 2410 m depth (sample SHCT-9061.8) opened between 165 °C and 182 °C (Fall et al., 2012). These fracture-opening temperatures are higher than those estimated for the Travis Peak Formation, and correspond to the highest temperatures estimated for Nikanassin outcrop samples. Fall et al. (2012, 2015) concluded that fracture opening started ca. 40 Ma, coinciding with Laramide contraction and the fastest burial rates, and continued until ca. 6 Ma, and onset of uplift and exhumation. Based on the reported fracture opening history (Fall et al. 2012), and the aperture of the fracture we analyzed, the average opening rate is ~18 μm/m.y. (Table 2). Thus in the Iles Formation, fracture opening rates are similar to those found in the tectonically quiescent East Texas Basin, and about three times slower than those that formed in the Alberta fold-thrust belt (Table 2).

3.3 Cotton Valley Sandstone (Taylor Sandstone) and Travis Peak Formation, East Texas Basin

The upper Jurassic–lower Cretaceous Cotton Valley Group and the unconformably overlying lower Cretaceous Travis Peak Formation were deposited in the rapidly subsiding East Texas Basin, part of the Gulf of Mexico passive margin basin. Both units subsequently had a relatively simple and well-preserved burial history of gradual subsidence and regional extension with only minor uplift (Worrall and Snelson, 1989; Laubach and Jackson, 1990).
Figure 3 (on this and following page). (A) Location map and sites of Nikanassin Formation samples (Alberta Foothills, Canada; after Fermor, 1999).
The lower Cotton Valley sandstone units (upper Jurassic) deposited in a delta (or tidal inlet; Dutton et al., 1993) system are referred to informally as the Taylor sandstones (Wescott, 1985). Opening-mode fractures formed by regional extension dip at high angles to beds and strike parallel to the basin margin (Laubach, 1988). Three samples, one Taylor sandstone (CV-1) and two Travis Peak sandstones (TP-1 and TP-2), from two nearby wells were analyzed (Figs. 2 and 5) from depths between 2818 and 3081 m (Table 2).

Taylor sandstones and Travis Peak Formation sandstones are very fine to fine, well-sorted quartzarenite to subarkose (Wescott, 1983; Dutton, 1987). Extensive quartz cement has reduced porosity and permeability of much of both sandstones to < 9% and 0.1 mD, respectively (Holditch et al., 1985; Trojan, 1985; Dutton and Land, 1988). East Texas samples that we analyzed are very fine, poorly sorted, and moderately compacted sublitharenites (intergranular volume ~29%). They are composed primarily of quartz (~75%) and sedimentary rock fragments (~20%–25%). Tightly cemented with abundant quartz (~15%–20%), they have trace porosity (<1.5%) (Table 1). Kinematic apertures of fractures analyzed are between 0.1 and 1 mm (Table 2). One sample (TP-2) spans the length of the fracture. Thus the aperture of this fracture ranges between close to no displacement at the tip and 1 mm at its widest point. Lengths of cut grains along fracture margins range between 0.01 and 0.22 mm (Table 2).

Based on fluid inclusion analyses, Becker et al. (2010) determined that fractures at 2999 m depth in the nearby SFE#2 well opened when temperatures were between 130 and 150 °C (Fig. 5). Becker et al. (2010) inferred that fracture opening started ca. 50 Ma and continued until close to the present day; they estimated slow rates of opening of 16–23 µm/m.y. SEM-CL images of quartz cement bridges in sample TP-1 from the SFOT1 well, however, indicate that early crack-seal increments in these quartz bridges are wider than increments opened later in the fracture opening and cement history (Alzayer et al., 2015). Average fracture opening rates estimated based on three quartz bridges in the TP-1 sample indicate that initial opening rates were 20–51 µm/m.y. between 50 and 41 Ma, 11–23 µm/m.y. during maximum burial between 41 and 36 Ma, and as slow as 2–14 µm/m.y. during uplift between 36 Ma and present day (A. Fall, 2014, written commun.) (Table 2).

4. RESULTS

4.1 Cement Textures

Cement textures comprise crystal zoning, growth facets, and cement-filled fractures (Bons et al., 2012). Crack-seal texture in quartz includes narrow cement deposits that filled gaps created by incremental fracture opening and faceted and zoned quartz that accumulated on surfaces facing open fracture cavities (Laubach et al., 2004a, 2004b) (Fig. 1). These gap deposits typically trap planar arrays of fluid inclusions along a centerline formed by cement accumulations on facing fracture walls. Such deposits are synkinematic in that crosscutting relations show they are contemporaneous with fracture widening (Laubach, 1988).

Figure 3 (continued). (B) A–A’ cross section near the town of Grande Cache (McMechan, 1996).
### TABLE 1. COMPOSITION OF THE HOST ROCK IN ANALYZED SAMPLES

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grains</th>
<th>Matrix</th>
<th>Cement</th>
<th>QFL</th>
<th>IGV</th>
<th>Grain size (mm)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Q</td>
<td>F</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>carbonate (mono)</td>
<td>quartz (mono)</td>
<td>plagioclase</td>
<td>mica</td>
<td>chert</td>
<td>chlorite</td>
</tr>
<tr>
<td>CV-1</td>
<td>7 51 2.2 0 0 0.87 0 0 7 1.75 0 0 0.87</td>
<td>6.5 1.31</td>
<td>17.5</td>
<td>3.93</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TP-1</td>
<td>3 51 1.35 0.35 0.7 0 0 7 1.75 0 0 0.87</td>
<td>2.7</td>
<td>0</td>
<td>16.8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>TP-2</td>
<td>1.5 35 0.2 0.3 0.1 0.35 0.7 0.35 9 0.7 0 2.5</td>
<td>1.1</td>
<td>0</td>
<td>12.2</td>
<td>7.5</td>
<td>2.5</td>
</tr>
<tr>
<td>NK-1</td>
<td>6 51 30.7 0 0 21.8</td>
<td>3.5</td>
<td>0</td>
<td>12.4</td>
<td>0 0</td>
<td>0</td>
</tr>
<tr>
<td>NK-2</td>
<td>4 51 35.7 0.9 0 0 12.2 0.9 0 1.9 0 0 0.5</td>
<td>9.4</td>
<td>0.5</td>
<td>5.16</td>
<td>5.16</td>
<td>0</td>
</tr>
<tr>
<td>NK-3</td>
<td>3.2 37.9 0.46 0 0 17.1 3.2 4.6</td>
<td>3.2</td>
<td>0</td>
<td>8.3</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>I-1</td>
<td>1.21 36.4 0.8 0 8.1 16.2 1.21 0 11.7</td>
<td>2.4</td>
<td>0</td>
<td>7.7</td>
<td>0</td>
<td>0</td>
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</table>

Note: Estimated based on point counting, visual estimates, and cathodoluminescence (CL) images, to account for heterogeneity and difficult-to-see cement. Mono—monocrystalline; poly—polycrystalline; plag—plagioclase; felds—feldspars; chl—chlorite; QFL—quartz, feldspars, lithics. IGV—intergranular volume.

### TABLE 2. CHARACTERISTICS OF FRACTURES ANALYZED IN THIS STUDY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Formation</th>
<th>Depth</th>
<th>True vertical depth (TVD) (ft)</th>
<th>Fracture aperture (mm)</th>
<th>Range of cut grain sizes (μm)</th>
<th>Range of crack-seal increment (gap) thickness (μm)</th>
<th>Average thickness of individual crack-seal increments (μm)</th>
<th>Degree of cement fill (%)</th>
<th>Carbonate cement</th>
<th>Temperature of cement precipitation (˚C)</th>
<th>Time of opening (Ma)</th>
<th>Average opening fluid inclusions (µm/m.y.)</th>
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<tr>
<td>CV-1</td>
<td>Cotton Valley (Taylor ss.)</td>
<td>9246.2</td>
<td>~9246.2</td>
<td>0.8–1.0</td>
<td>10–220</td>
<td>7–20</td>
<td>100</td>
<td>synkinematic (80%)</td>
<td>130–150</td>
<td>50 Ma–present</td>
<td>16–23</td>
<td></td>
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<tr>
<td>TP-1</td>
<td>Travis Peak</td>
<td>10106.85</td>
<td>~10106.85</td>
<td>0.7–0.9</td>
<td>10–220</td>
<td>1–30</td>
<td>93</td>
<td>&lt;1%</td>
<td>130–150</td>
<td>42–30</td>
<td>20–51; 11–23; 2–14</td>
<td></td>
</tr>
<tr>
<td>TP-2</td>
<td>Travis Peak</td>
<td>10104.7</td>
<td>10108.3</td>
<td>0.1–1.0</td>
<td>10–220</td>
<td>1–30</td>
<td>80</td>
<td>&lt;1%</td>
<td>130–150</td>
<td>42–30</td>
<td>20–51; 11–23; 2–14</td>
<td></td>
</tr>
<tr>
<td>NK-1 Frac A</td>
<td>Nikanassin</td>
<td>surface</td>
<td>surface</td>
<td>3.0 (min)/0.7 syn</td>
<td>50–950</td>
<td>2–9</td>
<td>6</td>
<td>100 (syn)</td>
<td>syn (50%) and post (70%)</td>
<td>120–170</td>
<td>60–50 Ma</td>
<td>~70</td>
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<td>NK-1 Frac B</td>
<td>Nikanassin</td>
<td>surface</td>
<td>surface</td>
<td>0.12–0.16</td>
<td>50–950</td>
<td>2–7</td>
<td>5</td>
<td>100 (syn)</td>
<td>syn (15%) and post (5%)</td>
<td>120–170</td>
<td>60–50 Ma</td>
<td>~15</td>
</tr>
<tr>
<td>NK-2 Frac C</td>
<td>Nikanassin</td>
<td>surface</td>
<td>surface</td>
<td>0.085–0.1</td>
<td>50–950</td>
<td>4–13</td>
<td>10</td>
<td>100 (syn)</td>
<td>synkinetic (50%)</td>
<td>120–170</td>
<td>60–50 Ma</td>
<td>~10</td>
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<td>NK-3 Frac D</td>
<td>Nikanassin</td>
<td>11482.6</td>
<td>~11482.6</td>
<td>0.2–0.3</td>
<td>86–350</td>
<td>1–19</td>
<td>2–5</td>
<td>100 (syn)</td>
<td>no</td>
<td>190–210</td>
<td>75–70 Ma</td>
<td>~50</td>
</tr>
<tr>
<td>I-1</td>
<td>Mesaverde (Iles Fm.)</td>
<td>9027.5</td>
<td>~7910.0</td>
<td>0.6–0.7</td>
<td>140–250</td>
<td>10–30</td>
<td>20</td>
<td>95</td>
<td>no</td>
<td>165–182</td>
<td>40–6 Ma</td>
<td>~18</td>
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</tbody>
</table>

Note: Frac—fracture; syn—synkinematic; post—postkinematic; ss.—sandstone; Fm.—formation; min—minimum.
We analyzed opening-mode fractures that lack textural evidence of shear offset where intact cement is preserved. All are nearly perpendicular to bedding. SEM-CL images reveal cement textures that indicate that most fractures have crack-seal and overlap textures, recording multistage filling. Some fractures contain evidence of concurrent accumulations of several phases (i.e., quartz and carbonate minerals). Using fluid inclusion temperature patterns compared to burial histories, fracture opening rates can be inferred. Assumptions and uncertainties in opening rates obtained in this way were described by Becker et al. (2010). The rates we used are from published studies, except in the case of the Nikanassin Formation, where unpublished rates we used were obtained using procedures identical to those of the published studies. Rates range from fast in the proximal foreland-basin Nikanassin Formation to slow to intermediate in the distal foreland Iles Formation, and passive margin Cotton Valley sandstone and Travis Peak Formation. In all four formations, fractures range from completely filled to partly open and bridged, depending on fracture width. Narrow fractures fill more readily than wider fractures owing to larger surface area:volume. Where cement is deposited while fractures are opening, fracture fill may reflect differences in opening rates (Lander and Laubach, 2015).

4.1.1 Fast Opening Rate, Nikanassin Formation

All fractures from the Nikanassin Formation we analyzed contain quartz and ankerite cements. Fractures A through C are from the Grande Cache outcrop. Fracture D is from a core. Fracture A in sample NK-1 is at least 3 mm wide. Only half of the fracture is preserved; the fracture split along the centerline and we did not observe the entire width (Fig. 6). The reconstructed fracture aperture reported in Table 2 is a minimum, and depends on how much pore space existed in the center of the fracture.
Figure 6 (on this and following page). (A) Scanning electron microscope-cathodoluminescence (SEM-CL) image of fractures analyzed in Nikanassin Formation (sample NK-1, fracture A). Red boxes show locations of insets shown in B. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge (q—quartz; a—ankerite). N—Nonspanning bridge with the highest spanning potential that did not span the fracture. (B) SEM-CL images showing crack-seal texture of quartz cement bridges near fracture wall (q1), and euhedral overgrowths away from the wall (q2). Crack-seal texture is also seen in ankerite near fracture wall (a1), whereas away from it ankerite is blady (a2). (C) Mineral phase map. Red—quartz; blue—ankerite. (D) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to the fracture wall (X direction of the reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to the fracture wall are shown in blue.
Figure 6 (continued). (E–J) Color-coded orientation maps of quartz c-axis. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. Crystals shown in gray in J are ankerite. White fields indicate lithologies other than quartz or ankerite.
This fracture is the widest of the Nikanassin fractures, and records several stages of quartz and ankerite cement (Table 2). Along the fracture wall, early quartz (q1) and early ankerite (a1) show crack-seal texture with fracture wall–parallel fluid inclusion trails, and local areas where quartz spans between fracture walls (quartz bridges; Fig. 1). Crack-seal textures show that these are quartz deposits contemporaneous with fracture opening. For texturally early deposits, deposits of quartz and ankerite occur where quartz grains and pre-existing nonquartz deposits are cut by the fracture. Quartz is located on quartz substrate and ankerite on rock mass dolomite or shale clast substrates. Quartz detrital grains overain by ankerite overgrowths have unfavorable crystallographic orientation of quartz substrate that inhibited quartz growth (see following). In the early textural history of fracture A, fracture volume is occluded by ~50% quartz and 50% ankerite (Fig. 6; Table 2). Crack-seal gap deposits and opening increments are 0.002–0.009 mm wide. Later deposits fill the interior parts of the fracture. Overlap relations show that these deposits postdate the initial fill, but they are contemporaneous with a later phase of fracture opening marked by late euhedral quartz that is rooted on q1 (q2), which are in turn surrounded by blady ankerite (a2) crystals.

Fracture B from the same sample is 0.12–0.16 mm wide, narrow compared to fracture A (Fig. 7). This fracture is mainly (85%) filled by synkinematic quartz cement (q1), with minor (15%) synkinematic ankerite cement (a1). In the imaged part of fracture B, seven quartz bridges span from wall to wall of the fracture. The bridges are 0.09–0.16 mm wide and as much as 0.5 mm long (taking into account the bisected clasts). Crack-seal gap sizes are 0.002–0.007 mm wide. Bridges occur on quartz grains. One bridge composed of ankerite having crack-seal texture is present. The base of the ankerite is on detrital dolomite in the fracture wall. Quartz and ankerite bridges are surrounded by fine-grained blocky quartz (q2), and minor blocky ankerite (a2) that fills the rest of the fracture.

Fracture C, sample NK-2, is similar in aperture to fracture B, but unlike fracture B it contains equal amounts of ankerite (a1) and quartz (q1) (Fig. 8). This fracture contains eight well-developed quartz bridges, which are mainly surrounded by contemporaneous (synkinematic) ankerite. Bridges are 0.05–0.13 mm wide and as much as 0.26 mm long, and crack-seal increments are 0.004–0.013 mm wide.

Fracture D in sample NK-3 is from core. The main fracture cement is synkinematic quartz (q1). Other fractures in this sample, however, also contain synkinematic ankerite (a1). Several bisected clasts, ranging between 0.16 and 0.35 mm in diameter, have developed into bridges that span the fracture and are as much as 0.8 mm long. Figure 9 shows a representative part of the sample where five such bridges are apparent.

4.1.2 Slow to Intermediate Opening Rate, Iles Formation, Cotton Valley Sandstone, and Travis Peak Formation

The fracture in Iles Formation sample I-1 is 0.6–0.7 mm wide filled (95%) with synkinematic quartz cement (Fig. 10). This fracture lacks carbonate cement and ~5% porosity is preserved. Bridges contain distinct fluid inclusion–rich cores composed of multiple crack-seal gap deposits surrounded by fluid inclusion–free lateral quartz deposits. Lateral and euhedral terminations of quartz crystals are best developed around fracture pores. Such lateral quartz deposits are absent in the Nikanassin samples, probably because of competition with surrounding ankerite cement that textures show was also being deposited concurrently with fracture opening. In the imaged section of the fracture in sample I-1, 12 bridges that span the fracture are present. Fracture-spanning bridges have a crack-seal core and lateral cement with euhedral terminations that grow into fracture porosity. Nonspanning quartz crystals are of two types: with a crack-seal core and euhedral terminations, and crack-seal free with euhedral terminations. The parts of the bridges with crack-seal texture are 0.14–0.25 mm wide and as much as 1 mm long, where individual crack-seal increments are 0.01–0.03 mm wide. Lateral quartz deposits are as much as 0.2 mm wide.

The fracture in sample CV-1 is 0.8–1 mm wide and contains 6 quartz bridges that exhibit exceptionally clear crack-seal textures (Fig. 11). As in sample I-1, bridge cores are surrounded by fluid inclusion–free lateral quartz deposit (Fig. 11B). Between quartz bridges, this fracture is filled by carbonate cement (80%), which also contains fracture wall–parallel fluid inclusion trails that reveal it was deposited during fracture widening. Only two quartz bridges span entirely between fracture walls (as much as 1.02 mm long). Four of six bridges do not span entirely across the fracture. We refer to this type of deposit as nonspanning in its current state, although to have crack-seal texture it must have spanning in the past. The parts of the quartz bridges with crack-seal texture are 0.2 mm wide on average. Individual crack-seal increments are 0.007–0.02 mm wide. Lateral quartz deposits are as much as 0.1 mm wide.

In the 0.9-mm-wide fracture in sample TP-1, quartz is volumetrically the main fracture cement. Most of this fracture is filled by well-developed quartz bridges that span from wall to wall (as much as 1.1 mm long) and contain abundant wall–parallel fluid inclusion trails and fluid inclusion–free lateral quartz deposits (Fig. 12). Unlike sample CV-1, in the TP-1 sample ankerite is essentially absent and ~7% of fracture porosity is preserved (Table 2). Where porosity is preserved, quartz crystals have euhedral terminations. The parts of the quartz bridges with crack-seal texture are as much as 0.4 mm wide, where individual crack-seal increments are 0.001–0.03 mm wide. Lateral quartz deposits are usually as wide as the crack-seal part of the crystal.

Sample TP-2 contains two fractures that preserve fracture tips (Fig. 13). The fractures diminish to no displacement at the tip and are as much as 1 mm wide. Maximum quartz bridge lengths, widths of crack-seal gap deposits, and widths of lateral quartz deposits are similar to those in TP-1. A difference is that here preserved fracture porosity is as much as 20%–25%. The size of the quartz bridges and the amount of fracture porosity decreases toward fracture tips.

4.2 C-Axis Orientations

Following Lander and Laubach (2015), we designate α as the angle between the c-axis of quartz crystals and the fracture wall (Fig. 14). Data are classified in 6 angular categories where α is in the ranges 0°–15°, 15°–30°, 30°–45°, 45°–60°, 60°–75°, and 75°–90°.
Figure 7 (on this and following page). (A) Scanning electron microscope-cathodoluminescence (SEM-CL) image of the fracture analyzed in Nikanassin Formation (sample NK-1, fracture B). M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge. Red boxes show the locations of CL images in B. (B) Insets showing the crack-seal texture of quartz cement bridges in the core, and lateral quartz deposits (q—quartz; a—ankerite). (C) Mineral phase map. Red—quartz; blue—ankerite (a). (D) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to the fracture wall (Y direction of the reference frame, perpendicular to the fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to the fracture wall are shown in blue.
Figure 7 (continued). (E–J) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. Crystals shown in gray in J are ankerite. White fields indicate lithologies other than quartz or ankerite.
Figure 8 (on this and following page). (A) Scanning electron microscope-cathodoluminescence (SEM-CL) image of the fracture analyzed in Nikanassin Formation (sample NK-2, fracture C) (q—quartz; a—ankerite). M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge. (B) Mineral phase map. Red—quartz; blue—ankerite. (C) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to fracture wall (Y direction of the reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to fracture wall shown in blue.
Figure 8 (continued). (D–I) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. Crystals shown in gray in J are ankerite. White fields indicate lithologies other than quartz or ankerite.
Figure 9 (on this and following page). (A) Scanning electron microscope–cathodoluminescence (SEM-CL) image of fracture analyzed in Nikanassin Formation (sample NK-3, fracture D). Red box shows location of B. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge. (B) SEM-CL image showing crack-seal texture of a quartz bridge (q—quartz). (C) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to fracture wall (Y direction of reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to fracture wall are shown in blue.
Figure 9 (continued). (D–I) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. White fields in I indicate lithologies other than quartz.
Figure 10 (on this and following page). (A) Scanning electron microscope–cathodoluminescence (SEM-CL) image of fracture analyzed in Iles Formation, Mesaverde Group (sample I-1). Red boxes show location of CL images in B. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge. (B) Inset showing crack-seal texture of quartz cement bridges in core, and lateral quartz deposits on the sides. (C) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to fracture wall (Y direction of reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to the fracture wall are shown in blue.
Figure 10 (continued). (D–I) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. White fields indicate lithologies other than quartz.
Figure 11 (on this and following page). (A) Scanning electron microscope–cathodoluminescence (SEM-CL) image of fracture analyzed in Cotton Valley Formation (sample CV-1). Red box shows the location of B. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge. (B) Inset showing crack-seal texture of a quartz cement bridge in the core, and the lateral quartz deposits. (C) Mineral phase map. Red—quartz; blue—ankerite. (D) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to the fracture wall (Y direction of the reference frame, perpendicular to the fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to the fracture wall are shown in blue.
Figure 11 (continued). (E–J) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. Crystals shown in gray in J are ankerite. White fields indicate lithologies other than quartz or ankerite.
Figure 12 (on this and following page). (A) Photomicrograph montage of the fracture analyzed in Travis Peak Formation (sample TP-1). Red box shows location of inset shown in B. (B) Photomicrograph showing crack-seal bridges with fluid inclusion–rich cores and fluid inclusion–free lateral quartz deposits. Blue is fracture porosity. (C) Scanning electron microscope–cathodoluminescence (SEM-CL) image showing crack-seal texture of bridge highlighted with the red box in B. (D) Inverse pole figure map. Quartz crystals with their [001] (c-axis) perpendicular to the fracture wall (Y direction of the reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to fracture wall are shown in blue. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge.
Figure 12 (continued). (E–J) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. White fields in J indicate lithologies other than quartz, or porosity. Note that nonspanning bridges in two dimensions might be spanning in three dimensions.
Figure 13 (on this and following page). (A) Photomicrograph montage of fracture analyzed in Travis Peak Formation (sample TP-2). Red box shows location of B. (B) Photomicrograph showing quartz cement and abundant fracture porosity (blue). Fine-grained black material in fracture pores is thin-section powder. Crystal on the right is barite. (C) Inverse pole figure map. Quartz crystals with their [001] c-axis perpendicular to fracture wall (Y direction of the reference frame, perpendicular to fracture wall) are shown in red. Quartz crystals with their c-axis oriented subparallel to fracture wall are shown in blue. M—bisected quartz grain with lowest spanning potential that forms a spanning quartz bridge. S—smallest bisected quartz grain that forms a spanning quartz bridge.
Figure 13 (continued). (D–I) Color-coded orientation maps. Colors correspond with orientations shown in the stereoplot adjacent to each image. Stereoplots are lower hemisphere projections. Each image highlights crystals within each of the six angular categories. White fields in I indicate lithologies other than quartz, or porosity. Note that nonspanning bridges in two dimensions might be spanning in three dimensions. Dark material infilling pores around quartz bridges is thin-sectioning grit.
4.2.1 C-Axis Orientations in Samples with No Fracture Porosity

In Nikanassin Formation fracture A, $\alpha$ is between 15° and 75° in all 21 quartz bridges (q1) (Table 3; Fig. 6). Most euhedral q2 quartz has crystallographic orientations that differ with respect to q1 bridges that q2 cements substrate on. However, the distribution of the orientation of c-axis is similar to that of q1 crystals, as most c-axes of q2 crystals are also between 15° and 75° with respect to fracture walls. Unlike q1 bridges, q2 euhedral crystals with a c-axis at a high angle to fracture walls (75°–90°) are abundant (5 of 27, or 18.5%). In fracture B, most c-axes of q1 bridges are oblique (30°–75°) to fracture walls and one is parallel (Fig. 7). In fracture C, the c-axis of 1 of 8 (12%) bridges is subperpendicular, 2 of 8 (25%) are subparallel, and 5 of 8 (62%) are oblique (15°–75°) to fracture walls (Fig. 8). In fracture D, all but 1 of 28 bridges have a c-axis between 15° and 60° to fracture walls (Table 3; Fig. 9), and 1 is subparallel to the wall (0°–15°).

![Spherical cap in three dimensions](image)

Figure 14. Spherical cap in three dimensions is defined as the portion of a sphere cut off by a plane. Variables: $r$—the radius of the sphere; $\alpha$—the angle between the fracture surface and the c-axis; $h$—height of the cap of a circular arc.

### Table 3. Probabilistic Analysis of c-Axis Distributions

<table>
<thead>
<tr>
<th>Sample</th>
<th>fracture-spanning (long) bridges</th>
<th>nonspanning (short) bridges</th>
<th>around pores</th>
<th>Normalized (1 =&gt; random)</th>
<th>Normalized (1 =&gt; random)</th>
<th>Normalized (1 =&gt; random)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 $\alpha$ = 75–90 $\alpha$ = 60–75 $\alpha$ = 45–60 $\alpha$ = 30–45 $\alpha$ = 15–30 $\alpha$ = 0–15 sum number of bridges</td>
<td>0 $\alpha$ = 75–90 $\alpha$ = 60–75 $\alpha$ = 45–60 $\alpha$ = 30–45 $\alpha$ = 15–30 $\alpha$ = 0–15</td>
<td>0 $\alpha$ = 75–90 $\alpha$ = 60–75 $\alpha$ = 45–60 $\alpha$ = 30–45 $\alpha$ = 15–30 $\alpha$ = 0–15</td>
<td>14.67 0.00 0.00 0.00 0.00 1.93</td>
<td>1.87 1.57 0.00 0.00 0.00 0.35</td>
<td>1.95 1.57 0.00 0.00 0.00 0.35</td>
</tr>
<tr>
<td>CV-1</td>
<td>0 1 0 0 0 1 2</td>
<td>0 2 1 0 0 4</td>
<td>14.67 2.50 0.00 1.21 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP-1</td>
<td>0 5 10 5 5 4 44</td>
<td>0 3 10 7 13 6 47</td>
<td>1.87 1.70 1.34 0.72 1.15 0.49</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP-2</td>
<td>0 7 11 2 1 5 8 34</td>
<td>0 4 9 5 4 5 32</td>
<td>3.67 1.25 1.57 2.07 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NK-1 Frac A (q1)</td>
<td>0 0 0 0 0 21</td>
<td>0 2 6 9 6 1 28</td>
<td>0.00 2.14 1.35 0.55 0.89 0.14</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NK-1 Frac B</td>
<td>0 0 0 0 0 1</td>
<td>0 1 3 0 1 7</td>
<td>0.00 2.86 0.90 2.07 0.00 0.00</td>
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<td></td>
</tr>
<tr>
<td>NK-2 Frac C</td>
<td>0 0 0 0 0 1</td>
<td>0 1 2 0 2 8</td>
<td>3.67 1.25 1.57 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NK-3 Frac D</td>
<td>0 0 0 0 0 1</td>
<td>0 1 2 0 2 8</td>
<td>3.67 1.25 1.57 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-1</td>
<td>0 0 0 0 0 1</td>
<td>0 1 2 0 2 8</td>
<td>3.67 1.25 1.57 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: $\alpha$ is the angle between the c-axis of quartz crystals and the fracture wall; N is number.

For a uniform probability distribution

- $\alpha$ range (°) N
  - 75–90 3.41
  - 60–75 9.99
  - 45–60 15.89
  - 30–45 20.71
  - 15–30 24.12
  - 0–15 25.88
In Cotton Valley sandstone sample CV-1, of the two bridges that span the fracture one has its c-axis oriented subparallel to fracture walls (0°–15°) and the other is between 75° and 90° (Table 3; Fig. 11). Half (2 of 4) of nonspanning bridges are oriented between 30° and 75° to fracture walls, whereas 2 of 4 are perpendicular (75°–90°).

In summary, in our data set quartz bridges in fractures with no preserved fracture porosity have their c-axis mostly oriented at an oblique angle with respect to fracture walls. Although a small sample, fractures in Cotton Valley sandstone have a higher proportion of wall-perpendicular c-axes than those in samples from the Nikanassin Formation.

4.2.2 C-Axis Orientations in Samples with Fracture Porosity

In Iles Formation I-1 sample, 25% (3 of 12) of fracture-spanning bridges have their c-axis subperpendicular (60°–75°) to fracture walls, 67% (8 of 12) are between 15° and 60°, and <10% (1 of 12) have c-axes nearly parallel to fracture walls (Table 3; Fig. 10). Sample I-1 has two main fracture pores, surrounded by five quartz crystals with euhedral terminations and three fracture-spanning bridges (Fig. 10). Nonspanning quartz crystals around fracture pores have their c-axis oblique (30°–75°) to fracture walls.

In Travis Peak Formation sample TP-1, the c-axes of 5 of 44 (11%) of fracture-spanning bridges imaged are nearly perpendicular to fracture walls (75°–90°), 15 of 44 (34%) are between 60° and 75°, 20 of 44 (45%) are oblique to fracture walls (15°–60°), and 9% (4 of 44) are nearly parallel (0°–15°). The distribution of c-axis orientations of nonspanning bridges is similar to those that span, as most of the c-axes are between 15° and 60° to fracture walls. Around fracture pores, crystals with euhedral terminations have their c-axis oblique to fracture walls (Table 3). In a representative part of the fracture (Figs. 12B–12J), 3 of 12 (25%) of bridges have c-axis orientations 60°–75° to fracture walls, 8 of 12 (67%) are between 15° and 60°, and 1 of 12 (<10%) is 0°–15°. Around the large fracture pore, three nonspanning crystals have their c-axis 75°–90° to fracture walls, whereas the rest are between 30° and 75°.

Fracture porosity is abundant in sample TP-2 (Table 2; Fig. 13). Unlike in other samples, here the c-axis of 19 of 34 (56%) fracture-spanning bridges are 60°–90° to fracture walls, whereas 8 of 34 (23%) are 0°–15°, and 8 of 34 (23%) are between 15° and 60° (Table 3). The c-axes of 23 of 32 (71%) nonspanning bridges are oblique to fracture walls (15°–60°). This is also the case for most crystals with euhedral terminations surrounded by fracture porosity (128 of 170 or 75%), whereas 37 of 170 (21%) have their c-axis nearly parallel to fracture walls (0°–15°).

In summary, in samples with preserved fracture porosity the c-axis of fracture-spanning and nonspanning quartz bridges, and crystals with euhedral terminations that are currently surrounded by fracture porosity, are primarily oblique (15°–60°) to fracture walls. In the sample with the most preserved fracture porosity (TP-2), however, ~50% of fracture-spanning bridges have their long axes subperpendicular (75°–90°) to fracture walls, and the c-axis of many euhedral crystals around fracture pores are subparallel or at a low angle to fracture walls (0°–30°).

4.2.3 Statistical Analysis of C-Axis Orientations in 3D

The preceding description considers a 2D slice through fractures, cement, and grains along fracture walls. However, the crystallographic orientation of grains cut by fractures and fracture cement deposits is a 3D problem. To rigorously analyze the distribution of c-axis orientations measured in our samples, we developed a stereological procedure to compare results with a uniform probability distribution of axial data. This algorithm is justified by the fact that a c-axis measurement constitutes a unit vector, so the probability that a measurement aligns with a cap on a unit hemisphere depends directly on surface area of the cap.

The height (h) of the cap of a circular arc (Fig. 14) is defined as:

$$h = r - r \cdot \sin \alpha = r (1 - \sin \alpha),$$  \hspace{1cm} (1)

where $r$ is the radius of the sphere and $\alpha$ is the angle between the fracture surface and the c-axis, as measured in EBSD. A spherical cap quantifies the portion of a hemispherical surface cut off by a plane that is parallel to the fracture in our coordinate system (Fig. 14), and the surface area ($S$) of the spherical cap is:

$$S = 2\pi rh = 2\pi r^2 (1 - \sin \alpha).$$  \hspace{1cm} (2)

As $\alpha$ approaches 0°, the spherical cap approaches a hemisphere and Equation 2 becomes:

$$S = 2\pi r^2.$$  \hspace{1cm} (3)

Therefore, the probability $P$ that a randomly oriented c-axis has $\alpha$ between $\alpha_1$ and $\alpha_2$ ($\alpha_1 > \alpha_2$) equals:

$$P = \frac{S_2 - S_1}{S_0} = \sin \alpha_1 - \sin \alpha_2.$$  \hspace{1cm} (4)

For example, the likelihood that a random measurement of $\alpha$ is between 15° and 0° is:

$$P = \sin 15° - \sin 0° = 25.9\%.$$  \hspace{1cm} (5)

For a uniform probability distribution of $N = 100$ axes (in our case c-axes) in a hemisphere, the number of axes that would be expected to plot within each degree interval is shown in Table 3. C-axis orientations measured in natural samples in this study are shown in Figure 15 normalized with respect to these values for a uniform probability distribution. A ratio of 1 in this graph is indistinguishable from random, >1 more abundant than random, and <1 less abundant than random.
Figure 15. C-axis distributions normalized to values for a uniform probability distribution. Degrees indicate deviation from fracture wall (α). A ratio of 1 indicates a distribution indistinguishable from random, >1 indicates more abundant than random, and <1 indicates less abundant than random. Sample designations as in text. (A) The c-axis orientation distributions of quartz crystals that form bridges that span the fracture. (B) The c-axis distributions of quartz bridges that do not entirely span the fracture. (C) The c-axis distributions of quartz crystals with euhedral terminations surrounded by fracture porosity.
In most samples, we observe a higher number of fracture-spanning quartz bridges whose c-axis are between $\alpha = 90^\circ$ and $60^\circ$ than would be expected for a random distribution of c-axis. In the case of sample CV-1, this difference is extreme, where bridges with c-axes between 75° and 90° from fracture walls are nearly 15 times more abundant than in a uniform probability distribution. In contrast, in most samples bridges with c-axes subparallel to fracture walls ($\alpha = 0^\circ$–15°) are less abundant than in a normal distribution. Fracture-spanning bridges whose c-axes are oriented between 15° and 60° to fracture walls are comparably abundant to those in a random distribution. Crystals with euhedral terminations around fracture pores also have normalized values near 1 for most values of $\alpha$.

5. DISCUSSION

5.1. Spanning Potential: Controlling Factors

Many textures in fracture cements reflect mineralogy and crystal growth competition (Bons et al., 2012), but widespread crystal growth patterns in quartz cement in sandstone fractures comprising thin veneers or rinds of quartz on fracture walls interspersed with highly localized, much thicker deposits known as bridges are not readily explained by growth competition alone. A model was proposed (Lander and Laubach, 2015) that predicts that for quartz deposited synchronously with fracture opening, the spanning potential, or likelihood of quartz deposits that are thick enough to span between fracture walls, depends on temperature history, fracture opening rate, size of the opening increments, and size, mineralogy, and crystallographic orientation of substrates in fracture walls (transected grains and cements). To understand how our EBSD data test the Lander and Laubach (2015) model, it is useful to describe the model and model premises.

Walderhaug (1994, 1996) identified that in low to moderate sedimentary basin environments the accumulation of quartz cement in sandstone pores depends on temperature-controlled rate of crystal growth and substrate surface area. The assumption that precipitation rather than production or transport of dissolved silica governs quartz accumulation has led to accurate predictions of quartz volumes in a wide range of thermal regimes, burial histories, and sandstone rock types (Lander and Walderhaug, 1999; Lander et al., 2008; Taylor et al., 2010). This assumption is reasonable for quartz cementation in near neutral pH fluids at temperatures in excess of ~80 °C, but may not be applicable to quartz precipitation in highly supersaturated fluids (e.g., in silcretes, saline-alkaline lakes, or in the presence of biogenic opal) (Lander and Laubach, 2015).

In sandstones, whether a quartz overgrowth that is rooted on a bisected quartz clast will form a bridge that spans across the fracture depends on (1) the ratio between net fracture opening rate and crystal growth rate, and (2) the crystallographic orientation of bisected detrital grain or cement substrate (Lander and Laubach, 2015). Quartz cement will span the fracture when the increase in fracture aperture is small for individual fracture events or gaps, and the rate of precipitation is greater than the rate of fracture opening. Quartz growth is fastest parallel to the crystallographic c-axis on noneuhedral (broken) surfaces, followed by a-axis-parallel growth on noneuhedral surfaces, euhedral growth normal to pyramidal faces, and euhedral growth normal to prismatic faces (Lander et al., 2008; Lander and Laubach, 2015). Therefore, as the ratio of fracture opening to quartz growth rate increases, grains with the greatest potential to span gaps are those with crystallographic orientations that provide for noneuhedral growth perpendicular to the fracture wall (Lander and Laubach, 2015).

In Lander and Laubach (2015) the dependency of noneuhedral c-axis growth perpendicular to the fracture wall (b) on the angle between the c-axis and the fracture wall (a) was calculated as:

$$b = h \sin a,$$

where $h$ is the amount of growth in the direction parallel to the c-axis. Because growth occurs simultaneously from both walls toward the center of the fracture (Laubach et al., 2004b), for a gap to be completely filled the ratio of the rate of quartz growth on the fastest growth surface to the net rate of fracture opening (spanning limit) must equal $2 \times b$. The maximum spanning limit will thus occur when the opening rate is twice as fast as the growth rate and the c-axis is perpendicular to the fracture wall. The spanning limit for growth on noneuhedral surfaces along the a-axis, pyramidal faces, and prismatic faces was calculated in Lander and Laubach (2015, fig. 5A therein); it was concluded that growth along the c-axis on noneuhedral surfaces has the greatest fracture-spanning potential when $\alpha$ is between 17° and 90°, but when $\alpha < 17^\circ$, growth is dominated by noneuhedral growth along of the a-axis as the c-axis has the greatest spanning potential (crossover in Lander and Laubach, 2015, fig. 5A therein).

5.2. Model Evaluation

5.2.1 Preferred Orientation of C-Axis

The Lander and Laubach (2015) model predicts that a preferred orientation of spanning bridges whose c-axis is at a high angle to fracture walls should be strongest in samples where quartz growth is slow (i.e., at low temperature) and fracture opening rates are fast. The statistical analysis presented here indicates that a CPO of fracture-spanning bridges with a c-axis oriented perpendicular to the fracture wall is present in most samples (Table 3; Fig. 15). Our data also suggest that spanning bridges with c-axes oriented at a low angle to fracture walls (slow-growing direction is wall normal) are less abundant than in a uniform probability distribution.

5.2.1.1 Effect of temperature. Fractures cemented at the lowest temperatures (130–150 °C) in our sample suite are in Cotton Valley sandstone and Travis Peak Formation samples (Table 2). In sample CV-1, spanning bridges with c-axes at a high angle to fracture walls are nearly 15 times more abundant...
than in a uniform probability distribution, and in samples TP-1 and TP-2 they are 3 and 6 times more abundant, respectively (Table 3). In accordance with the model, these are the strongest CPOs observed in our sample suite (Fig. 16).

Fractures in the Iles Formation core and Nikanassin Formation outcrop samples were cemented at intermediate temperatures (165–182 °C and 120–170 °C). In these samples, CPOs of fracture wall-perpendicular c-axes are as much as three times more abundant than in a uniform probability distribution, but most are equally or two times more abundant. The fracture cemented at the highest measured temperature in our sample suite is in the Nikanassin Formation core sample (190–210 °C). Here, bridges with c-axes perpendicular to fracture walls are less abundant than in an even distribution (anticluster), and those with c-axes between 60° and 75° to fracture walls are only as much as 2 times more abundant (Table 3; Fig. 16). These data indicate that in accordance with the model a larger proportion of crystals with lower spanning potential developed into spanning bridges in these fractures in hotter rocks, when quartz growth rates were faster. Samples cemented at intermediate temperatures show a CPO that is less pronounced than in colder samples. In all samples, spanning bridges with c-axis nearly parallel to fracture walls (lowest spanning potential) are equally abundant as in a uniform probability distribution or less abundant (values are <1).

5.2.1.2 Effect of fracture opening rate. Nikanassin Formation fractures opened at rates as fast as 70 μm/m.y., whereas Iles Formation, Cotton Valley sandstone, and Travis Peak Formation fractures opened at relatively slow rates of a few tens of micrometers per million years (Table 2). Because favorably oriented crystals are more likely to span at faster opening rates, a stronger CPO would be expected in the fast-opening Nikanassin Formation samples, but Nikanassin and Iles Formations samples have similar c-axis orientation patterns. This suggests that the growth of spanning bridges depends on multiple other factors, including grain size and crack-seal gap sizes. The effect of these factors is discussed in the following.

5.2.1.3 Effect of growth competition. Differences in growth rates along different crystallographic orientations can result in a growth competition where crystals outgrow others and could give rise to CPO (Bons, 2001; Hilgers and Urai, 2002; Zhang and Adams, 2002; Bons and Bons, 2003; Hilgers et al., 2004; Nollet et al., 2005; Nüchter and Stöckhert, 2007; Okamoto and Sekine, 2011; Wendler et al., 2015) (Fig. 1B). In quartz, the fastest growth direction is parallel to the c-axis, and dominance of c-axis preferred orientation at a high angle to fracture walls should be expected when growth competition governs textures (Cox and Etheridge, 1983; Bons, 2001; Nüchter and Stöckhert, 2007; Okamoto and Sekine, 2011).

Open-space growth competition can coexist with crack-seal bridging processes. Such competition is likely at high temperatures where accumulation on all surfaces may be fast enough to fill space (Lander and Laubach, 2015; Wendler et al., 2015) and where different phases are accumulating concurrently. The processes need to be distinguished by their characteristic textures, which for growth competition includes marked crystal coarsening away from the fracture wall, where most of the initially growing seed crystals are overgrown by a few large survivor crystals (Hilgers et al., 2004). Growth competition need not be accompanied by crack-seal texture, whereas the bridging process relies on rapid crystal accumulation on broken crack-seal surfaces to achieve differences in crystal size between fracture-spanning and faceted but nonbridging crystals.

For quartz, growth competition can lead to the development of a CPO of a c-axis at a high angle to fracture walls (Cox and Etheridge, 1983; Bons, 2001; Nüchter and Stöckhert, 2007; Okamoto and Sekine, 2011; Lander and Laubach, 2015, fig. 20C therein) (Fig. 1B). Growth competition is likely also operative in rocks in which quartz and ankerite were concurrently growing into open fractures (Nikanassin outcrop samples and Cotton Valley sandstone sample). Where fracture fill consists largely of synkinematic quartz (Nikanassin core sample NK-3) growth competition and crack seal cannot be distinguished texturally, unless a difference in grain size from small initial seed crystals along the fracture wall to overgrown large crystals toward the middle of the fracture is present. We do not observe such grain-size distributions in samples with no preserved porosity and attribute the CPO in these samples, especially strong in CV-1, to the bridging mechanism.

In samples with bridges and preserved fracture porosity, for example, both Travis Peak (TP-1 and TP-2) and Iles (I-1) samples, we also do not see textural evidence that growth competition governed preferred orientations. In these samples, a CPO is manifested by spanning bridges and to a lesser extent by nonspanning bridges (Table 3). Crystallographic orientation distributions of crystals with euhedral terminations around fracture pores are mostly similar to the c-axis orientation patterns in fracture cement as a measure of fracture opening rate

Figure 16. Temperature of fracture opening versus c-axis preferred orientation plot indicating a stronger crystallographic preferred orientation at lower temperature. The c-axis preferred orientations are normalized with respect to these values for a uniform probability distribution (see Table 3). Sample designations as in text.
to those in a uniform probability distribution, and wall-parallel orientations are anticlustered. The CPO and anticlustered distribution observed in these samples is best accounted for by the crack-seal bridging mechanism.

5.2.2 Relationship Between Grain Size and Gap Spanning Limits

Given the relationship between crystallographic orientation and growth rate in quartz, the likelihood that the two halves of a bisected grain will come into contact across the fracture as the gap widens decreases as α becomes smaller. In Lander and Laubach (2015) the limit d where two halves meet was calculated as:

$$d = g \tan \alpha,$$

(7)

where g is the diameter of the growth substrate (Fig. 17A). The ratio of growth limit to grain diameter varies between 30% when α = 17° and 128% when α = 52°. When α < 17°, the spanning potential due to growth along the c-axis decreases because growth is likely to be faster on noneuhedral surfaces at a high angle to one of the a-axes. Therefore, in such cases there may be an anticorrelation between c-axis orientation and crystal-spanning. Above 52° the spanning potential is controlled by euhedral terminations. Thus, overgrowths nucleating on a very fine sand quartz grain (100 μm in diameter) that is sliced longitudinally will span fractures with apertures ranging from 30 to 128 μm for c-axis orientations ranging from 17° to 52° to fracture walls.

To evaluate the model, we calculated the spanning potential of quartz crystals based on the size of the bisected quartz grain. We measured longitudinal dimensions of cut grains along the fracture wall, c-axis orientations of transected grains, and crack-seal gap sizes in bridges that span fractures (Table 4). We calculated the spanning potential of different grain sizes on the basis of the maximum gap size measured in each sample using Equation 6. We then compared cut grain sizes and c-axis orientations between those that form bridges that span fractures and those that do not. For this comparison, Travis Peak samples TP-1 and TP-2 were chosen because (1) these fractures lack synkinematic ankerite cement and contain preserved porosity, growth competition textures are absent, and sizes of nonspanning grains can be measured, (2) the host rock contains particles as fine as medium silt, and (3) crack-seal increments (gap sizes) are relatively large (Table 2).

Our data show that the c-axes of many quartz bridges are not in the plane normal to fracture walls, i.e., some of the c-axes go into and out of the plane of section (Fig. 17B). To account for three-dimensionality, α can be derived as the dot product (scalar product) between the c-axis orientation and the orientation normal to the fracture wall:

$$c^\cdot n^* = \sin \propto = C_r n_x + C_n n_y + C_r n_z.$$

(8)

Using the reference frame in Figure 17B, c' and n' are as follows:

$$c' = (\sin C_{\text{trend}} \cos C_{\text{plunge}}, \cos C_{\text{trend}} \cos C_{\text{plunge}} \sin C_{\text{trend}}),$$

(9)

$$n' = (\cos \hat{\alpha}, -\sin \hat{\alpha}, 0);$$

(10)

α can therefore be derived as:

$$\sin \propto = \cos C_{\text{plunge}} (\cos \hat{\alpha} \sin C_{\text{trend}} - \sin \hat{\alpha} \cos C_{\text{trend}}).$$

(11)

Measured crack-seal gap sizes in our samples are as narrow as 1 μm in sample TP-1 to ~30 μm in Iles, Cotton Valley, and Travis Peak samples (Table 2). Most samples in our suite are poorly sorted and contain silt-sized quartz grains as fine as 20 μm (Table 1). In the absence of competing cements, such as synkinematic ankerite, sand- and even silt-sized quartz grains with c-axis perpendicular to fracture walls would easily span gap sizes as wide as 30 μm. In contrast, when the c-axis deviates from normal to fracture walls, the spanning potential of very fine sand– or silt-sized quartz grains decreases rapidly. For example, in the extreme case of the smallest grain in our samples (20 μm) to span the largest gap measured (30 μm), α would need to be >56°. At such high c-axis angles the overgrowth crystals on these small grains are likely to
reach euhedral termination before they can span the fracture aperture. Once euhedral termination occurs, the likelihood that the overgrowths will span the fracture aperture decreases substantially due to much slower rates of growth.

Using measured cut grain sizes and x measurements for detrital substrates that form bridges that span from wall to wall of the fracture, we calculated (1) the minimum x required for the smallest cut grain to span the maximum gap size measured in the corresponding bridge, and (2) the minimum x required for the detrital substrate with the least spanning potential to form overgrowths that span this maximum gap size (Table 4). We find that in all samples, measured x of the smallest cut grain is greater than the calculated minimum x required. For bridges with the lowest spanning potential, measured x is greater than the calculated minimum in all cases, except for samples TP-2 and NK-2 fracture C (gray text in Table 4). In both of these exceptions x is ~5° smaller than the calculated minimum. We speculate that this difference arises because the cut grain is larger in 3D than the apparent grain size that can be measured in this 2D slice (i.e., the thin section).

Samples TP-1 and TP-2 contain representative examples of bisected grains that did not develop into spanning bridges, but form crystals with euhedral terminations that line the walls of the fractures and are not in contact with crystals growing off the opposite fracture wall (Fig. 18). Given the size of these cut grains (39–87 μm) and assuming a conservative maximum gap size of 20 μm, the estimated minimum x value required for these grains to develop into spanning bridges is 12°–31° (Table 5). Measured x is smaller than these values in almost all cases, so they did not span the gap size; this is in accord with the model prediction. However, two crystals have x values smaller than those predicted by the model (gray text in Table 5). Documented gap sizes typically have a narrow size range (e.g., Alzayer et al., 2015), but if the range in opening increment sizes includes some large increments, spanning may not occur. The 10° discrepancy might arise if these 2 crystals needed to span maximum gap sizes larger than the 20 μm on which we based our calculations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>T range (°C)</th>
<th>g (bisected grain size = smallest cut grain size in sample of spanning bridge) (μm)</th>
<th>d (distance = maximum gap size in bridge) (μm)</th>
<th>x of smallest cut grain forming a spanning bridge (μm)</th>
<th>Cut grain size of bridge with lowest spanning potential (μm)</th>
<th>x of grain with lowest spanning potential</th>
<th>min x required for smallest grain among spanning bridges to span the maximum gap size in this sample (arc tan d/g)</th>
<th>min x required for spanning bridge with lowest spanning potential to span the maximum gap size in this sample (arc tan d/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV-1</td>
<td>130–150</td>
<td>152</td>
<td>18</td>
<td>73.5</td>
<td>219</td>
<td>7.5</td>
<td>6.75</td>
<td>4.70</td>
</tr>
<tr>
<td>TP-1</td>
<td>130–150</td>
<td>41</td>
<td>13</td>
<td>27.6</td>
<td>116</td>
<td>13.3</td>
<td>17.59</td>
<td>6.39</td>
</tr>
<tr>
<td>TP-2</td>
<td>130–150</td>
<td>63</td>
<td>19</td>
<td>71</td>
<td>125</td>
<td>2.2</td>
<td>16.78</td>
<td>8.64</td>
</tr>
<tr>
<td>NK-1 Frac A</td>
<td>120–170</td>
<td>94</td>
<td>7</td>
<td>24.37</td>
<td>94</td>
<td>24.37</td>
<td>4.26</td>
<td>4.26</td>
</tr>
<tr>
<td>NK-1 Frac B</td>
<td>120–170</td>
<td>69</td>
<td>7</td>
<td>7.6</td>
<td>99</td>
<td>7.6</td>
<td>5.79</td>
<td>5.79</td>
</tr>
<tr>
<td>NK-2 Frac C</td>
<td>120–170</td>
<td>49</td>
<td>9</td>
<td>51.5</td>
<td>54</td>
<td>3.9</td>
<td>10.41</td>
<td>9.46</td>
</tr>
<tr>
<td>NK-3 Frac D</td>
<td>190–210</td>
<td>86</td>
<td>19</td>
<td>17</td>
<td>350</td>
<td>4</td>
<td>12.46</td>
<td>3.11</td>
</tr>
<tr>
<td>I-1</td>
<td>165–182</td>
<td>66</td>
<td>12</td>
<td>70.7</td>
<td>117</td>
<td>6.16</td>
<td>10.30</td>
<td>5.86</td>
</tr>
</tbody>
</table>

Note: T—temperature; min—minimum; Frac—fracture; x is the angle between the fracture surface and the c-axis. Grayed text indicates bridges with the lowest spanning potential for which measured alpha is lower than the calculated minimum (see text).

5.3. Preferred Orientation as a Measure of Fracture Opening Rate

Following Lander and Laubach (2015), it is possible to estimate whether an overgrowth on bisected quartz grain will span a fracture if the ratio of quartz growth rate to fracture opening rate and x are known. Moreover, if quartz growth rates are known, it is possible to calculate the maximum fracture opening rate at which grains with the least spanning potential (low x) would grow into bridges.

As discussed in Lander and Laubach (2015), quartz growth kinetics extrapolated from laboratory experiments tend to overpredict quartz abundance. By constraining kinetic parameters based on host-rock quartz cement abundances, models have made successful predictions (e.g., Lander and Waldenhaus, 1998; Lander et al., 2008), so some form of calibration of rates likely will be needed. An approach to rate calibration is to use the temperature history during quartz accumulation independently measured using fluid inclusions (e.g., Bodnar, 2003; Becker et al., 2010; Fall et al., 2012, 2015) and the corresponding quartz cement amounts along various types of surfaces and crystallographic directions.

If the temperature at fracture opening and x are known for substrates with the least spanning potential, it is possible to estimate maximum fracture opening rates using the kinetics of quartz precipitation for noneuhedral surfaces at a high angle to the c-axis. Such estimates may then be evaluated using fluid inclusion data from the quartz cement in fractures. Temperature can be calculated using fluid inclusion thermometry, and x of the crystal with the least spanning potential can be measured using EBSD. The kinetics of quartz growth rates used in the following calculations were calibrated for the East Texas Basin (see Lander et al., 2008). We compare rates calculated for an activation energy, Ea, for quartz precipitation values of 49, 50, and 51 kJ/mol for growth on noneuhedral surfaces (Table 6; see Supplemental File’).
In east Texas, fluid inclusion analyses indicate that fractures in a similar depth range as our CV-1 sample in a nearby well opened when temperatures were between 130 and 150 °C (Becker et al., 2010). In our east Texas CV-1 sample (Fig. 11), the quartz bridge with the lowest spanning potential on the right side of the image (Fig. 11A, M bridge) has its c-axis oriented at a low angle to fracture walls ($\alpha = 7.5^\circ$) (Table 6). This crystal has low spanning potential, yet it forms a well-developed quartz bridge across the fracture. Quartz growth rates along the a-axes (fastest growing direction when $\alpha = 7.5^\circ$) at 130 °C and 150 °C for this study area are estimated to be 8.5 and 17 µm/m.y., respectively, at 49 kJ/mol, 6.3–12.7 at 50 kJ/mol, and 4.7–9.6 at 51 kJ/mol (Lander and Laubach, 2015; see Supplemental File).

For this bridge to have developed, spanning potential is estimated to have been 0.61 (based on Lander and Laubach, 2015, fig. 5A therein). Given this spanning potential and quartz precipitation rates discussed herein, the fastest fracture opening rates at which quartz precipitation would have been able to keep up with fracture opening would have been ~15 µm/m.y. at 130 °C and ~30 µm/m.y. at 150 °C (Table 6). Had fracture opening rates been faster, this detrital grain would not have formed a fracture-spanning quartz bridge. These estimates are comparable to the 16–23 µm/m.y. fracture opening rates estimated by Becker et al. (2010) using fluid inclusions (Table 2).

Failed quartz bridges are cement deposits with crack-seal texture that once spanned between fractures walls but no longer do so. Sampled opening increments tend to have a narrow range of sizes (Laubach et al., 2004b), so bridge failure could occur if an opening increment is larger than can be spanned, the temperature decreases, or the fracture opening rate increases. Where failed quartz bridges are present, if opening increment sizes are small and the tem-

### Table 5. Analysis of Minimum $\alpha$ Required for Crystal with Lowest Spanning Potential That Is Currently Surrounded by Porosity to Have Formed a Spanning Bridge

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cut grain number</th>
<th>Gap size (d)</th>
<th>Cut grain size (g)</th>
<th>$\alpha$</th>
<th>Minimum $\alpha$ required for spanning bridge with lowest spanning potential to span the maximum gap size in this sample (arctan d/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP-2</td>
<td>non2</td>
<td>20</td>
<td>44</td>
<td>35.66</td>
<td>24.44</td>
</tr>
<tr>
<td>TP-2</td>
<td>non3</td>
<td>20</td>
<td>39</td>
<td>6.11</td>
<td>27.15</td>
</tr>
<tr>
<td>TP-2</td>
<td>non4</td>
<td>20</td>
<td>56</td>
<td>10.22</td>
<td>19.65</td>
</tr>
<tr>
<td>TP-2</td>
<td>non5</td>
<td>20</td>
<td>51</td>
<td>31.20</td>
<td>21.41</td>
</tr>
<tr>
<td>TP-2</td>
<td>non6</td>
<td>20</td>
<td>33</td>
<td>2.18</td>
<td>31.22</td>
</tr>
<tr>
<td>TP-2</td>
<td>non7</td>
<td>20</td>
<td>58</td>
<td>13.40</td>
<td>19.03</td>
</tr>
<tr>
<td>TP-2</td>
<td>non8</td>
<td>20</td>
<td>52</td>
<td>11.16</td>
<td>21.04</td>
</tr>
<tr>
<td>TP-1</td>
<td>non9</td>
<td>20</td>
<td>87</td>
<td>4.88</td>
<td>12.95</td>
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<tr>
<td>TP-1</td>
<td>non10</td>
<td>20</td>
<td>48</td>
<td>14.19</td>
<td>22.62</td>
</tr>
</tbody>
</table>

Note: $\alpha$ is the angle between the fracture surface and the c-axis. d indicates microns. Gray text indicates alpha values that are smaller than those predicted by the Lander and Laubach (2015) model (see text).
TABLE 6. MAXIMUM AND MINIMUM FRACTURE OPENING RATES CALCULATED ON BASIS OF SPANNING POTENTIAL AND QUARTZ GROWTH RATES

<table>
<thead>
<tr>
<th>Sample</th>
<th>θ of grain with lowest spanning potential (°)</th>
<th>Quartz growth rate at minimum T estimate (along noneuclidean a-axis below 17, c-axis between 17 and 90) (μm/m.y.)</th>
<th>Quartz growth rate at maximum T estimate (along noneuclidean a-axis below 17, c-axis between 17 and 90) (μm/m.y.)</th>
<th>Spanning potential of bridge</th>
<th>Maximum opening rate at lowest T (μm/m.y.)</th>
<th>Maximum opening rate at highest T (μm/m.y.)</th>
<th>θ of failed bridge with highest spanning potential (°)</th>
<th>Quartz growth rate at minimum T estimate (along noneuclidean a-axis below 17, c-axis between 17 and 90) (μm/m.y.)</th>
<th>Quartz growth rate at maximum T estimate (along noneuclidean a-axis below 17, c-axis between 17 and 90) (μm/m.y.)</th>
<th>Spanning potential of failed bridge</th>
<th>Minimum opening rate at lowest T (μm/m.y.)</th>
<th>Minimum opening rate at highest T (μm/m.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV-1</td>
<td>7.50</td>
<td>8.48</td>
<td>16.92</td>
<td>0.61</td>
<td>27.80</td>
<td>55.48</td>
<td>82.99</td>
<td>28.83</td>
<td>57.53</td>
<td>1.90</td>
<td>30.35</td>
<td>60.56</td>
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<td>TP-1</td>
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<td>8.48</td>
<td>16.92</td>
<td>0.60</td>
<td>28.27</td>
<td>56.40</td>
<td>37.40</td>
<td>28.83</td>
<td>57.53</td>
<td>1.20</td>
<td>48.05</td>
<td>95.88</td>
</tr>
<tr>
<td>TP-2</td>
<td>2.20</td>
<td>8.48</td>
<td>16.92</td>
<td>0.60</td>
<td>28.27</td>
<td>56.40</td>
<td>74.06</td>
<td>28.83</td>
<td>57.53</td>
<td>1.80</td>
<td>32.03</td>
<td>63.92</td>
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<tr>
<td>NK-1 Frac A</td>
<td>24.37</td>
<td>19.88</td>
<td>107.88</td>
<td>0.82</td>
<td>48.49</td>
<td>263.12</td>
<td>47.37</td>
<td>19.88</td>
<td>107.88</td>
<td>1.40</td>
<td>28.40</td>
<td>154.11</td>
</tr>
<tr>
<td>NK-1 Frac B</td>
<td>7.60</td>
<td>5.85</td>
<td>31.73</td>
<td>0.60</td>
<td>19.50</td>
<td>105.77</td>
<td>54.63</td>
<td>19.88</td>
<td>107.88</td>
<td>1.70</td>
<td>23.39</td>
<td>126.92</td>
</tr>
<tr>
<td>NK-2 Frac C</td>
<td>3.90</td>
<td>5.85</td>
<td>31.73</td>
<td>0.61</td>
<td>19.18</td>
<td>104.03</td>
<td>54.63</td>
<td>19.88</td>
<td>107.88</td>
<td>1.70</td>
<td>23.39</td>
<td>126.92</td>
</tr>
<tr>
<td>NK-3 Frac D</td>
<td>4.00</td>
<td>56.35</td>
<td>95.42</td>
<td>0.61</td>
<td>184.75</td>
<td>312.85</td>
<td>54.63</td>
<td>19.88</td>
<td>107.88</td>
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Note: T is temperature; θ is the angle between the fracture surface and the c-axis. Ea is activation energy. Dashes indicate no data.

Permeability variation is small, low, or has not been recorded, the maximum and minimum fracture opening rates can be estimated if appropriate crystal growth kinetics are available. For example, in Nikanassin fracture A, bridge M is the fracture-spanning bridge with the lowest spanning potential (θ = 24°), whereas bridge N is the nonspanning bridge with the highest spanning potential that did not span the fracture (θ = 45°) because fracture opening rates exceeded maximum spanning quartz growth rates (Fig. 6). Maximum fracture opening rates estimated from bridge M between 120 °C and 170 °C at 51 kJ/mol are ~25–150 μm/m.y. (Table 6). However, bridge N indicates that fracture opening rates must have exceeded ~15 and 90 μm/m.y. at 120 and 170 °C, respectively, at 51 kJ/mol. Overall, minimum estimates based on failed bridges in Nikanassin samples are compatible with the 70 μm/m.y. estimated rate based on fluid inclusions. Rates for the rest of the samples we analyzed also agree with those independently estimated using fluid inclusion data (Tables 2 and 6). More comparisons need to be made to understand the ranges of precision and accuracy in this type of analysis, but these results are encouraging inasmuch as bridges are widespread and geological fracture opening rate information is rare. Note that we used quartz growth rates calibrated for the East Texas Basin for all calculations; kinematic calibrations that are specific to each area would most likely result in more accurate estimates.
5.4 Implications for Interpretation of Geomechanical Models

Geomechanical models predict fracture attributes such as length, aperture, and spacing, as well as rates of fracture growth (Olson, 1993, 2004; Renshaw and Pollard, 1994; Maerten et al., 2006; Borghi et al., 2015). Some of these models predict fracture pattern development over several millions of years (e.g., Olson et al., 2009), implying cumulative opening rates that are slow. For fracture patterns that develop slowly, quartz precipitation rates can exceed fracture opening rates; this could lead fractures to become sealed by quartz, and possibly become barriers for fluid flow (Fig. 19). Although other diagenetic processes can seal fractures, fracture network growth in deeply buried sandstones implies that fracture opening rate exceeds quartz growth rate (Laubach, 2003; Lander and Laubach, 2015). Simulations show that when the ratio of fracture opening to maximum quartz precipitation rate is <0.5 the fracture will be pervasively sealed, whereas when the ratio exceeds a value of 2, only rims of euhedral quartz along fracture walls will develop (Lander and Laubach, 2015). Fracture-spanning quartz bridges will develop at intermediate ratios. Therefore, knowing the rate of fracture opening versus quartz growth rate can contribute to predicting the effective permeability and porosity of a naturally fractured reservoir (Olson et al., 2009).

Although comparing natural opening rates with those predicted by fracture mechanics–based models would be helpful for assessing the models, measuring and independently validating natural fracture opening rates is not trivial. One method, noted herein, is to combine crack-seal texture mapping using SEM-CL, fluid inclusion–based thermometry, and burial history curves (Becker et al., 2010; Fall et al., 2012, 2015). Fluid inclusion thermochronology of tight gas sandstones indicates that fractures open over tens of millions of years; this is in accord with rates estimated by some geomechanical models. However, this method is time consuming and its applicability is restricted to samples containing (1) quartz bridges with crack-seal textures and crosscutting relationships of individual opening gaps discernible using SEM-CL, (2) two-phase aqueous fluid inclusion assemblages larger than ~5 μm, and (3) well-established burial histories. Structural diagenetic models such as that of Lander and Laubach (2015) also can provide rate estimates. However, a rapid, rock-based observation would be useful for assessing natural fracture patterns. In contrast, EBSD maps can be acquired easily and rapidly; our results suggest that EBSD maps can provide a useful measure of relative opening rates within populations of quartz-filled fractures formed under sedimentary basin conditions where opening increment sizes are small. Additional requirements for the application of this method are restricted to (1) finding the spanning crystal with the lowest spanning potential, and (2) an independent estimate of the temperature at which the fracture was infilled by quartz cement.

6. CONCLUSIONS

In fractures from four sandstones, quartz cement CPOs are consistent with the Lander and Laubach (2015) model, which predicts that for quartz deposited synchronously with fracture opening, the spanning potential depends on temperature history, fracture opening rate, size of the opening increments, and size, mineralogy, and crystallographic orientation of substrates in the fracture wall. Examples are from the Jurassic Nikanassin Formation (northern Alberta Foothills, Canada), the Cretaceous Iles Formation (Piceance Basin, Colorado), and the upper Jurassic and Cretaceous Cotton Valley sandstone and Travis Peak Formation (east Texas).

Our CPO analysis builds on a combination of EBSD, cathodoluminescence images, and fluid inclusion data and a new 3D stereological technique where observed orientations are compared with a uniform probability distribution. The CPO is stronger in samples where quartz precipitated at low temperatures (<~150°). Preferred orientation results from a tendency for crystals with favorable crystallographic orientations to form faster and span the few-micron-wide incremental gap openings during crack-seal deformation, whereas unfavorably oriented crystals have a lower probability of spanning and subsequently grow at slower rates that tend not to span. These CPO variations highlight the importance of the spanning potential for the cementation of fractures.

Based on this correspondence, the model can be used to estimate fracture opening rates if (1) the crystallographic orientation of the spanning crystal with...
the least spanning potential and (2) an independent estimate for quartz precipitation temperature (e.g., obtained through fluid inclusion thermometry) are known. Calculated opening rates using this method are maximum estimates; had opening rates been faster, such crystal would not have spanned the fracture, whereas at lower opening rates, an even less favorably oriented crystal would span. Minimum opening rates can be calculated based on the crystallographic orientation of failed bridges that did not span incremental opening gaps. Calculated rates are comparable to those derived independently from fracture temperature histories based on burial history and multiple sequential fluid inclusion assemblages. EBSD maps can thus provide a simple and useful measure of fracture opening rates to input into basin and fracture development models.

ACKNOWLEDGMENTS

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Erratum to this article

Quartz c-axis orientation patterns in fracture cement as a measure of fracture opening rate and a validation tool for fracture pattern models
Estibalitz Ukar, Stephen E. Laubach, and Randall Marrett
(v. 12, no. 2, p. 400–438, doi:10.1130/GES01213.1)

On page 401, the source reference for part A in the Figure 1 caption appears incorrectly. Instead of “(after Lander et al., 2008)” it should read “(after Lander and Laubach, 2015).” The corrected caption appears below:

Figure 1. (A) The effect of crystallographic orientation in the development of quartz bridges during active fracture opening (after Lander and Laubach, 2015). (B) Preferred crystallographic orientation of quartz crystals with c-axis at a high angle to fracture walls as a result of growth competition during passive growth into fractures (after Bons et al., 2012; Lander and Laubach, 2015).