Insights into rates of fracture growth and sealing from a model for quartz cementation in fractured sandstones

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ABSTRACT

A new model accounts for crystal growth patterns and internal textures in quartz cement in sandstone fractures, including massive sealing deposits, thin rinds or veneers that line open fracture surfaces, and bridge structures that span otherwise open fractures. High-resolution cathodoluminescence imaging of bridge structures and massive sealing deposits indicates that they form in association with repeated micron-scale fracturing of growing quartz crystals, whereas thin rinds do not. Model results indicate that the three morphology types develop in response to (1) the ratio of the rates of quartz growth to fracture opening and (2) the substantially faster growth rate that occurs on noneuhedral surfaces in certain crystallographic orientations compared to euhedral crystal faces. Rind morphologies develop when the fracture opening rate exceeds two times the fastest rate of quartz growth (along the c-axis on noneuhedral surfaces) because growing crystals develop slow-growing euhedral faces. Massive sealing, on the other hand, develops where the net rate of fracture opening is less than twice the rate of quartz growth on euhedral faces because all quartz growth surfaces along the fracture wall seal the fracture between fracturing events. Bridge structures form at fracture opening rates that are intermediate between the massive sealing and rind cases and are associated with crystallographic orientations that allow growth to span the fracture between fracturing events. Subsequent fractures break the spanned crystal, introducing new, fast-growing noneuhedral growth surfaces where quartz grows more rapidly compared to the euhedral faces of nonspanning crystals. As the ratio of fracture opening to quartz growth rate increases, the proportion of overgrowths that span the fracture decreases, and the range in c-axis orientations for these crystals comes progressively closer to perpendicular to the fracture wall until the maximum spanning limit is reached. Simulation results also reproduce “stretched crystal,” “radiator structure,” and “elongate blocky” textures in metamorphic quartz veins.

The model replicates a well-characterized quartz bridge from the Cretaceous Travis Peak Formation as well as quartz cement abundances, internal textures, and morphologies in the sandstone host rock and fracture zone using the same kinetic parameters while honoring fluid-inclusion and thermal-history constraints. The same fundamental driving forces, in both in the host rock and fracture system, are responsible for quartz cmentation, with the only significant difference within the fracture zone being the creation of new pore space as well as new noneuhedral surfaces for cases where overgrowths span fractures between fracturing events. Rates of fracture growth and sealing may be inferred from fracture cement textures using model results.

INTRODUCTION

Fracture growth profoundly affects the evolution of crustal attributes such as permeability, strength, and seismic response (National Academy of Sciences, 1996), yet little is known about rates of fracture growth in the Earth’s crust. For opening-mode (extensional) fractures at depth, fracture timing is commonly indeterminate, and growth is usually not detectable. Likewise, fracture geometry and patterns in core or outcrop are not diagnostic of the time of formation or growth rate. Engineering experience shows that fractures in rock can form abruptly and grow rapidly (on human time scales), but fracture-mechanics models predict growth durations reaching millions to tens of millions of years (Olson, 1993; Renshaw and Harvey, 1994; Olson et al., 2009) for fractures that form by subcritical crack growth (Atkinson and Meredith, 1987) at typical crustal strain rates and with typical rock-mechanical properties. Without independent methods to interpret or predict fracture timing or growth rates, these geomechanical model predictions lack key constraints, leading to unacceptable uncertainties in many practical applications.

The best hope for constraining timing and opening rates comes from the properties of cements that precipitate within fractures. Correlation of fracture cement isotopic or fluid-inclusion data with thermal-history models can provide broad insights on timing (Laubach, 1988; Evans, 1995; Parris et al., 2003; Lavenu et al., 2014). Recent studies of temperature sequences in fluid-inclusion assemblages from fractured quartz deposits correlated with burial histories reveal that some fractures represent the cumulative expression of hundreds of micron-scale fracturing events that took place over millions to tens of millions of years (Becker et al., 2010; Fall et al., 2012).

Quartz cement is a ubiquitous component of most fracture systems in deeply buried sandstones and thus far has proven to be the most useful source of constraints on fracture-opening history by virtue of associated fluid-inclusion properties, crack-seal textures, and isotopic and chemical compositions (Laubach, 1988; Parris et al., 2003; Laubach and Ward, 2006; Becker et al., 2010; Fall et al., 2012). Additionally, synkinematic quartz growth appears to affect size distributions in fracture systems (e.g., Clark et al., 1995; Laubach et al., 2010; Hooker et al., 2012, 2013), which vary widely in both sedimentary and metamorphic rocks (e.g., Marrett et al., 1999; Bonnet et al., 2001; Renard et al., 2005; Hooker et al., 2014).

Unlike metamorphic veins where cements generally fill the fracture volume (e.g., Hilgers et al., 2001; Bons et al., 2012), in sedimentary rocks cements often occur as thin veneers or rinds on fracture walls interspersed with highly localized, much thicker deposits known as bridges. Existing vein cmentation models (e.g., Ramsay, 1980; Bons, 2001; Hilgers et al., 2001; Zhang and Adams, 2002; Nollet et al.,...
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reproduce well-known textures in quartz veins be used to constrain fracture-opening histories. and the geometries and sizes of pores. We then account for the effect that the fracturing process stone fracture zones after adapting the model to internal textures of quartz cements within sand- cementation in unfractured sandstones is able to reproduce the abundances, morphologies, and volumes to rates of fracture opening, the time when fractures were active, and the persistence of fracture pore space. Next, we describe important characteristics of quartz cement in natural sandstone frac- tures that any process model should be able to explain. We then outline the controls on quartz cement growth, the likely sources for cement solutes, the impact that fracturing has on growth mechanisms, and the limitations on the ability of quartz cements to span fractures between micro-fracturing events. Subsequently, we describe how an approach for forward modeling of quartz cementation in unfractured sandstones is able to reproduce the abundances, morphologies, and internal textures of quartz cements within sand- stone fracture zones after adapting the model to account for the effect that the fracturing process has on creation of noneuhedral growth surfaces and the geometries and sizes of pores. We then compare model predictions to a natural example and discuss how this modeling approach may be used to constrain fracture-opening histories. Finally, we examine the ability of the model to reproduce well-known textures in quartz veins from metamorphic environments.

MODES OF QUARTZ CEMENT OCCURRENCE IN SANDSTONE FRACTURES

Sandstones that have been exposed to temper- atures in excess of 90 °C for millions of years or lower temperatures for tens to hun-
dreds of millions of years generally contain sig- nificant volumes of quartz cement (McBride, 1989; Bjureklÿkke and Egberg, 1993; Lander and Walderhaug, 1999). This cement nor- mally forms as overgrowths, where growth occurs on preexisting quartz surfaces such as detrital grains (Sorby, 1880) and earlier-formed cements. Fractures in sandstone that have been exposed to elevated temperatures over geologic time scales commonly contain quartz overgrowth cement as well as other dia- genetic phases such as carbonate and clay min- erals. Where other phases are present, overlap textures often show that quartz formed first, although in some fractures, competitive growth textures indicate that quartz and other phases (e.g., carbonate minerals) grew contemporane- ously (Kirschner et al., 1995; Laubach et al., 2010, their fig. 3).

Quartz cement in fractures exhibits sys- tematic patterns that correlate with fracture size and fracture timing relative to the rock’s burial history. For example, narrower fractures typically are more completely filled with quartz compared to wider fractures of the same set (Laubach et al., 2004a). Fractures of the same set and size in deeper, hotter rocks commonly are more completely quartz filled compared to fractures at shallower depths in the same forma- tion (Laubach, 1988). Where several fracture sets are present in the same rock, older fractures of all sizes usually are more completely quartz filled compared to younger fractures (Laubach and Ward, 2006; Laubach and Díaz-Tushman, 2009). Where fractures of the same age and thermal history exist in adjacent sandstones of differing composition, fractures in quartzose sandstones contain more quartz cement com- pared to fractures in sandstones with greater abundances of feldspar and lithic grains (Ellis et al., 2012).

Quartz cement textures vary as a func- tion of cumulative kinematic aperture (i.e., present-day opening displacement or width) for approximately contemporaneous fractures of a specific set. Microfractures (cumulative kinematic apertures of ~0.5 mm or less) fre- quently are filled with quartz (Laubach, 1997) and may show textures that resemble those in metamorphic veins (Fall et al., 2014, their fig. 4). The sealing of these thinner fractures is so pervasive that Laubach (2003) coined the term “emergent threshold” to describe the cumulative kinematic aperture below which all fractures are quartz filled. The emergent threshold normally ranges from 0.1 to 1 mm (Laubach, 2003). The transition from mostly sealed narrow fractures to wider, porous (or at least less quartz filled) fractures is present in many sandstone fracture sets, including most commercial tight gas sand- stones (Laubach, 2003). For a given fracture set, this transition occurs over a restricted range in cumulative kinematic apertures (approximately one order of magnitude). As discussed below, the cumulative kinematic aperture (net open- ing displacement) associated with preserved fracture void space (the emergent threshold) is expected to be a function of the fracture opening rate, temperature during fracture opening, and sandstone composition and texture.

Quartz cement in the portions of fractures that have cumulative kinematic apertures exceeding the emergent threshold tends to occur as inconspicuous micron-thick thin veneers or rinds that line otherwise open fractures. Surpris- ingly, wider fractures of the same set commonly contain less quartz compared to fractures in the same set with cumulative kinematic apertures near the emergent threshold (Fig. 1A). Indeed, the tips of fractures with cumulative kinematic apertures exceeding the emergent threshold characteristically have larger quartz cement vol- umes compared to centers (Fig. 1A).

Quartz cement bridges are common in frac- tures with cumulative kinematic apertures approaching the emergent threshold. Bridges are highly localized cement accumulations that span fracture walls and are surrounded by, or interspersed with, areas of fracture walls that have much thinner rinds of quartz cement (Laubach, 1988; Laubach et al., 2004b). Bridges are widespread, occurring in many fractured sand- stones (Laubach et al., 2004a), although they may be present only in some fractures within a given area or set. Bridges generally are oriented at a high angle to the fracture walls and are enigmatic because they imply growth rates that exceed those of adjacent rind overgrowths by a much larger margin than that observed in other geologic settings. For example, bridges in Cre- taceous sandstones from the East Texas Basin are up to 5–20 times thicker than overgrowths on adjacent, nonbridging fractures. These appar- ent growth anisotropies exceed those shown by existing models of crystal growth into metamor- phic veins by a considerable margin (e.g., Bons, 2001; Hilgers et al., 2001; Zhang and Adams, 2002; Nollet et al., 2005; Ankí et al., 2013).

High-resolution cathodoluminescence imag- ing of quartz cement with sealing (Fig. 1B) and bridge morphologies (Fig. 1C) records textures that reveal repeated cracking and cementing of microfractures within the crystals (Figs. 1E–1G; Laubach et al., 2004a, 2004b). Quartz cement rinds in otherwise open fractures, on the other hand, commonly lack crack-seal texture or have overlapping massive or zoned quartz depos- its that indicate that crack-seal growth was restricted to the earliest phases of fracture develop- ment (Fig. 1D).
Reconstructions of crack-seal texture show that bridge-opening histories involve a few to several hundred, mostly 1–10 μm, opening increments (Figs. 1E–1G). Fluid-inclusion assemblages within a given crack-seal band tend to have tightly clustered entrapment temperatures (often less than 1 °C and rarely more than 2–3 °C in the studies of Becker et al. [2010] and Fall et al. [2012]). Unlike crack-seal textures described from metamorphic veins, where the entire fracture is commonly filled with cement (e.g., Ramsay, 1980; Bons et al., 2012), as mentioned earlier, bridges with crack-seal texture are common within porous fractures. In sandstones with extreme thermal exposures, crack-seal bridges may be engulfed by massive quartz deposits that lack crack-seal texture (Laubach and Díaz-Tushman, 2009).
Quartz growth and fracture rates

Overlapping relations, however, show that these massive deposits grew into open pore space after bridges had formed.

SILICA SOURCE

There are many potential local sources for the silica that precipitates as quartz overgrowths in sandstones. Quartz dissolution associated with grain-to-grain contacts and grain-stylo-lite contacts is driven by surface corrosion in association with phases such as muscovite and illite (Kristiansen et al., 2011), as well as by increased stresses at contacts compared to surfaces bordering pores. Additionally, silica may be produced as a by-product of a number of silicate reactions, such as smectite-illitization, the formation of illite from the reaction of kaolinite and K-feldspar, and plagioclase albitionization. Reviews of potential sources of silica for quartz overgrowths are found in McBride (1989) and Worden and Morad (2000).

Fluid flow and solute transport are important in some natural fracture systems (Evans, 1995; Eichhubl et al., 2004; Fischer et al., 2009; Bell and Bowen, 2014). The spatial distribution of quartz cement in fractures, however, appears to be inconsistent with the solutes being derived primarily by large-scale advection through the fracture network. As mentioned earlier, quartz cementation in sandstone fractures with apertures less than 0.1–1 mm is typically pervasive (Laubach, 2003). Such fractures, however, would be expected to have much lower net fluid fluxes through them compared to associated larger fractures, given their much lower permeabilities (due to narrower fracture apertures). Furthermore, core and outcrop observations show that pervasively sealed fractures rarely are linked with fracture networks capable of transporting significant extraformational fluid volumes exclusively through the fracture system (Olson et al., 2007).

An additional line of evidence regarding silicic sources comes from the quartz cement distribution within fractures with kinematic apertures larger than the emergent threshold (~1 mm). In such fractures, the absolute amount of quartz cement per fracture wall area is greater at the tips compared to the center of the fracture (Fig. 1A). Fracture tips, however, should have been exposed to lower overall fluid fluxes compared to the open centers of fractures due to younger ages, lower permeabilities from smaller pore apertures, and greater distances from intersections with other fractures. A final line of evidence against large-scale advective flow pulses as a control on cement distribution is the lack of temperature excursions in fluid-inclusion assemblages from one crack-seal band to the next in quartz bridges that have been studied in detail to date (Becker et al., 2010; Fall et al., 2012), given that temperature excursions associated with advection of heat would be expected in such cases.

The volume of quartz cement within fractures is a small fraction of the overall quartz cement abundance in the rock. For example, in the Cretaceous Williams Fork Formation in the Piceance Basin (Ozkan, 2010), fracture-surface analyses indicate strains ranging from 0.0001 to 0.0069, with an average value of 0.0028 (Hooker et al., 2014). Even if all of this fracture volume were filled by quartz cement (which it is not), less than 2.5 volume percent of the overall quartz cement abundance would reside in fractures, given that the host rock has an average of 12% quartz cement. Thus, it seems reasonable that the source of silica for the host rock should be able to supply the required solutes for cement growth in the fracture system as well.

SIMULATING QUARTZ CEMENTATION IN FRACKURES

We propose that the processes responsible for quartz cementation within the undeformed parts of sandstones also apply to cement that forms in associated fractures. Four lines of evidence support this hypothesis: (1) It does not appear to be the case that the distribution of quartz cement within many sandstone fracture systems is controlled by large-scale advective flow through the fracture network, as already discussed. (2) Flow models suggest that fluid temperatures and fluxes are likely to be similar within the rock mass as within fractures (Taylor et al., 1999; Rossen et al., 2000; Philip et al., 2005; Olson et al., 2009). (3) Detailed studies of quartz bridges (Becker et al., 2010; Fall et al., 2012) indicate that quartz cement growth and fracturing opening may occur over time scales reaching tens of millions of years, providing ample time for molecular diffusion to homogenize fluid compositions within the host rock and fracture zones. (4) The proportion of the overall volume of quartz cement that resides within fractures is miniscule compared to the volume within the unfractured portion of the host sandstone. We suggest therefore that the peculiarities in quartz morphologies in fracture zones compared to the unfractured portion of the rock are caused solely by the effect of repeated crystal fracturing on creation of pore space and non-euhedral growth substrates.

In this section, we review models for quartz cement growth in unfractured sandstones and methods for extending them to consider the influence of fracturing. Walderhaug (1994, 1996, 2000) postulated that in unfractured portions of most sandstones, the rate-limiting control on quartz overgrowth cementation is the crystal precipitation rate. While the crystal growth-rate limitation on quartz precipitation does not explicitly constrain the source or transport mode of the cement solutes, flow and mass balance calculations argue for mainly local sources (Bjorklykke and Egeberg, 1993; Giles et al., 2000; Harwood et al., 2013). Variations in quartz supersaturation state are likely to be of secondary concern for growth kinetics given that most formation fluids have near-neutral pH values and are at or slightly above saturation with quartz (Livingstone, 1963). Consequently, the dominant controls on spatial and temporal variations in quartz growth rates in most deeply buried sandstones are temperature and the area of suitable growth substrates (Walderhaug, 1994, 1996, 2000). The volume of quartz, \( q \) (cm\(^3\)), which forms at a constant temperature \( T \) (K) over time \( \Delta t \) (s), may be estimated using the following function, which assumes uniform growth rates on all surfaces \( S \) (cm\(^2\)):

\[
q = S \frac{A_o e^{\frac{E_a}{R T}}}{M} \frac{M}{P} \Delta t,
\]

where \( A_o \) is a pre-exponential Arrhenius constant mol/(cm\(^2\)·s) that also implicitly incorporates a supersaturation term, \( E_a \) is the activation energy for quartz precipitation (J/mol), \( R \) is the real gas constant (8.314 J/[mol·K]), \( M \) is the molar mass of quartz (60.09 g/mol), and \( P \) is the density of quartz (2.65 g/cm\(^3\)) (Walderhaug, 2000).

Although Equation 1 implies uniform rates of growth on all surfaces, in fact quartz overgrowths have important variations in growth rate depending on the nature of the growth substrate (Heald and Renton, 1966). For instance, the characteristic elongated form of a quartz prism along its \( c \) axis reflects faster growth rates on pyramidal compared to prismatic faces (Fig. 2). Natural hydrothermal quartz crystals display growth rate anisotropies of three to five times among these euhedral faces (Lander et al., 2008). Even larger variations in rates occur when overgrowths develop on noneuhedral as opposed to euhedral substrates (Fig. 2). For instance, experimental studies show that quartz growth along the \( c \) axis is ~20 times faster on noneuhedral (0001) surfaces compared to pyramidal crystal faces (Lander et al., 2008).

Lander et al. (2008) suggested the following growth-rate ratios with respect to noneuhedral \( c \)-axis parallel growth: 0.31 for noneuhedral growth along one of the \( a \) axes on noneuhedral surfaces, 0.063 for euhedral growth normal to pyramidal faces, and 0.015 for euhedral growth normal to prismatic faces (Fig. 2). Thus, the
maximum anisotropy in growth rate approaches two orders of magnitude. To derive absolute growth rates, we apply these ratios with non-euhedral growth along the c axis determined using Equation 1, where the kinetic parameters refer strictly to growth on this surface type.

Quartz cementation models for the unfractured portions of sandstones that account for the differences in growth rate with substrate type show that, other factors being constant, the differences in growth rate with substrate types calculated using Equation 1 for growth along the c axis on noneuhedral surfaces and the suggested rate ratios for other surface types from Lander et al. (2008) (see Figure 2). The dark black lines show results for an Ea value of 50 kJ/mol for growth along the c axis on noneuhedral surfaces. The lighter lines show results with ±1 kJ/mol. All calculations assume an Ao value of $9 \times 10^{-12}$ mol/cm$^2$s.

While laboratory studies of kinetics are essential for process understanding, models that employ kinetics derived from laboratory experiments to silicate reactions tend to overpredict the extent of reaction in the diagenetic realm by orders of magnitude (e.g., Blum and Stillings, 1995; Brosse et al., 2000; White and Brantley, 2003; Ajdukiewicz and Lander, 2010; Lander and Bonnell, 2010). Consequently, unlike some previous approaches for simulating quartz growth in fractures (e.g., Fisher and Brantley, 1992; Hilgers et al., 2004; Wangen and Munz, 2004), we do not use kinetics derived from laboratory experiments in our model. Instead, we constrain kinetic parameters based on measured host rock quartz cement abundances, textural and compositional characteristics, and thermal reconstructions. Models that incorporate this kinetic approach together with the assumption of precipitation rate limitation have had impressive success at reproducing quartz cement abundances in sandstones from a broad range of geologic settings (i.e., Lander and Walden, 1999; Walden, 2000; Bloch et al., 2002; Taylor et al., 2004; Lander et al., 2008; Toby et al., 2010; Taylor et al., 2010). Predictions made using this kinetic approach are consistent with high-resolution isotopic data from quartz overgrowths (Harwood et al., 2013).

We obtained an optimal activation energy of ~50 kJ/mol for growth on (0001) non-euhedral c-axis surfaces (see Fig. 2) in the unfractured portion of Cretaceous sandstones from east Texas using an Ao value of $9 \times 10^{-12}$ mol/cm$^2$s and the Prism2D model, which is described below. The implications of these values for the rates of quartz growth with temperature are shown in Figure 3 for each of the four surface types considered in this study. The maximum potential growth rates increase
from ~5 to ~30 to ~200 μm/y, as temperature rises from 100 °C to 150 °C to 200 °C, respectively.

**FRACTURE-SPANNING LIMITS**

The ratio of the net fracture opening rate to crystal growth rate is a fundamental control on cement spanning potential. Because quartz overgrowths require detrital grain substrates for nucleation, spanning potential also is influenced by the crystallographic orientation of the substrate grain with respect to the fracture wall and whether the grain was bisected by the fracture.

Overgrowths on grains that are bisected by a fracture are more likely to span the fracture gap compared to nonfractured grains because overgrowths grow into the fracture from both walls. Among bisected grains, those with the greatest potential to span gaps are cut longitudinally and compared to nonfractured grains because overgrowths require detrital grain substrates for nucleation, spanning potential also is influenced by the crystallographic orientation of the substrate grain with respect to the fracture wall and whether the grain was bisected by the fracture.

Overgrowths on grains that are bisected by a fracture are more likely to span the fracture gap compared to nonfractured grains because overgrowths grow into the fracture from both walls. Among bisected grains, those with the greatest potential to span gaps are cut longitudinally and have crystallographic orientations that provide for noneuhedral growth perpendicular to the fracture wall. Overgrowths on grains with c-axis orientations perpendicular to the fracture wall have the greatest spanning potential (Fisher and Brantley, 1992), given that this is the fastest-growing quartz surface, as discussed earlier, and because the crystal can grow farther before reaching euhedral termination compared to non-euhedral growth along one of the a axes (Fig. 4A). The distance t that the crystal can grow prior to reaching euhedral termination may be approximated as follows:

\[ t = \frac{g}{2} \tan \beta \].

where \( \beta \) in this case is the angle (51.8°) between the pyramidal euhedral faces and the c axis (Fig. 2), and \( g \) is the diameter of the growth substrate. By this calculation, the crystal can grow ~64% of the length of \( g \) into the fracture before reaching euhedral termination. Because growth takes place into the fracture from both sides of a bisected grain, the limit of noneuhedral growth for sealing a microfracture is twice this value (i.e., ~1.3 times the diameter of longitudinally bisected grains). Equation 2 also may be used to approximate the maximum extent of noneuhedral growth along the a-axes plane into the fracture (Fig. 4A) by substituting a value of 30° for \( \beta \). (This is where the fracture wall is perpendicular to one of the a axes but parallel to the c axis.) Thus, for noneuhedral a-axis–parallel growth, the crystal may grow to ~29% of the growth surface diameter into the fracture prior to reaching euhedral termination. By these approximations, the microfracture aperture sealing limit for noneuhedral growth for a very fine quartz grain (100 μm diameter) that is bisected longitudinally would be ~130 μm for c-axis–parallel growth or ~58 μm for a-axis–parallel growth.

These calculations represent the cases where the crystallographic orientations are optimally suited for growth that spans fractures. The impact of a nonoptimal c-axis orientation is illustrated in Figure 4B. In this case, the amount of noneuhedral c-axis growth perpendicular to the fracture wall, \( b \), may be approximated by this expression:

\[ b = h \sin \alpha \].

where \( h \) is the amount of growth along the c-axis direction, and \( \alpha \) is the angle of the c axis with respect to the fracture wall. The dependency of \( b \) on \( \alpha \) is illustrated in Figure 5A. The y axis in the figure is defined in terms of the spanning limit for growth where the fracture longitudinally bisects a quartz grain (thus the values are 2 × \( b \)). This limit is defined as the ratio of the rate of quartz growth on the fastest growth surface type (noneuhedral along the c axis) to the net rate of fracture opening. The maximum spanning limit is where the opening rate is twice as fast as this growth rate and the c axis is perpendicular to the fracture wall for a bisected grain. The figure also shows the spanning limit for growth on (1) noneuhedral surfaces along an a axis, (2) pyramidal faces, and (3) prismatic faces (all as normalized with respect to the fracture wall).
to c-axis noneuhedral rates). Growth along the c axis on noneuhedral surfaces has far greater fracture-spanning potential compared to other surfaces, except where the c axis is less than ~17° from the fracture wall, in which case noneuhedral growth along one of the a axes has greater spanning potential. The spanning potential for the euhedral crystal faces is greatly outstripped by that of the noneuhedral surfaces.

A final consideration for spanning potential is that overgrowths from the halves of bisected grains that have c-axis orientations that are far from perpendicular to the fracture wall will become progressively less likely to come into contact across the fracture as the gap widens (Fig. 4C). The limit, d, where the two overgrowths may come in contact across the fracture gap may be approximated given the c-axis orientation α and the diameter of the substrate surface g along the fracture wall:

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

The dependence of d on α is illustrated in Figure 5B. The y axis in the figure shows the value of d normalized to the substrate size g. The limit where the two overgrowth halves may come into contact across the fracture gap is approximately equal to the grain diameter for the case where the c axis is at a 45° angle to the fracture wall for a longitudinally bisected grain or about half of the grain diameter for a 27° angle. The shaded portion on the right side of the plot indicates that at c-axis angles greater than ~52°, the ability of the crystal halves to come into contact across the fracture gap is more likely to be controlled by euhedral termination (Fig. 4A) than by displacement gap. Crystals that have c axes less ~17° to the fracture wall (the shaded area on the left of Fig. 5B), on the other hand, will tend to have growth rates into the fracture that are dominated by noneuhedral growth along one of the a axes, as discussed previously. Within the ~17°–52° range, the spanning limit varies from being approximately equal to the diameter of a longitudinally fractured grain to ~30% of the grain diameter. Thus, the expected threshold for a crystal rescaling a microfracture gap is ~30–100 μm for 100-μm-diameter quartz grains that are sliced longitudinally. These bridging thresholds are large compared to microfracture apertures in nature, which typically are on the order of 1–10 μm. Equation 3 then provides a useful basis for a first approximation of gap-spanning limits (Fig. 5A). Using this approximation, it is possible to estimate the cumulative distribution for the limit on sealing potential for the case where the crystallographic axes are randomly oriented (Fig. 6A). The plot indicates, for instance, that roughly half of bisected grains should be able to span a micron-scale microfracture when the ratio of the average rate of fracture opening to quartz growth on noneuhedral c-axis surfaces is ~1.4. The inflection in the distribution at rate ratios less than ~0.6 reflects crystals where the c axis is so close to being parallel to the fracture wall that noneuhedral growth along a axes dominates the spanning potential (less than 17° in Fig. 5B).

It is possible to relate the spanning potential to absolute fracture opening rates using Equation 1. We have done this in Figure 6B, where we apply the same kinetic parameters used for Figure 3. These results indicate that approximately half of bisected quartz crystals should be able to span fractures that open at rates of ~6, 40, and 175 μm/m.y., respectively, for temperatures of 100, 150, and 200 °C.
Figure 6. Cumulative distribution in the proportion of bisected crystals that will span a small fracture gap for a set of random crystallographic orientations for host grains. These approximations apply to the case where fracture gaps are sufficiently small so that growth on the crystal fragments is able to come into contact across the gap and crystals do not reach euhedral termination. (A) Case where the rate is defined in terms of the ratio of the average fracture opening rate to the quartz growth rate on noneuhedral (0001) surfaces. (B) Case where the opening rate is in terms of \( \mu m/m.y. \) given the kinetic parameters discussed in the text and shown in Figure 3 for 100 \(^\circ\) C, 150 \(^\circ\) C, and 200 \(^\circ\) C. At these temperatures, 50% of bisected grains along fractures would be estimated to span the fractures opening at rates of ~6, 40, and 175 \( \mu m/m.y. \), respectively.

SIMULATING THE INTERACTION OF FRACTURE OPENING AND QUARTZ GROWTH

We adapted the Prism2D model discussed in Lander et al. (2008) for simulation of quartz growth in fracture zones. This model considers the impact on crystal-spanning behavior of temperature, growth on euhedral versus noneuhedral surfaces, and the creation of noneuhedral growth surfaces from crystal fracturing. The model has been applied to quartz growth in unfractured sandstones (Lander et al., 2008) as well as to dolomite growth within dolostone fractures (Gale et al., 2010).

Prism2D is a continuous-value cellular-automata-type model where growth takes place at discrete time steps in a two-dimensional orthogonal grid. At each time step, properties of cells may change depending on environmental conditions (i.e., temperature and elapsed time from the previous step), the cell’s properties at the start of the time step, and the properties of neighboring cells. For quartz cells, the crystallographic orientation is defined by the projection of the quartz \( c \)-axis in the plane of the orthogonal grid (azimuth) and the angle of the axis with respect to the modeled plane (bearing). The azimuth is constrained to values of 0\(^\circ\), 45\(^\circ\), 90\(^\circ\), and 135\(^\circ\), but the bearing may vary continuously from 0\(^\circ\) (\( c \)-axis parallel to the modeled plane) to 90\(^\circ\) (\( c \)-axis perpendicular to the modeled plane). The model does not consider quartz that grows into the simulated two-dimensional (2-D) plane from substrate surfaces outside of the plane.

Quartz cells may grow if they retain unfilled porosity or are completely filled but adjacent to cells lacking any solid materials. The rate of quartz growth depends on the nature of the growth surface and the environmental conditions. The system currently recognizes noneuhedral growth along the \( c \)-axis and the \( a \)-axes in addition to growth on pyramidal and prismatic faces (Fig. 2). The surface type is determined by the slope of the growth surface, which is derived from the properties of the neighboring cells, as well as from the \( c \)-axis orientation of the cell. The amount of growth is based on the rate for the surface type in question with respect to the noneuhedral \( c \)-axis surface and the \( c \)-axis bearing for the cell. The noneuhedral \( c \)-axis surface rate may be constant for each time step or determined as a function of the current temperature using Equation 1. In either case, time-step durations are selected so that quartz may grow no more than one cell on the fastest-growing surface type.

Fractures are introduced into the model reference frame as discontinuities that extend from the top to the bottom of the grid. The fracture trace may have an arbitrary angle with respect to the orthogonal grid, and the displacement vector for the portion of the grid to the right of the fracture trace may be defined to allow for pure extension or some amount of lateral displacement. When microfractures are introduced, solid materials within the fracture zone are broken only if they extend continuously from one fracture wall to the other. Consequently, no solid materials are broken for cases where there is a continuous pore along the length of the fracture. Microfractures with defined apertures may be introduced at random within the fracture zone or at prescribed positions.

In the sections that follow, we begin with simple simulations of individual bisected grains to evaluate the ability of the model to reproduce the morphologies and internal textures of quartz cement displayed in natural fractures. We then consider the morphologies that arise through the interplay of cementation and microfracturing using more realistic depictions of the sandstone host rock. We next apply the model to a thoroughly documented quartz bridge from a Cretaceous sandstone in east Texas and demonstrate that it reproduces the salient features of this natural example. We conclude our analysis by comparing simulated growth textures to those found in quartz veins of metamorphic origin.

SINGLE-GRAIN FRACTURE AND CEMENTATION MODELS

In this set of 2-D models, we study fracture sealing capacity by simulating quartz growth on single grains. These models are more rigorous than the approximations discussed earlier because they consider all of the spanning limit mechanisms simultaneously while also accounting for the effects of growth that takes place concurrently on all exposed crystal surfaces. As discussed later, the crystal morphologies and internal textures predicted by these models compare favorably with natural examples, supporting the efficacy of the model assumptions.

A zoomed-in view from the topmost portion of a quartz bridge is shown in Figure 7 for a bisected grain that has its \( c \)-axis perpendicular to the fracture and within the plane of the image. The images show the geometry of the
fracture zone and cements that grow within it at various time steps, where a step represents the time required to grow one cell on a noneuhedral (0001) surface. Vertically oriented microfractures with 50 cell kinematic apertures are introduced in the simulation at steps 50, 100, and 150, resulting in a net growth to opening-rate ratio of 1 (i.e., the rate of microfracture opening is equal to the rate of growth along [0001] surfaces).

Quartz cement that grows on the freshly generated (0001) fracture surfaces (red color) is able to span the microfractures 25 steps after they form (Fig. 7). Once the gap is spanned (e.g., steps 80, 130, and 180), there is no remaining noneuhedral (0001) surface area. The overgrowths develop euhedral pyramidal faces (green color) at the vertical boundaries of the fractured crystal as they fill in the remaining portion of the fracture gap. The slower rate of growth and inclined angle of these surfaces with respect to the fracture wall lead to the development of a “sawtooth” texture, where the base of the “valley” represents the point where the two crystal halves

Figure 7. Zoomed-in views of the evolution in simulated quartz growth textures along the top of a developing quartz bridge where the c axis is oriented perpendicular to a vertical fracture. The step value in the images indicates the simulation step (quartz began growing at step 1 and finished at step 1000). Microfractures with 50 cell kinematic apertures were introduced at steps 50, 100, and 150. The red color indicates cement that nucleated on fast-growing noneuhedral (0001) surfaces, the green color shows slower-growing cement that grew on pyramidal faces, and the cyan color indicates growth on prismatic faces, the slowest-growing surface type. Gray indicates the detrital quartz grain, and black indicates porosity. Simulation results are shown at 10 step increments through step 200 (labels shown in white), when the step increment increases to 100 (labels in yellow). Note that although growth takes place continuously on the pyramidal and prismatic faces, noneuhedral (0001) growth is restricted in time to steps 50–75, 100–125, and 150–175 and stops once microfractures are spanned by cement (steps 75–99, 125–149, 175–1000). A “sawtooth” texture develops initially as the microfractures are spanned (steps 50–180). The “sawtooth” valleys (e.g., step 80) are progressively filled in by pyramidal growth (green cells), whereas the “plateaus” above them (e.g., step 300) experience slower rates of growth on prismatic faces (cyan cells). An example of leftward lateral migration for a “plateau” is indicated by the arrows in steps 500, 600, and 700.
came in contact across the fracture gap (i.e., step 80). These valleys are progressively filled in by pyramidal growth, whereas the “plateaus” above them experience slower rates of growth on prismatic faces (cyan cells; e.g., step 300). The plateaus form at different heights depending on the relative timing of microfracturing associated with the adjacent valleys and the proximity to the detrital grain surface. Plateaus spread laterally along the bridge by growth on the pyramidal faces that define their lower flanks. An example of the lateral migration of a plateau is indicated by the arrows shown for steps 500, 600, and 700. With time and in the absence of disturbances caused by new microfracturing events, the active plateau tops become progressively larger, while the flank slopes diminish due to the overrunning of taller plateaus over shorter ones. For instance, the plateau edge shown in step 500 grows over the cyan-capped area just to the left of it by the end of step 600.

When the c-axis is not perpendicular to the fracture wall, somewhat different textures and morphologies emerge. (We simulate arbitrary c-axis angles with respect to the fracture wall using inclined fracture traces that have corresponding orthogonal displacement vectors.) The driving force for the difference is illustrated schematically in Figure 4B for a case where the c-axis is at an angle greater than 90° from the fracture wall. Note that not all of the surface growing along the c-axis overlaps once the fracture gap is spanned. (The nonoverlapping portion is shown by double line segments.) This surface area is above the slow-growing prismatic face on the top of the crystal that grew from the left side. Given time, this geometry permits faster-growing quartz from the right half of the crystal bridge to grow leftward over the top of the overgrowth that grew from the left wall of the fracture. The opposite pattern occurs at the bottom portion of the bridge, where crystal growth from the left side of the fracture will develop a layer over the outer surface of the crystal from the right side. Bridge structures that have c-axis angles less than 90° from the fracture wall will show a mirror image of this pattern.

The impact of this inclined geometry on simulation results is illustrated in Figure 8 for a case where the c-axis is at an 80° angle to the fracture wall. The “plateaus” on the outer surface of the lower portion of the quartz bridge have a regular step-like pattern, where plateaus to the right grow leftward and overrun plateaus to the left (Fig. 8B). The locations of prismatic faces defining the plateau flanks are indicated by the yellow arrows (Fig. 8E provides an overview of the overall simulated area). This morphology is similar to that indicated by yellow arrows for a natural bridge (Fig. 8A).

Simulated crack-seal textures in bridges with c-axis angles less than 90° show asymmetrical “valley” forms, with the steeper side of the valley on the right flank of the top of the bridge. An example of this texture is shown by the “V” symbol in Figure 5D. This geometry mimics the observed crack-seal texture illustrated by the same symbol in Figure 8C. The white arrows shown in Figures 8C and 8D show a similar slot-like structure. In the simulation, this structure formed where lateral growth over an earlier crack-seal structure was bisected by subsequent microfractures that were then filled by crack-seal growth. The distinctive “lateral” layers along the lengths of the natural bridge shown in Figure 8C tend to begin just to the right of crack-seal structures at the top of the bridge and continue in a rightward direction until they are

Figure 8. Comparison of morphologies and textures for a natural quartz bridge with simulation results where the c-axis is oriented at 80° from the fracture wall, and quartz growth rate is sufficient to span microfracture gaps. The color conventions from Figure 7 apply to the simulation results. (A) Scanning cathodoluminescence image of a quartz bridge from sample SFE3-9246 from the Travis Peak Formation in the East Texas Basin. The lower portion of the bridge shows distinct inflection points indicated by the arrows that are associated with zoned quartz that overlaps with and postdates crack-seal textures. (B) Zoomed-in view of simulation results for the area indicated in part E. The arrows show pyramidal crystal faces that are migrating along the length of the simulated bridge and appear to be analogous to morphology indicated by arrows in A. (C) High-magnification cathodoluminescence image of the natural quartz bridge where we have color coded the texture to indicate interpreted crack-seal (red shades) and “laterals” (green shades). The “V” label indicates the interpreted spanning position for cement that filled a microfracture gap. Lateral zones appear to originate in many cases from the top of crack-seal structures and to extend rightward along the bridge. The yellow dashed area shows one such zone. (D) Zoomed-in view of simulation results for the area indicated in E. The tops of crack-seal structures show a similar asymmetrical form as in C, as exemplified by area shown by the “V” label. The yellow dashed area extends rightward from the top of a crack-seal texture and shows a similar form and geometry to the dashed area outlined in C. (E) Zoomed-out view of the simulated region with the dashed lines showing the areas displayed in B and D.
interrupted by subsequent crack-seal events or intersect the outer boundary of the crystal. One such layer is shown with a yellow dashed outline in the upper-right portion of Figure 8C. In the growth simulation, regions with extensive prismatic growth (cyan color) form in similar positions and have comparable geometries as shown by the area outlined with a yellow dashed line in the upper-right portion of Figure 8D.

Given that the outer morphologies and internal textures shown by the models reproduce the main textural attributes of natural quartz bridges, it is worthwhile to more rigorously evaluate the controls of c-axis orientation and opening rates. Figure 9 shows the result of a suite of simulations where fracturing takes place repeatedly during the first 2000 of 2500 step runs and where, as above, each step corresponds to the ability of a quartz overgrowth to grow one cell along the c axis on noneuhedral (0001) surfaces. The fracture is introduced so that it bisects a 1200-cell-diameter circular grain longitudinally and microfractures have 50-μm cell kinematic apertures that are introduced at a constant rate at random locations within the fracture zone. The model, however, will not break overgrowth crystals that do not span the fracture gap prior to the opening of a new microfracture. Small nucleation discontinuities are randomly introduced over 35% of the detrital grain surfaces to simulate the effect of poorly developed grain coatings, transport damage zones, and other features that inhibit overgrowth development. By contrast, crystal surfaces that result from microfracturing have no nucleation discontinuities. All simulations in this group assume that the c axis is within the 2-D plane of the simulated region. (This is not the case for simulations described in subsequent sections.)

The quartz cement distribution and fracture geometries are shown for the final simulation step for several opening rates and crystallographic orientations in Figure 9. The cement abundance in the fracture zone increases with increasing opening rates until the fracture-spanning limit is reached, at which point the cement amount drops precipitously, as illustrated for a bisected crystal with its c axis oriented perpendicular to the fracture trace in Figure 10A. At opening rates below the spanning limit, the rate of quartz growth is reduced because the fracture gap is spanned in advance of the next opening event. Once the fracture gap is filled, noneuhedral growth surfaces are generally lost as described previously (for example, at step 80 in Fig. 7).

For a given opening rate, the amount of cement that grows in the fracture zone increases as the c-axis angle diverges from being normal to the fracture wall until the spanning limit is reached. For the 0.8 rate ratio, for instance, the simulation with a c axis at 45° to the fracture wall has –30% more quartz cement compared to the 90° case (Fig. 10B). The driving force for this increase in quartz abundance is the greater growth potential along the c axis and on pyramidal faces for crystals that deviate from being perpendicular to the fracture trace, as illustrated schematically by the double-line segments in Figure 4B.

Once the fracture gap has been spanned by crystal growth, the remaining surface area is largely restricted to slow-growing euhedral surfaces along the sides (lateral). In massively sealed fractures, overgrowths that are adjacent to other quartz overgrowths that also are growing into the fracture may have little or no remaining growth area after the fracture gap is spanned. Growth may continue laterally along the fracture, however, where overgrowths invade pores associated with positions along the fracture that are bounded by materials other than quartz (e.g., where the fracture borders nonquartz grains as shown in Fig. 1B).

**GRAIN-PACK FRACTURE AND CEMENTATION MODELS**

The single-grain simulations reproduce the morphology and internal textures of individual quartz overgrowths in fractures but do not consider the pore and cement geometry for the broader fracture zone or host rock. In this section, we expand the model frame of reference to incorporate a larger portion of the fracture zone as well as the unfractured sandstone. In these simulations, we randomly assign crystallographic orientations to the quartz grains. The c axis may project out of the plane of the section, resulting in slower apparent growth rates within the modeled plane. Within the modeled plane, the c-axis projections are restricted to the following orientations with respect to the fracture trace: 0°, 45°, 90°, and 135°. As with the previous set, this group of simulations assumes constant rates of fracture opening and quartz cementation.

Results for multiple time steps (T1–T4) are shown for three fracturing rates in Figure 11. Quartz cement in the figure is color coded by the rate of growth such that blue colors represent slow growth on euhedral faces and greens and reds are fast growth on noneuhedral surfaces. Quartz grains are shown in light gray, nonquartz grains are shown in dark gray, and pores are shown in black. The leftmost column of images in the figure shows results for the case where growth on prismatic faces, the slowest-growing surface type, exceeds the fracture opening rate. In these simulations, the fracture is massively sealed by quartz cement at all positions where the fracture has bisected...
Figure 10. (A) Total amount of quartz cement in the fracture zone as a function of opening rate for grains with the c-axis perpendicular to the fracture wall. The cement amount shown on the y-axis is normalized to the amount for the simulation with a c-axis orientation of 90° to the fracture wall and an opening rate of 1.8 times the noneuhedral (0001) surface growth rate. The x-axis shows the ratio of the fracture opening rate to the growth rate on noneuhedral (0001) surfaces. The circles indicate simulation results shown in Figure 9. Filled circles show where growth spanned the fracture aperture, whereas the open circle indicates where it did not. At rate ratios less than two (solid line), the overgrowth spans the fracture between microfracturing events, and the amount of quartz growth is limited by the amount of new porosity created by fracture opening. At ratios above two (dashed line), the quartz overgrowth is unable to span the fracture, and growth rates decline precipitously after the crystal reaches euhedral termination. The quartz cement abundance in the fracture is constant for rate ratios above the spanning threshold. (B) Total quartz cement in the fracture zone for single-grain simulations as a function of opening rate and the orientation of the c-axis with respect to the fracture wall. The cement amount is normalized to the amount for the simulation with a c-axis orientation 90° to the fracture wall and an opening rate of 1.8 times the noneuhedral (0001) surface growth rate. Filled symbols indicate where the bisected overgrowths grew rapidly enough to span the microfractures, whereas open symbols indicate where they did not.

Figure 11. Prism2D simulations of grain packs with three distinct ratios of fracture opening to crystal growth. The red and green colors indicate fast growth along noneuhedral (0001) surfaces, whereas the cyan color indicates growth on euhedral faces. Black is porosity, light gray indicates quartz grains, and dark gray is nonquartz grains. The leftmost column shows simulation results for the case where the fracture opening rate is exceeded by the rates of growth on euhedral faces. The middle column shows results for the case where some but not all overgrowths are able to span the fracture between microfracturing events. The right column shows results where the fracture opening rate outstrips the fastest growth rate. The rows in the figure correspond to the simulated fracture geometry and cement abundances at various time steps in the simulation (T1 through T4).
quartz grains. These results correctly reproduce the restriction of pores to portions of the fracture trace bounded by nonquartz grains and the occurrence of crack-seal texture on all quartz cement within the fracture zone (Figs. 12A and 12B).

The rightmost column shows results for the other end-member case: where the fracture opening rate exceeds twice the fastest growth rate (noneuhedral c-axis surfaces). In the initial phase of fracture opening (T1), the noneuhedral growth on grains that have their c axes approximately perpendicular to the fracture trace nearly keeps pace with the fracture as it widens. Once the overgrowths reach euhedral termination (T2), however, the rate of quartz growth drops precipitously and is far outstripped by the fracture opening rate. The resulting thin rind is comparable to natural examples (Figs. 12E and 12F) that lack late-stage crack-seal structure.

The center simulation result shows the case where the fracture opening rate is intermediate between the other two end members. In this simulation, one grain has its c axis at a high angle to the fracture wall, enabling it to span the fracture between microfracturing events, eventually developing a bridge morphology (Figs. 12C and 12D). The crystallographic orientations of the remaining grains, however, are less optimally oriented and develop euhedral terminations consistent with thin rind morphologies.

These results compare favorably with transitions in the quartz cement morphologies and abundances along the natural fracture shown in Figure 13. Near the tip of the fracture (top of image), most of the fracture aperture is filled by quartz cement, as expected when the local opening rate is slow compared to the quartz growth rate. Toward the center of the fracture (bottom of image), on the other hand, the fracture is not spanned by quartz cement and has the least absolute amount of cement. Quartz bridges are found at intermediate positions, becoming increasingly abundant toward the fracture tip, as predicted by the simulation results.

The simulation results depicted in Figure 14 underscore that it is the ratio of opening rate to growth rate, and not the cumulative kinematic aperture, that dictates the amount of cement that grows within the fracture zone. These simulations have the same cumulative kinematic aperture, number of time steps, and onset of fracture opening, but in the faster opening cases, the fractures stop moving earlier, and quartz...
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has a longer time to grow into the static fracture void. The amount of cement for the two simulations that have fracture-opening to non-euhedral (0001) growth-rate ratios greater than two is identical because the overgrowths never span the microfracture gaps between opening events. For slower opening rates, the amount of quartz cement in the fracture zone is inversely proportional to the opening rate. Increased cement volumes form at slower opening rates because bisected grains with a broader range of crystallographic orientations are able to span the microfracture gaps between opening events.

COMPARISON OF A SIMULATED BRIDGE WITH A NATURAL EXAMPLE

As a final assessment of the model performance in sedimentary basins, we simulate the evolution of a thoroughly characterized quartz bridge from the Cretaceous Travis Peak Formation in the East Texas Basin. This quartz bridge ("9840p5") was the subject of a detailed fluid-inclusion study that was done in concert with high-resolution scanning cathodoluminescence imaging (Becker et al., 2010). These data together with the thermal reconstruction of the well from which the sample was obtained (Dutton, 1987) make it possible to demonstrate that the bridge was subject to repeated crack-seal events over the past 48 m.y. The average opening rate over this time was ~23 μm/m.y. at temperatures ranging from ~130 °C to 154 °C (Becker et al., 2010). The interval of interest is characterized by abundant stylolites that may have served as local sources for quartz cement.

We conducted an additional fine-scale analysis of the bridge, wherein we identified the kinematic apertures and positions of the 375 constituent crack-seal structures that we recognized in high-resolution color cathodoluminescence images. The interpreted kinematic apertures of the associated microfractures range from ~1 to 18 μm and have an average value of ~3 μm. We developed a sequence for these crack-seal events based on crosscutting relationships and the thickness of lateral deposits (Laubach et al., 2004a, 2004b; Laubach and Ward, 2006). While there is significant uncertainty in the sequence at the individual crack level, the overall order is relatively straightforward to discern and shows a systematic tendency for microfractures to be introduced on the right side of the bridge (Becker et al., 2010). The only exceptions to this ordering are for several of the most recent microfractures, which formed on the left side of the bridge.

Our first step for simulating the bridge development was to determine reasonable values to use for the quartz precipitation kinetics. As dis-
cussed previously, we did this by adjusting the $E_a$ value (Eq. 1) for nonenhedral (0001) growth so that the simulated present-day quartz cement abundance in the host rock (very fine-grained, moderately sorted, quartz arenite sandstone) is in accord with the measured value near the 9840p5 bridge. Using the scenario 1 temperature history shown in Figure 15A, we found that an $E_a$ value of 50 kJ/mol matched the measured quartz cement abundance in the modeled region to within 2 vol% (we used a constant $A_0$ value of $9 \times 10^{-12}$ mol/cm$^2$ s and the rate ratios for growth on other surfaces shown in Fig. 2). The model reference frame for the fracture simulation has a grid resolution of 0.4 $\mu$m per cell and is a portion of the area used to constrain the kinetic parameters in the unfractured portion of the sample. The fracture in the baseline model is oriented vertically and placed in the center of the modeled area. We randomly assigned $c$-axis orientations for the monocristalline quartz grains, with the exception of two of the grains that are bisected by the fracture trace. We changed the $c$-axis orientation for a grain near the center of the fracture trace so that it would be oriented optimally to span the microfracture gaps, and we changed the $c$-axis of one other grain near the edge of the modeled area to an orientation less favorable for spanning.

Armed with the optimized kinetic parameters, we started the simulation at the time of deposition (128 Ma) while accounting for the impact of the temperature history on quartz growth rates. With the exception of a few late microfractures that formed on the left side of the bridge, new microfractures were introduced at a random position within 75 $\mu$m of the right-hand boundary of the bridge as it developed. In our baseline simulation, we assumed a constant rate of fracture opening (“linear” in Fig. 15B), and the temperature history was derived from the burial history reconstruction of Dutton (1987) (“scenario 1” in Fig. 15A).

This baseline simulation produces a quartz bridge for the center grain that is flanked by fracture walls with a thin rind texture (Fig. 16B). Unlike the actual quartz bridge, the simulation predicts thinner lateral deposits (indicated by the blue color) sandwiching the red crack-seal region on the right side of the bridge. Unlike the actual quartz bridge (Fig. 16A), however, the baseline simulation predicts neither the thick lateral deposits at the center of the bridge nor the slight deviation from the horizontal for portions of the bridge’s upper and lower boundaries. As discussed in greater detail below, these differences in bridge morphology likely result from the bridge’s $c$-axis orientation diverging somewhat from being perpendicular to the fracture trace.

An additional disparity between the simulation results and observations has to do with the predicted pattern of quartz precipitation temperatures along the axis of the bridge compared to fluid-inclusion entrapment temperatures as illustrated in Figure 17A. The simulation approximates the range in fluid-inclusion temperatures as well as the values observed on each end of the bridge. It departs from the observations, however, in the location of the peak temperature. In the simulation, the peak temperature occurs near the left end of the bridge, whereas the fluid-inclusion entrapment temperatures peak near the bridge center. Because the simulated fracture opening rate is constant, the modeled pattern for the quartz precipitation temperatures reflects the scenario 1 temperature history, which peaks after 12.5% of the time of active fracture opening has elapsed (Fig. 15A).

Two potential explanations for the peak fluid-inclusion temperatures occurring near the center of the bridge rather than near the left side are: (1) Instead of opening at a constant rate, the fracture opened more rapidly during the initial phases of growth and then slowed down, and (2) the peak temperature of the modeled sample occurred later than is assumed in the scenario 1 burial history of Dutton (1987).

While these two possibilities are not mutually exclusive, we evaluated the first of them in isolation by running a simulation where the fracture opened to approximately half of its present-day kinematic aperture by 42 Ma (“fast to 42 Ma” in Fig. 15B), the time of peak temperature in the scenario 1 burial history. In this simulation (Fig. 16C), a bridge did not form, however, because the initial rapid period of opening is more than twice as fast as quartz growth on non-enhedral $c$-axis surfaces. Although it is possible to increase the kinetics of quartz growth to the point where the fracture may be bridged with this opening-rate scenario, doing so results in unrealistically large volumes of quartz cement in the unfractured portion of the sandstone.

The other end-member alternative involves using a constant rate of fracture opening but delaying the time the peak temperature was reached from 42 to 26 Ma (“scenario 2” in Fig. 15A). This scenario comes closer to matching the fluid-inclusion entrapment temperature pattern (Fig. 17B) while producing a bridge morphology (Fig. 16D) that is similar to the baseline model (Fig. 16B). Regrettably, there are no available data with which to evaluate which of these thermal histories is more geologically reasonable. The thermal reconstruction of Dutton (1987) bases maximum burial depth on the estimated magnitude of erosion of early Eocene (Wilcox) sedimentary rocks across the Sabine Arch (Laubach and Jackson, 1990; Jackson and Laubach, 1991). For lack of any better constraint, Dutton (1987) assumed that the rate of erosion was linear from the time that the eroded interval was finished being deposited at 42 Ma and has been constantly linear since then. This assumption is not supported by the available data (see Fig. 15A).
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Figure 16. Comparison of the image analysis interpretation of (A) the “9840p5” bridge studied by Becker et al. (2010) and (B–E) the present-day results for various Prism2D simulations. (B) Simulation that uses the scenario 1 burial history (Fig. 15A), the “linear” fracture opening history (Fig. 15B), and a c-axis orientation for the bridging crystal that is perpendicular to the fracture. (C) Simulation that uses the scenario 1 burial history (Fig. 15A), the “Fast to 42 Ma” fracture opening history (Fig. 15B), and a c-axis orientation for the bridging crystal that is perpendicular to the fracture. (D) Simulation that uses the scenario 2 burial history (Fig. 15A), the “linear” fracture opening history (Fig. 15B), and a c-axis orientation for the bridging crystal that is perpendicular to the fracture. (E) Simulation that uses the scenario 2 burial history (Fig. 15A), the “Fast to 35 Ma” fracture opening history (Fig. 15B), and assumes a c-axis orientation for the bridging crystal that is at a 95° angle to the fracture trace. The “1” and “2” labels indicate where the ankerite deposits from the actual fracture shown in A were emplaced in the simulation. The “3” label indicates where the simulated crack-seal region “necked down” and shows a similar geometry to the “3” labeled area in the actual bridge (A). The “4” label indicates where the simulation predicts a thicker lateral cement zone that is comparable to the “4” label position in the actual bridge (A).

Additionally, in this scenario, the fracture opening (“fast to 35 Ma” in Fig. 15B). A more rapid compared to the latter half of the initial stages of fracture opening are somewhat than 42 Ma (“scenario 2” in Fig. 15A) and the peak temperature is reached at 26 Ma rather than 42 Ma (“scenario 2” in Fig. 15A) and the initial stages of fracture opening are somewhat more rapid compared to the latter half of the fracture opening (“fast to 35 Ma” in Fig. 15B). Additionally, in this scenario, the c-axis for the bridging grain is oriented at 95° to the fracture trace rather than 90°, and we introduce ankerite cements near the quartz bridge in accordance with its presence in the actual fracture (Figs. 16A and 16E, “1” and “2” labels). Increasing the initial fracture opening rate and delaying the time of peak temperature produce the best match to the fluid-inclusion data among all of our simulations (Fig. 17C). Additionally, this scenario yields thickness variations in the crack-seal region along the left-hand portion of the bridge that are more consistent with the observed pattern (Figs. 16A and 16E, “3” label). The simulated variability in the crack-seal thickness occurs early in the bridging history when the quartz-sealing rate barely keeps pace with the fracture opening rate, leading to a necking down of the bridge during this stage of its development (Fig. 18, 40 Ma). The bridging grain’s 5° offset in the c-axis orientation from being perpendicular to the fracture wall leads to thicker lateral deposits along the middle part of the bridge that compare more favorably to the observed thickness (Figs. 16A and 16E, “4” label).

We introduced ankerite crystals with morphologies derived from the region of the actual bridge along the left-hand portion of the bridge at 35 Ma when the simulated thicknesses of the lateral deposits were comparable to those observed in the actual bridge (Figs. 16A and 16E, “1” label). An additional ankerite rhomb was introduced at 28 Ma along the top middle portion of the bridge (Fig. 16E, “2” label) when a comparable lateral thickness formed there. The simulation correctly reproduces the thicker lateral deposit on the right side of this rhomb compared to the left and the west-northwest/east-southeast orientations of the outer boundaries of these lateral surfaces. The simulated evolution in the bridge and host sandstone is depicted in Figure 18 for selected geologic snapshots, and an animation of the simulation from 50 Ma to present is available from the GSA Data Repository.1

An important aspect of the simulations is that although the same quartz precipitation kinetics are used both for the host rock and the fracture zone, the net growth rates, temperatures, and morphologies associated with the quartz cements in these two portions of the rock show distinct differences. In the simulations, the only dissimilarity between the fracture zone and the host rock is the breakage of quartz crystals and the creation of new pore space that occur in

1GSA Data Repository item 2014339, animations of simulations of quartz growth into fractures, is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.
response to microfracture events. The impact of this difference on the average surface area normalized growth rate is shown in Figure 19. In the host rock, the average surface area normalized growth rate declines after the onset of fracturing despite the concurrent increase in temperature, which leads to faster growth rates for a given type of substrate surface. This decrease occurs because the quartz growth surfaces become progressively dominated by slower-growing surface types as the overgrowths develop (Lander et al., 2008). Within the fracture zone, however, the average surface area normalized growth rates are as much as an order of magnitude higher than growth rates in the host rock (Fig. 19). These fast rates result from the continued creation of fast-growing, noneuhedral (0001) surfaces that develop on the bridge crystal as it is broken by microfracturing events. The upper boundary of the rate envelope in the fracture zone reflects the rapid crack-seal growth that occurs before the cement manages to span a microfracture. Growth also occurs simultaneously during this time along the bridge laterals, albeit at slower rates. The lower boundary of the envelope represents where the bridge has been spanned and growth occurs exclusively along the bridge laterals. The variations in the upper and lower bounds through time reflect the temperature history and the fracture opening rates such that higher temperatures and faster opening rates lead to faster average surface area normalized rates, provided that quartz is able to span the microfractures between microfracture events.

**RATES OF FRACTURE GROWTH AND SEALING**

Fractures are difficult to use as structural and tectonic markers because the shape and opening displacement of opening-mode fractures provide no explicit evidence for the timing or rates of fracture growth, and multiple alternative loading paths have the potential to produce an equivalent fracture pattern (Engelder, 1985). Fracture relative timing, however, may be obtained by analyzing cement textures. Our quartz cement model explains the complex textures within localized quartz cement deposits in sandstone fractures and allows these textures to be viewed as detailed records of the timing and rates of fracture growth and sealing. The model predicts absolute fracture opening rates and timing information when temperature history and kinetic parameters that are optimized to match quartz cement abundances in the host rock are available. These results may be tested using fluid-inclusion or isotopic data from fracture cements. Model results augment such sparse

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**Figure 17.** Comparison of fluid-inclusion entrapment temperatures reported by Becker et al. (2010) with simulation results from the long axis of the simulated bridge. The black triangles represent data from fluid-inclusion assemblages, whereas the white circles indicate data from single fluid inclusions. The gray “x” symbols show results from the simulations: (A) Results for the bridge shown in Figure 16B that incorporated the “scenario 1” burial history (Fig. 15A) and the “linear” fracture opening history (Fig. 15B), (B) Results for the bridge shown in Figure 16D that incorporated the “scenario 2” burial history (Fig. 15A) and the “linear” fracture opening history (Fig. 15B). (C) Results for the bridge shown in Figure 16E that incorporated the “scenario 2” burial history (Fig. 15A) and the “Faster to 35 Ma” fracture opening history (Fig. 15B).
Quartz growth and fracture rates

Figure 18. Simulation results at selected geologic times for the bridge shown in Figure 16E that incorporated the “scenario 2” burial history (Fig. 15A) and the “Faster to 35 Ma” fracture opening history (Fig. 15B). An animation of the simulation is available from the GSA Data Repository (see text footnote 1).

Figure 19. Comparison of the average surface area normalized rate of quartz growth with geologic time for the unfractured portion of the host rock (gray line) and the fracture zone (black line) for the simulation depicted in Figure 18.

Our model explains how fracture porosity in sandstones can persist in the presence of reactive fluids for millions of years, while host rock porosity is destroyed by cementation. Although the example application discussed previously considers extremely slow opening rates in a passive-margin setting, the model is applicable to other fracture types in sedimentary basins, as well as to some aspects of metamorphic vein formation. For example, the model reproduces both “stretching” and “elongate blocky” textures in metamorphic veins.

“Stretching veins” or “stretched crystals” (Bons, 2000; Bons et al., 2012) in metamorphic rocks form by a crack-seal process. Stretched crystals have large aspect ratios that are oriented at a high angle to fracture walls and tend not to show significant changes in crystal width across the vein. These crystals also lack a strong pattern in c-axis orientations with distance from the fracture walls. “Elongate blocky” vein textures, on the other hand, are characterized by crystal coarsening from the walls to the centers of fractures (Fisher and Brantley, 1992; Bons, 2000). Additionally, unlike smaller crystals near the fracture margins, the larger crystals in the centers of the elongate blocky veins have c axes that are preferentially oriented perpendicular to the fracture trace (Cox and Etheridge, 1983; Bons, 2001; Nüchter and Stöckhert, 2007; Okamoto and Sekine, 2011).

We simulated the development of each of these vein textures using the same approach as described for quartz cementation in sandstones. The stretching vein simulations are comparable to those for the massive sealing of microfractures in sandstones (left column images in Fig. 11) in the sense that they represent the case where growth on slow-growing euhedral faces is sufficient to seal microfractures. The only significant difference is that the cumulative kinematic aperture for the vein simulations is many times the size of the crystal domains that serve as the initial growth substrates for the overgrowth crystals, whereas sealed microfractures in sandstones tend to have apertures that are comparable to grain diameters.

We simulated two stretching vein scenarios: In one, we considered a pure opening-mode displacement (Fig. 20A), whereas in the other, we prescribed a constant 15° right-lateral displacement (Fig. 20B). Microfractures were introduced at random positions within the frac-
ture zone between microfracturing events, and the host rock was pure quartz with no porosity at the onset of fracturing. For simplicity, the simulations assumed constant temperature and supersaturation.

The simulation results compare favorably with “stretched crystal” textures (Bons et al., 2012), as shown in Figure 20A and Figure 20B (see the GSA Data Repository for corresponding animations [see footnote 1]). The crystals have elongate, parallel forms that are at high angles to the fracture walls and display a narrow range in thicknesses perpendicular to the axis of elongation. Additionally, the simulations reproduce serrated crystal boundaries or “radiator structures” that are characteristic of this syn-taxial vein type in nature (Bons et al., 2012). In the simulations, these structures arise because some crystals are able to grow a small distance into a neighbor’s crack prior to complete sealing. This invasion is most pronounced where the invader’s $c$ axis parallels the fracture wall and points toward a neighboring crystal’s $a$-axis surface. We illustrate this case in Figure 21 using a simulation of a single crack-seal cycle in a zoomed-in view of the boundary between two crystal domains. The top crystal has its $c$ axis
Figure 21. Simulation of the development of the “radiator structure” at crystal boundaries associated with stretched crystal-type quartz veins. The simulation is a zoomed-in view of the interface between a pair of neighboring crystals during a single crack-seal cycle, where the top crystal invades the crack of the bottom crystal due to a more favorable crystallographic orientation. The colors represent the quartz overgrowths from the current crack-seal cycle, and the darker shades represent preexisting crystals. Black is porosity, and the step value represents the simulation step, where the maximum quartz growth per step is one grid cell along the c axis on noneuhedral growth substrates. An animation of this simulation is available from the GSA Data Repository (see text footnote 1).

A prediction of the model is that radiator structures should be poorly developed where neighboring crystals both have c-axis orientations perpendicular to the fracture wall. With this geometry, the lateral growth rates along the fracture trace for each crystal are equivalent for both crystals, resulting in limited potential for crack invasion. Similarly, we expect that neighboring crystals that have c axes pointing at each other and comparable a-axis orientations also will show limited extents of crack invasion. The simulations for elongated blocky veins are analogous to the open “rind” simulations in sandstones (the column of images on the right side of Fig. 11) in the sense that the rate of opening of the fracture exceeds the spanning capacity for all quartz overgrowths. The difference in the simulations has only to do with the extent of passive quartz growth into the fracture void. As with the stretched vein simulations, we consider constant growth rates for a pure opening-mode scenario as well as a scenario with a 15° right-lateral offset (Figs. 20C and 20D; see the GSA Data Repository for corresponding animations [see footnote 1]). As expected, results show that crystals with c-axis orientations that are more nearly perpendicular to the fracture walls “sur vive” by overgrowing crystals with less favorable orientations. For the pure opening-mode case, the survivor crystals rejoin in the fracture center and become continuous across the fracture. These crystals develop large aspect ratios even though crack seal is not invoked in the simulations. In the right-lateral simulation, however, biseected crystals are unable to come into contact across the fracture, resulting in smaller maximum sizes and aspect ratios for the crystals. These results suggest that the only fundamental difference between fracture cementation in diagenetic and metamorphic conditions has to do with the absolute rates of quartz growth. In the diagenetic realm, cement growth rates are extremely slow, making it possible to preserve fracture porosity for millions of years for fractures that open sufficiently quickly. In the elevated temperatures associated with metamorphic environments, however, quartz growth rates are far faster, so that porosity is short-lived—even for cases where the fracture opening rate exceeds the cement spanning rate.

While the model predicts textures and morphologies that are comparable to metamorphic quartz veins, the growth kinetics approach described here may not be appropriate in metamorphic conditions because (1) the rate-limiting process for quartz growth may be transport or supply (e.g., Fisher and Brantley, 1992), rather than precipitation rate as in sedimentary basins, and (2) there may be much higher degrees of quartz supersaturation in some metamorphic systems compared to most diagenetic ones (Bons et al., 2012). The former of these factors will tend to decrease the rate compared to the current kinetic approach, whereas the latter will have the opposite effect.

CONCLUSIONS

The model for quartz cementation that we describe reproduces important characteristics of quartz cement in sandstone fracture systems, including crack-seal and lateral textures in bridges and massive sealing, bridge, and rind morphologies. Model results show that extreme variations in quartz overgrowth cement volumes associated with bridge structures develop when the rate of fracture opening approaches the growth rate of the fastest-growing surface type. In such cases, overgrowth crystals are more...
likely to span fractures between microfracturing events when the c axes of bisected grains are at a high angle to the fracture wall. The fracturing of spanning crystals leads to the perpetuation of fast growth because the fracturing process creates new, noneuhedral growth surfaces, where overgrowths grow much more rapidly compared to euhedral crystal faces. Conversely, crystals that are unable to span microfracture overgrowths develop euhedral terminations and grow at far slower rates.

It is worth mentioning that bridge-like structures with crack-seal textures may form from overgrowth crystals that do not have c-axis orientations at a high angle to the fracture trace. These structures, however, are associated with situations where there is a paucity of substrate surface area available for quartz overgrowths. Examples include sandstones with few monocristalline quartz grains, as well as situations where, in addition to quartz, other phases such as carbonates or sulfates grow concurrently with fracture opening and act to restrict the pore space available for quartz cement to invade. The model is consistent with such scenarios provided that the rate of fracture opening is slower than, or comparable to, twice the rate of quartz growth on euhedral faces (i.e., conditions that normally lead to massive sealing).

The model matches quartz cement abundances both in the host rock and the fracture zone using the same fundamental growth assumptions and kinetic parameters. In the Travis Peak Formation example, it correctly predicts the common observation in many tightly cemented sandstones that the bulk of the quartz cement in the host rock and fracture zone, it is a useful alternative and to fluid-inclusion, isotopic, trace-element, and basin modeling studies for constraining fracture opening rates and thermal conditions. The model also can provide forward geometrical models with improved constraints on geologic evolution of host rock and fracture zone properties such as porosity, cement volumes, and microstructure. This approach also may be used to simulate fracture arrays with geometries and kinematics that differ from that explicitly modeled here, as fault rocks.

While the focus of this study has been on quartz growth in sandstone host rock and fracture zones, it is a useful alternative and to fluid-inclusion, isotopic, trace-element, and basin modeling studies for constraining fracture opening rates and thermal conditions. The model also can provide forward geometrical models with improved constraints on geologic evolution of host rock and fracture zone physical properties such as porosity, cement volumes, and microstructure. This approach also may be used to simulate fracture arrays with geometries and kinematics that differ from that explicitly modeled here, as fault rocks.

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