Practical approaches to identifying sealed and open fractures

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ABSTRACT

For one essential ingredient of permeable fracture networks (degree of fracture pore-space preservation in large fractures), I show how the characterization challenge presented by sparse fracture sampling can be overcome by measuring a surrogate, the abundance of rock-mass cement that precipitated after fractures ceased opening. Sampling limitations are overcome because the surrogate is readily measured in small rock samples, including sidewall cores and cuttings, permitting site-specific diagnosis of the capacity of fractures to transmit fluid over a wider range of sample depths than conventional methods allow. A diverse core database shows that this surrogate correctly predicts where large fractures are sealed. Information on timing of fracture opening relative to cement sequence can be obtained in two ways. First, evidence of fracture-movement history and cement sequences in sparse large fractures can be extrapolated to areas having only cement data. Alternately, evidence of fracture timing can be acquired from sealed, micrometer-scale fractures. Distribution of porosity-reducing cement is commonly heterogeneous (from bed to bed and location to location) in siliciclastic and carbonate rocks. However, because patterns of sealed or open fractures cannot be delineated using fracture observations alone, surrogates have practical value for production fairway mapping and other applications in which identifying open fractures is essential. This study highlights the vital interplay among structural and diagenetic processes for fracture-porosity preservation or destruction.

SEEKING OPEN FRACTURES

Knowledge of where natural fractures are open and capable of transmitting fluid would aid exploration, development, and management of many petroleum reservoirs. Many reservoirs having

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low porosity are known to be productive largely because natural fractures enhance hydrocarbon delivery to wellbores. However, exploration and development decisions must often be made in the face of great uncertainty about the contribution of fractures to production. This uncertainty stems, in part, from paucity of data on fracture attributes. The role of fractures is commonly deciphered from well tests and from discrepancies between observed and expected production instead of from site-specific observations of fracture porosity, size, and connectivity. Repercussions of severely limited fracture data include foregone exploration and development opportunities and risk of surprises in production response. Undiagnosed fracture-system heterogeneity can cause unexpected exploration and development outcomes even where horizontal drilling is employed.

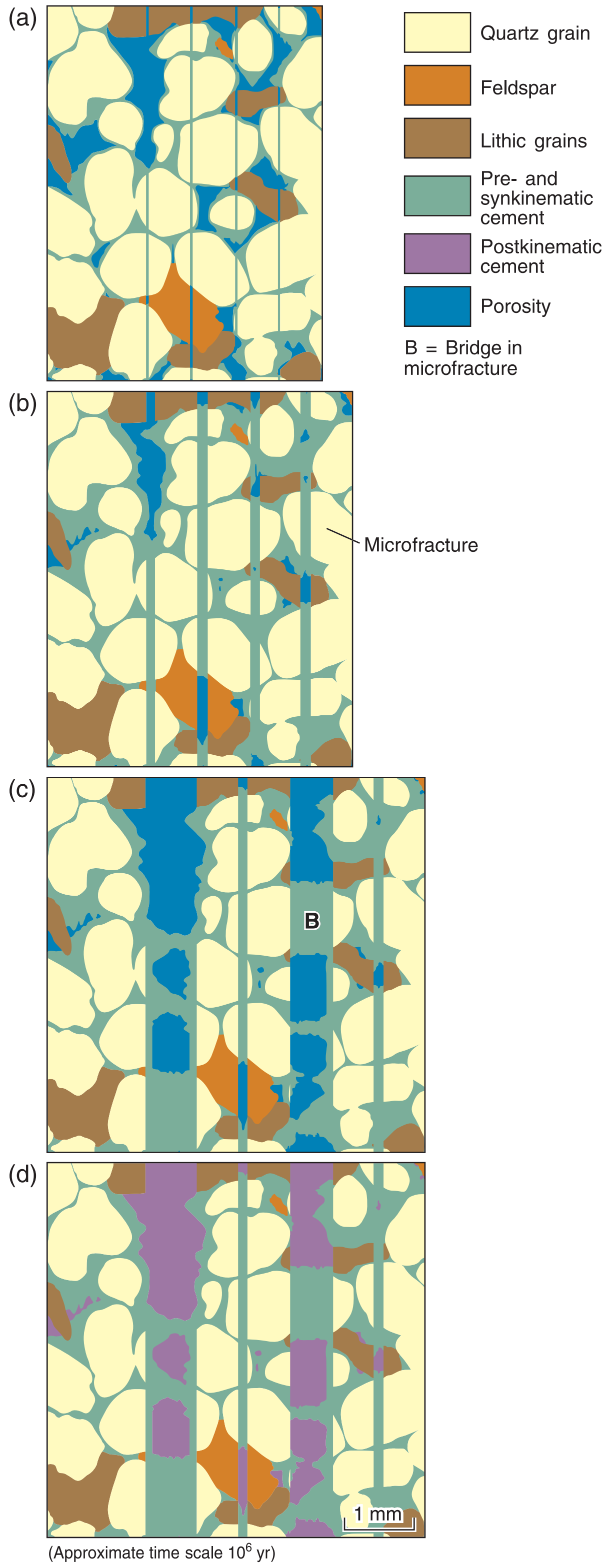
Thanks to the advent of logging tools that image fractures in the wellbore wall and coring procedures that maintain core integrity in fractured rock, log- and core-based methods usually provide some information on fracture attributes. However, data are commonly incomplete because meaningful samples of fracture networks are inherently difficult to obtain. This difficulty occurs because the probability of intercepting vertical fractures with vertical wells is exceedingly small, approximately the ratio of wellbore diameter to average fracture spacing (Terzaghi, 1965; Narr, 1991; Lorenz and Hill, 1992). For the many areas where large fractures are moderately to widely separate or are arrayed in swarms, even the most complete logging and coring program will frequently miss large fractures. Thus, conventional analysis of vertical wellbores provides only nonsystematic and incomplete samples of fracture arrays and observations that are frequently sparse or ambiguous. Consequently, a central challenge of subsurface fracture characterization is obtaining data on essential fracture attributes where direct observation is unlikely.

What properties make fractures effective fluid conduits, and how can these be identified? Fracture permeability is proportional to the cube of aperture. Effective fracture permeability also depends on length and connectivity (lateral persistence) of fracture porosity. Apertures and lengths of fractures remaining open and effective for fluid flow reflect fracture growth, modern state of stress, and diagenesis. Of these, fracture diagenesis (mineral precipitation and dissolution in fractures and host rocks) has received little systematic study. Present-day effective stress is widely viewed as a prime control on variation in fracture aperture (and fracture closure) (Crampin, 1994; Barton et al., 1995; Heffer et al., 1997). However, in many petroleum provinces, orientation and location of open fractures are indifferent to stress regime (Dyke, 1995; Stowell et al., 2001).

Mineral deposits can preserve or destroy fracture-system permeability. Mineral deposits in fractures are widespread, ranging from isolated crystals lining open fractures to massive cements that completely fill fractures (Nelson, 1985; Laubach, 1988; Dyke, 1995). It would be surprising if fractures that formed in the subsurface, in the presence of high temperatures and reactive fluids, were not subject to the same dissolution and precipitation phenomena that affect other pores in these rocks, and, as described in following sections, fracture and host-rock diagenesis are commonly closely linked. Moreover, great heterogeneity is present in the distribution of fracture-filling minerals in subsurface rocks, presenting an opportunity for targeting fractures that contribute to fluid flow and avoiding those that do not.

Surrogates are substitutes or proxies for fracture observation. For large fractures microstructure surrogates have previously been used to assess fracture strike (Laubach, 1997) and fracture intensity (Marrett et al., 1999; Gale, 2002). However, as shown herein, micrometer-scale fractures readily seal with cements that differ from those that close large fractures, and so alone, they are inadequate guides to porosity preservation in large fractures (Figure 1). The purpose of this paper is to show how information on the volume and timing of cement precipitated in the rock mass itself (not in fractures) can be used as a proxy for direct fracture observation to predict whether large fractures are open. Empirical evidence from siliciclastic rocks, dolomite, and a few limestones shows patterns that are sufficiently systematic to allow sealed or open fractures to be inferred from a combination of observed host-rock microstructures and cements. I summarize evidence of these patterns in regional opening-mode fracture sets and show how they allow the fracture-sampling problem to be circumvented.

Models that quantify feedback between fracture growth, diagenetic reactions, rock-property evolution, and pore-pressure changes (Olson et al., 2001; Lander et al., 2002; Milliken, 2002; Noh and Lake, 2002) are beyond the scope of this paper. Much remains to be learned before linked diagenetic and mechanical models can make reliable fracture-porosity predictions in advance of sampling in a given location. Fortunately, without sophisticated process-oriented models but with inexpensive site-specific petrographic observations, accurate and useful qualitative fracture predictions concerning the vicinity of the sample are now feasible.



DATA AND METHODS

Conclusions presented here are based on a large core database (see Appendix). Most samples are from siliciclastic and carbonate rocks (primarily dolomite) in oil and gas reservoirs at depths of 6000–14,000 ft (1828–4267 m), with some samples from outcrops and some from depths to 21,000 ft (6400 m). Fractures are typical opening-mode (extension) fractures (Nelson, 1985). They are mostly inclined at close to right angles to bedding, so that they are nearly vertical in flat-lying beds. Sets are marked by consistent, preferred orientations over wide areas (approximately several kilometers). Results are therefore most applicable to regional opening-mode fractures in siliciclastic rocks and dolomite that experienced moderate to deep and/or protracted burial. Because of space limitations, illustrations and discussion in this paper focus on sandstones.

Two essential aspects of cement patterns in fractures and rock mass are evident only through extensive imaging using scanning electron microscope (SEM) based cathodoluminescence (scanned CL). By illuminating subtle chemical differences in cement and rock composition, scanned CL demonstrates widespread, otherwise mostly invisible, micrometer-scale sealed fractures (Figure 2). Images also reveal crack-seal textures in large fractures (Figures 3, 4), formerly only documented in a few regional fracture systems (Laubach,

Figure 1. Two ways that opening-mode fractures seal. (a–c) Microfractures sealed concurrently with fracture opening (synkinematic cement), whereas porosity is preserved in large fracture. B is the synkinematic cement bridge. (d) Large fractures lined by synkinematic cement but sealed by postkinematic cement, which is in both fractures and host rock. Fracture timing information and cement data combine to make a surrogate for fracture observation. Cements can be divided into those that predate, accompany, and postdate fracture opening (Laubach, 1988). The terms pre-, syn-, and postkinematic focus attention on links between fracture-movement history (kinematics) and rock and fracture diagenesis, underlining the role that fracture timing plays in porosity preservation. Rocks may have several fracture-opening events, as well as complex and repetitive sequences of precipitation and dissolution. Terms therefore refer to a specific fracture-opening event, and a postkinematic phase for one fracture set is pre- or synkinematic for the next. The classification refers to cements in fractures and the rock mass. Diagram illustrates fracture patterns described in this paper and Laubach (1988), but this image is based on modeling results from Lander et al. (2002).

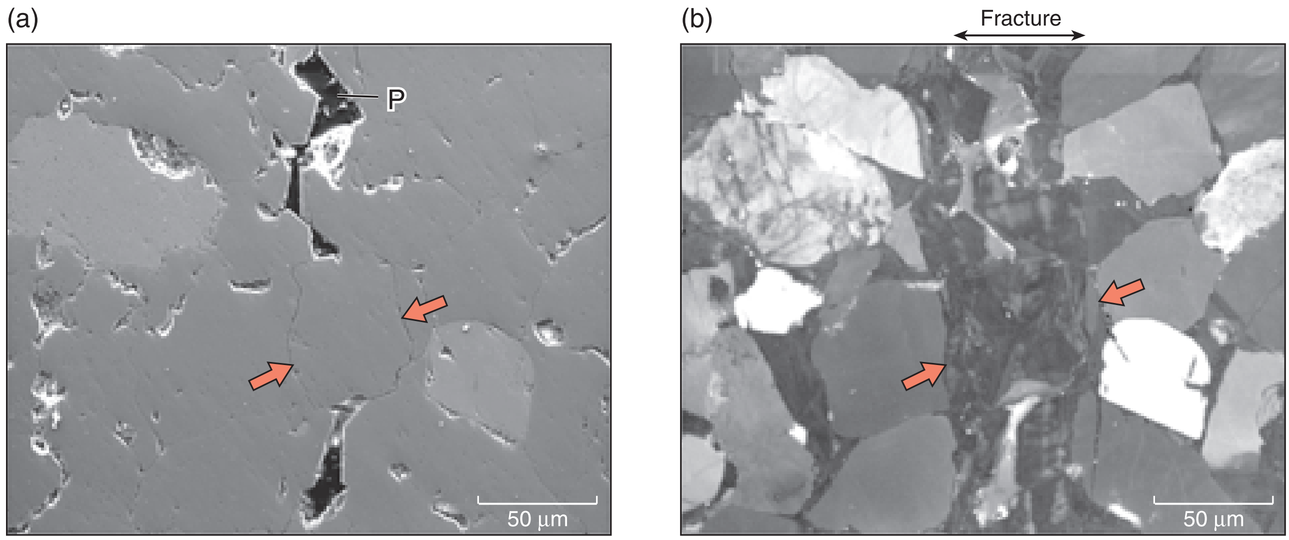


Figure 2. Sealed microfractures detected using scanned CL. (a) Microfractures, Cambrian Flathead sandstone, Wyoming. Secondary electron image (SEI). Fractures are not visible. Black areas are porosity (P). (b) Scanned CL of the same area, fracture is visible. Authigenic quartz is black, porosity and grains are gray. Arrows mark fracture walls. Because of small aperture sizes, sensitive imaging of chemical contrasts afforded by scanning electron microscope (SEM)-based cathodoluminescence (scanned CL) is essential for discerning cement and microstructure patterns. A Philips XL-30 SEM having a high-resolution CL detector is our primary instrument (Reed and Laubach, 1996; Reed and Milliken, in press). Images were also collected using photomultiplier-based CL detectors on JEOL T330A and T300 SEMs (Milliken and Laubach, 2000). Elemental analysis included an SEM-based EDS system supplemented by microprobe analysis.

1988). Crack-seal texture defines fracture-opening history relative to cement sequence.

PATTERNS IN FRACTURE SEALING

Diagenesis refers to chemical and mechanical processes that convert sediment to rock. In many rocks, cement precipitation is a dominant process. Under moderate to deep burial, freshly broken fracture surfaces are highly favorable sites for cement growth. Because sedimentary rocks are porous, permeable media, shared precipitation (and dissolution) in rock and fracture network is unsurprising. To a certain extent, fractures fill with cement in the same way that other pores fill. However, fracture-opening processes, timing, and size are critically different between fractures and pores.

Figure 1 generalizes two patterns in preservation or destruction of fracture porosity. In the first pattern (Figure 1a, b, c), synkinematic cements contemporaneous with fracture-opening seal microfractures (Figure 2), whereas large fractures remain open because of their larger size (Figure 3), smaller surface-area-to-volume ratios, and, possibly, more frequent reopening (Figure 4). Large aperture size is crucial to porosity preservation, and a critical threshold size marks the transition from sealed microfracture to open macrofracture. Synkinematic cements are frequently the most voluminous cement phases in the rock mass: quartz in siliciclastic rock, dolomite in dolomites, and calcite in limestone. However, synkinematic cements are rarely the most prevalent in large fractures.

In the second pattern, late cements seal some large fractures but not others (Figure 5). Large fracture size is no guarantee that fracture porosity is preserved. Cements precipitated in static instead of opening fractures typically seal large fractures in data sets summarized here. Moreover, traces of the late fracture-sealing cements are normally present in the rock mass as well as in fractures (Figure 6). Fracture-porosity preservation above a certain threshold size defined by synkinematic cement suggests that material closing large fractures is cement that precipitates after fractures cease opening. At that stage, fractures are merely another variety of pore to be filled, and the quality of fractures as fluid conduits depends on the volume of cement available to clog the fracture system: postkinematic cement. Where postkinematic cement is prevalent, flow in fractures should be impeded.

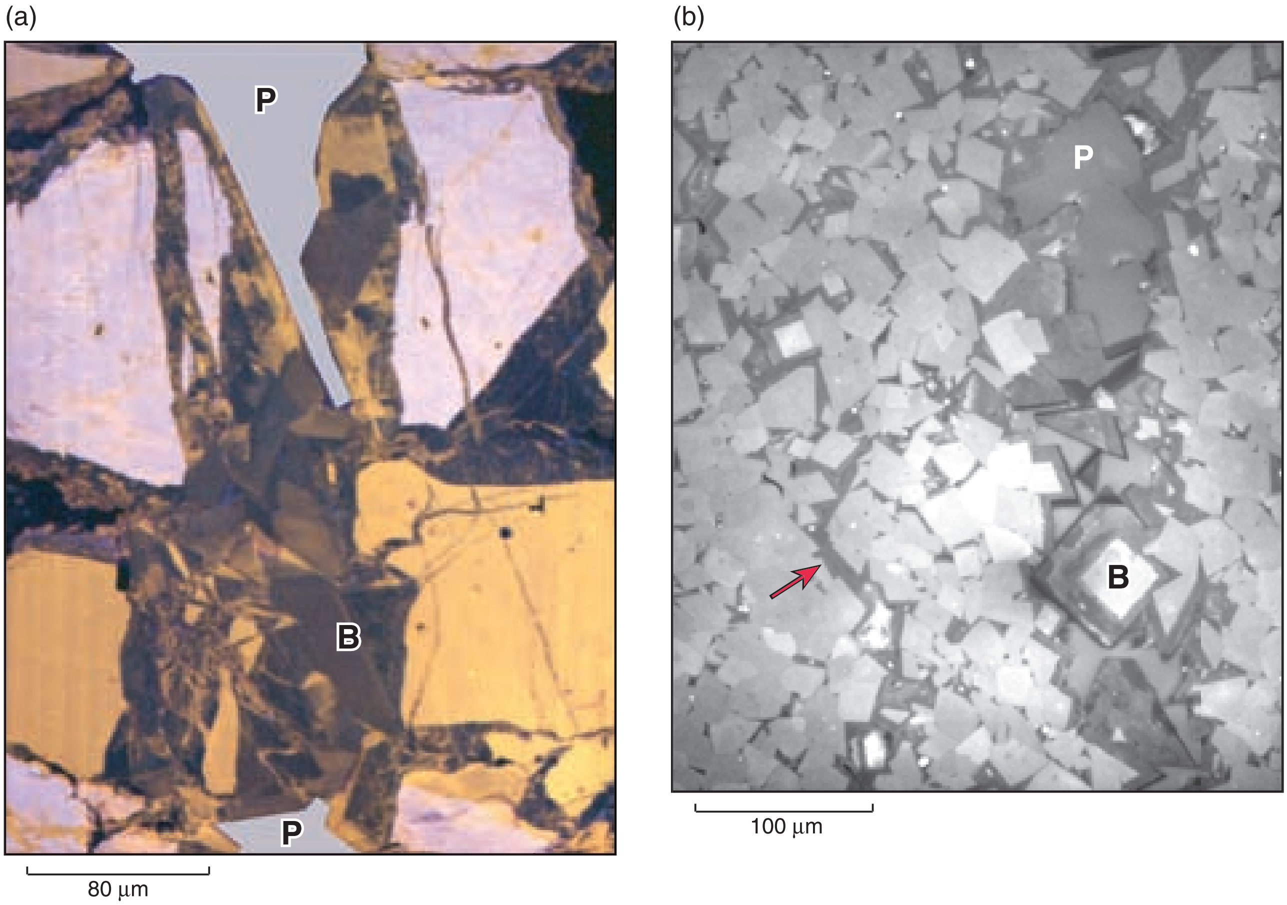


Figure 3. Large and small fractures illustrating emergent threshold. (a) Open, bridged fracture and associated sealed microfractures (arrow), Cretaceous Lance Formation, Green River basin, Wyoming. P, porosity. Note crack-seal texture in bridge, B. (b) Bridged, B, macrofracture having porosity, P, and sealed microfracture (arrow), Permian Ellenburger dolomite, Barnhart field, west Texas (Gomez et al., 2001). Scanned CL image. Conventional microscopy and scanned CL images ($\sim$200$\times$ to $\sim$1000$\times$) having areas of as much as several square millimeters of documented composition and structure. Typically 200–300, locally 1000, counts of stained thin sections and in some core sets, fluid-inclusion and stable-isotope measurements on selected minerals in fractures and hosts, corroborated paragenetic relations.

The surrogate for observing fractures that might be open or sealed is thus (1) fracture-timing information relative to diagenetic sequence, which identifies postkinematic cement and (2) the volume of postkinematic cement. In the absence of any macrofracture observations, fracture timing can be obtained from microfractures, although they are typically sealed because of a systematic transition from sealed microfractures to potentially open larger fractures, a transition defined here as ''emergent threshold.'' The following section illustrates these patterns.

Cement Textures in Fractures

Cements line or fill most fractures in the data set (Figures 2–6). Cement fill may be obvious or so subtle that detection requires a microscope and careful sample handling to preserve veneers fractions of a millimeter thick. Fracture pore shapes range from isolated and equant (including minute fluid inclusions in microfractures), through discontinuous and anastomosing channels, to continuous and tabular. Crystal morphology provides evidence of growth conditions. Faceted (euhedral) and massive (anhedral) to blocky crystal habits are common. Where they line fractures, inward-projecting faceted crystals mark growth into open pores (Figures 4–6). Crystals projecting inward may increase in size but decrease in number toward fracture centers because some crystals crowd out others as growth proceeds. A common texture is faceted crystals surrounded by anhedral crystals, marking cement growth into open space succeeded by infilling during

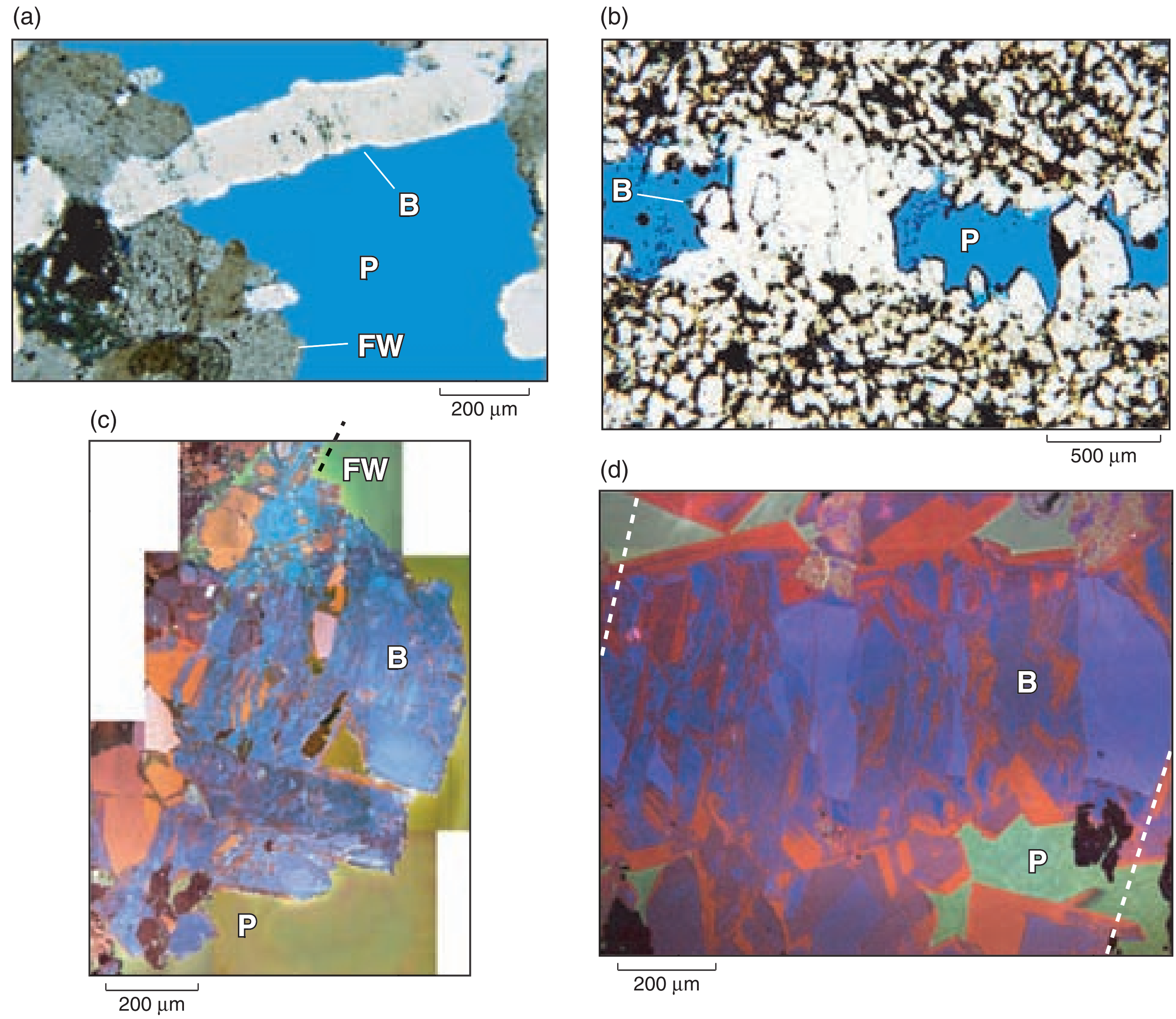


Figure 4. Bridges and crack-seal texture. (a) Narrow quartz bridge, B, and open fracture, P, Cretaceous Travis Peak Formation, east Texas. FW, fracture wall having veneer of unfractured cement. Faceted crystals that grew into open cavities cannot record fracture-wall movement. Transmitted light. (b) Wide quartz bridge, B, and porosity, P, Cretaceous Travis Peak Formation, east Texas. Transmitted light. (c) Bridge, B, having crack-seal texture and porosity, P, Cretaceous Williams Fork Formation, Colorado. Fracture wall (FW) is parallel to dotted line. Scanned CL. (d) Narrow bridge, B, with crack-seal texture and serrate margins. Dotted lines, fracture wall; residual porosity, P. Cretaceous Frontier Formation, Wyoming, with depth of about 20,000 ft. Scanned CL.

fracture sealing (Figure 5). Subhedral and anhedral crystals may also record etching and dissolution of fracture-filling minerals.

Cement spans some fractures, forming mineral bridges that range from isolated, narrow ($<$0.05 mm) pillars to wide, semicontinuous masses having contact areas on fracture walls of tens of square millimeters or more (Figure 4). Bridge substrates range from individual grains that have nucleated cement growth to areas much larger than those of individual grains. Bridges are common in siliciclastic rocks, dolomite, and limestone over a range of fracture sizes. Some result from incomplete cement fills in static fractures, but many are a consequence of cement precipitation in opening fractures. As discussed in the next section, they contain compelling evidence of fracture-opening history.

Evidence of Fracture-Opening History

Crack seal is a deformation mechanism in which small increments of extension repeatedly occur across a planar discontinuity, followed by repeated sealing by

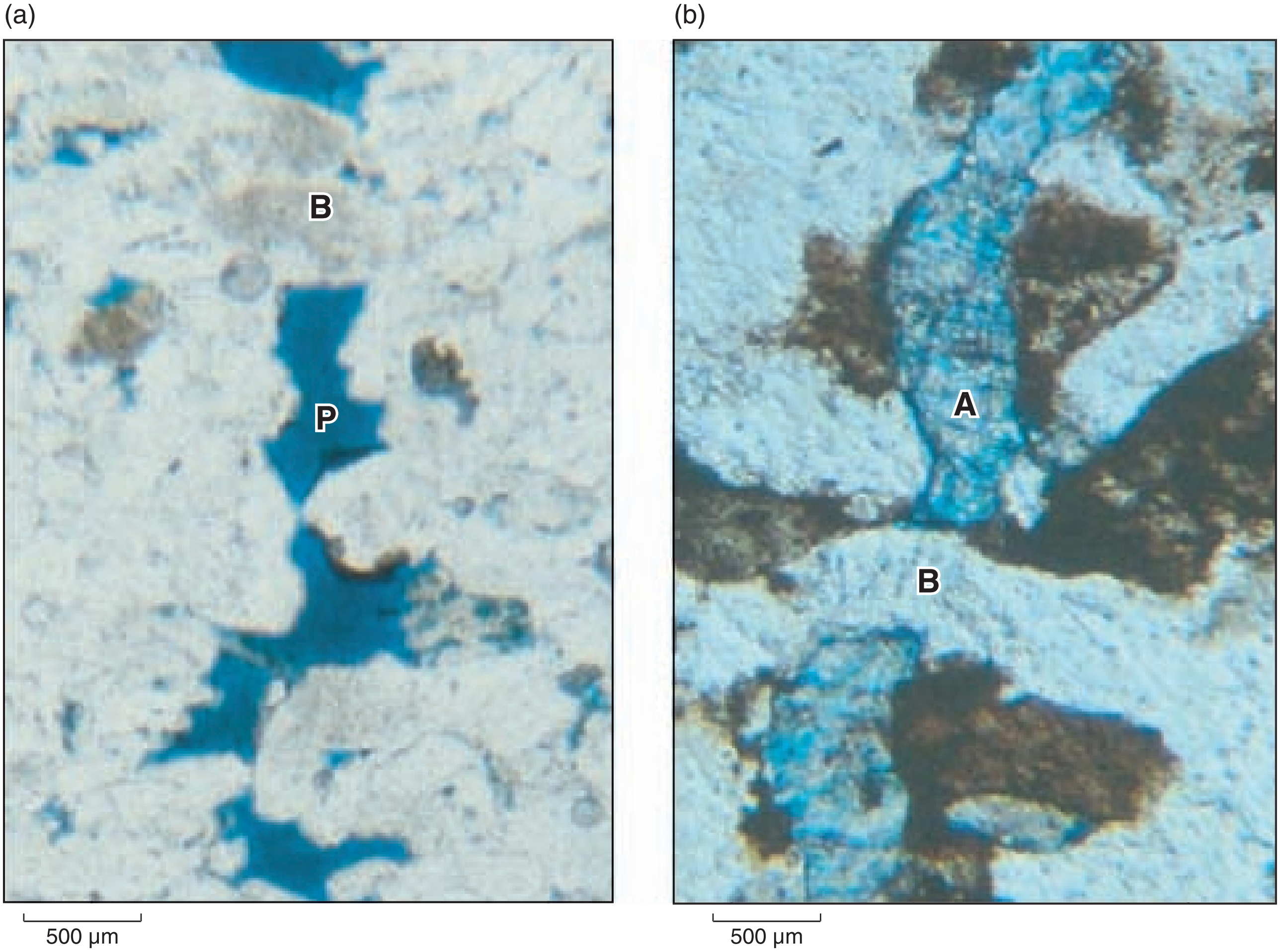


Figure 5. Open and sealed large fractures above emergent threshold. (a) Open bridged fracture, B, and porosity, P, Jurassic Cotton Valley sandstone, east Texas. (b) Bridged fracture, B, sealed with postkinematic ferroan dolomite, A, Cretaceous Cody Sandstone, Wyoming. Emergent threshold is fossilized by late Fe-dolomite cement. In siliciclastic rocks, common postkinematic cements include calcite, ferroan calcite and ferroan dolomite, ankerite, barite, and clay minerals. In dolomites, common postkinematic cements are anhydrite, calcite, and ferroan dolomite.

cement (Hulin, 1929; Ramsay, 1980). Crack seal is ubiquitous in cemented, moderately to deeply buried siliciclastic rocks, and even in unstructured rocks distant from large folds and faults. Some fracture-fill fabrics are layered, banded or, rarely, fibrous, with layers paralleling fracture walls and crystal bands or fibers aligned at a high angle to walls. Layered fabrics are frequently faint or obscure under transmitted light. Scanned CL shows that layering and banding in fracture-filling cements is crack-seal texture. This texture is marked by lamination parallel to fracture walls defined by wall-rock inclusions, broken cement inclusions, cement zoning cut by fractures, and fluid-inclusion planes (Figures 3, 4). Crack-seal processes also produce inclusion trails and elongate crystals oriented at high angles to fracture walls. The latter result from fills in crystallographic continuity with wall-rock grains. In quartz and dolomite, bridges commonly have alternating wide and narrow segments (serrate structure) that reflect cement growth from broken wall-rock particles and connecting cement. Contemporaneous cement outside bridges is commonly an inconspicuous micrometer- to millimeter-thick veneer on fracture walls.

Crack-seal texture is common in isolated single crystals or clusters of crystals that span or that formerly spanned a fracture. These cement bridges are contemporaneous with fracture opening (Figure 4). Some bridges show dozens to hundreds of micrometer-scale, sealed fractures. Euhedrally terminated crystals growing into fractures (partial bridges and fracture-lining material) commonly show crack-seal texture at their bases.

Wide fractures may have no bridges in their centers because cement precipitation rates (or durations) were insufficient to bridge during fracture growth. These fractures have only relict crack-seal texture near formerly bridged segments. Intact bridges are evidence of cessation of fracture widening; more fracturing would have broken the bridge. Cements that postdate intact bridges must therefore have precipitated in dormant fractures.

Crack-seal texture identifies which cements precipitated during fracture opening. In siliciclastic rocks, crack-seal texture is common in quartz. Crack-seal texture is present in dolomite bridges in dolomites and in calcite-lined fractures in limestone, although it is less obvious because textures in carbonate minerals are challenging to discern using existing CL imaging methods (Reed and Milliken, in press). In these rocks, bridges having serrate structure mark crack-seal processes.

Crack-seal texture is present in fractures as narrow as 35 μm, so a large fracture is not required to infer fracture timing relative to cement-precipitation sequence. Many of the smallest fractures lack crack-seal texture because they sealed after only one increment of opening. Fracture-timing information from these is recorded by crosscutting arrays of small and widely separated fractures that formed and filled progressively as cement precipitated (Reed and Laubach, 1996).

Fractures having bridges, crack-seal texture, and adjacent areas of porosity (or later cement) (Figures 3–5) are widespread. Bridges are flanked either by porosity or by cements deposited after fracture growth ceased, showing that bridges and adjacent pore space developed concurrently. Fracture-porosity destruction, if it occurs, is a later event.

Fracture-Size Effect

Fracture size is an important variable for understanding fracture-porosity preservation. Shared cements and textures that reflect fracture opening (as well as orientation and size distribution) link micro- and macrofractures. However, fractures of contrasting size may differ markedly in the extent to which they retain pore space.

It is convenient to approximate fracture size with kinematic aperture, the distance fracture walls have moved apart (Marrett, 1996; Marrett et al., 1999). Because of cement, kinematic aperture is usually greater than any open gaps (aperture as conventionally defined). Kinematic aperture sizes were measured on high-resolution (>200×) CL images, with micrometers on transmitted-light microscopes, and with hand lens using graduated aperture comparators (Marrett et al., 1999). Apertures of sampled fractures range from several micrometers to tens of centimeters, but most fractures in the data set have apertures of a few millimeters or less. Outcrop studies show lateral persistence (length, connectivity), having dimensions of a few micrometers to as much as several kilometers.

Fractures having apertures of less than 0.1 mm are termed ''microfractures.'' Some reflect processes operating only at microscale, and others in clastic rocks are inherited (Laubach, 1997). In many rocks, however, both micro- and macrofractures have a spectrum of sizes that follow systematic patterns (Marrett, 1996). Where these size distributions are quantified, they have many small and fewer large fractures; populations can be described with power laws over a wide range of sizes (Marrett et al., 1999; Ortega and Marrett, 2000; Gillespie et al., 2001; Ortega et al., 2001; Gale, 2002). Arrays have timing and orientation that match associated large fractures (Laubach, 1997). In many respects, these micro- and macrofractures are merely different-size fractions of the same fracture sets.

However, microfractures tend to be sealed, or they have only small, discontinuous areas of porosity, whereas large fractures of the same set may be open (Figures 2, 3). Size-dependent porosity is most evident where micrometer- to millimeter-scale fractures and large fractures of the same set are present, a pattern observed in more than 55 siliciclastic units. As width diminishes, many fractures show increasing bridging, with partial to complete fill more prevalent near tips, where apertures are smaller. Typically, a single phase is responsible for sealing microfractures (i.e., quartz, dolomite, or calcite). In a single set, the same cement that fills smaller fractures lines or bridges larger fractures.

Size-Dependent Fill and Emergent Threshold

For cements associated with fracture opening, as fracture size increases, degree of contemporaneous cement fill decreases. A transition, the emergent threshold, marks the fracture size where porosity development predominates over rates of synkinematic-cement precipitation during fracture opening. Emergent threshold is commonly in the range of about 0.01–1 mm in siliciclastic rocks and dolomite. Limited data in limestone suggest a similar pattern, but possibly because of rich sources of $CaCO_3$ in limestone undergoing burial and pressure solution, transitions from sealed to open fractures occur at larger aperture sizes (~1–10 mm or more) (Gale, 2002). The gradational transition from sealed to open fractures for synkinematic cements is apparent in small fractures that are well represented in core. Emergent threshold is generally measurable, and those large fractures that could have the biggest impact on flow are generally well above the threshold.

There are regional differences in emergent threshold. Fractures having apertures greater than 0.1 mm have preserved pore space in Cretaceous sandstones in a passive margin setting in east Texas at depths of about 3000 m, but fractures having apertures of 0.001 mm or less are open in Cretaceous sandstones from South American foreland basins at similar depths. These contrasts could reflect different times of fracture formation (Lander et al., 2002). The South American fractures may be of recent origin in this tectonically active area. Although cement volumes and precipitation rates are sensitive to temperature, solute concentration, and rock type, under uniform precipitation rates, micrometer- to millimeter-scale fractures will seal first, whereas more time is needed for accumulating cement sufficient to fill larger fractures. Numerous opening events and competition between fracture opening and sealing could help conserve voids in large fractures (Laubach, 1988; Lander et al., 2002).

Emergent threshold is defined by cement precipitated during fracture opening, and it is not equivalent to a fracture-porosity threshold. Thus, in polymineralic fractures, late cements may substitute for porosity, preserving evidence of shifts from sealed to open fractures defined by synkimematic cement (Figure 5). An emergent threshold is present in fossilized form in these fractures. For late cements that may partly fill or seal fractures above the emergent threshold, evidence of size-dependent fill is uncommon because of the narrow range of large fracture sizes in most data sets. Moreover, late-cement quantities vary abruptly and may even be absent, further obscuring any size effects.

The emergent threshold is important because microfractures having sizes below the threshold are not evidence that larger fractures of the same set are sealed. Microfractures can specify when fractures formed in a rock's diagenetic history. However, they cannot record cements that could damage large fractures because micrometer-scale fractures rarely preserve polymineralic relations or porosity. Microfractures alone therefore cannot be proxy for degree of occlusion in large fractures. Information about polymineralic cement sequences from another source is needed.

Cement Sequence and Sealing of Large Fractures

A rock's intragranular and intergranular volume can provide evidence of late cements that is lacking in microfractures (Figure 6). Although microfractures are longer than, or comparable in length to, many pores, microfracture surfaces are initially mostly fresh and hence disposed to cement nucleation. They typically have slotlike aspect ratios that assure small volume relative to surface area as compared with that of pores. They are thus more prone to seal under the same burial conditions. Primary and secondary pores can potentially more faithfully record postfracture deposits in the rock and in nearby large fractures.

Many large fractures are lined with a single mineral phase, whereas others contain two or more phases that may show overlapping and crosscutting relations defining coprecipitation or, most commonly, precipitation sequence (Figures 5, 6). Overlapping relations among phases mark paragenetic sequence of precipitation and dissolution. In sedimentary rocks, cements in opening-mode fractures are frequently the same as those in the intergranular and intragranular volume. Where fractures having several generations of cement are present, sequences in fractures and host rock commonly match (Figure 6).

In the sample suite, early cements in fractures tend to be the same phases as those that dominate in the substrate. In siliciclastic rocks, fracture-lining cement is predominantly quartz, in dolomite rock, dolomite, and in limestone, calcite. These are the same phases, respectively, that are most abundant as cement in associated rocks. Congruence between initial fracture cement and overall rock composition mostly holds, even where rock composition varies. For example, initial quartz along fractures is evident in siliciclastic rocks having moderate amounts (~20%) of prefracture calcite and dolomite cements, although it is not noticeable in sandy limestones. Initial dolomite precipitation is apparent in dolomites having abundant prefracture anhydrite and calcite cements. This pattern also holds where more than one fracture set is present, even where polymineralic fracture fill exists in early-formed fracture sets. These patterns suggest that rock composition influences initial cement precipitated in new fractures. This influence is not surprising if fracturing is a relatively rare event and geochemical reactions are dominated by the composition of the host rock.

The first cement to precipitate in most fracture arrays can be identified with confidence (Figure 6). Within fractures in siliciclastic rocks, sharp, broken

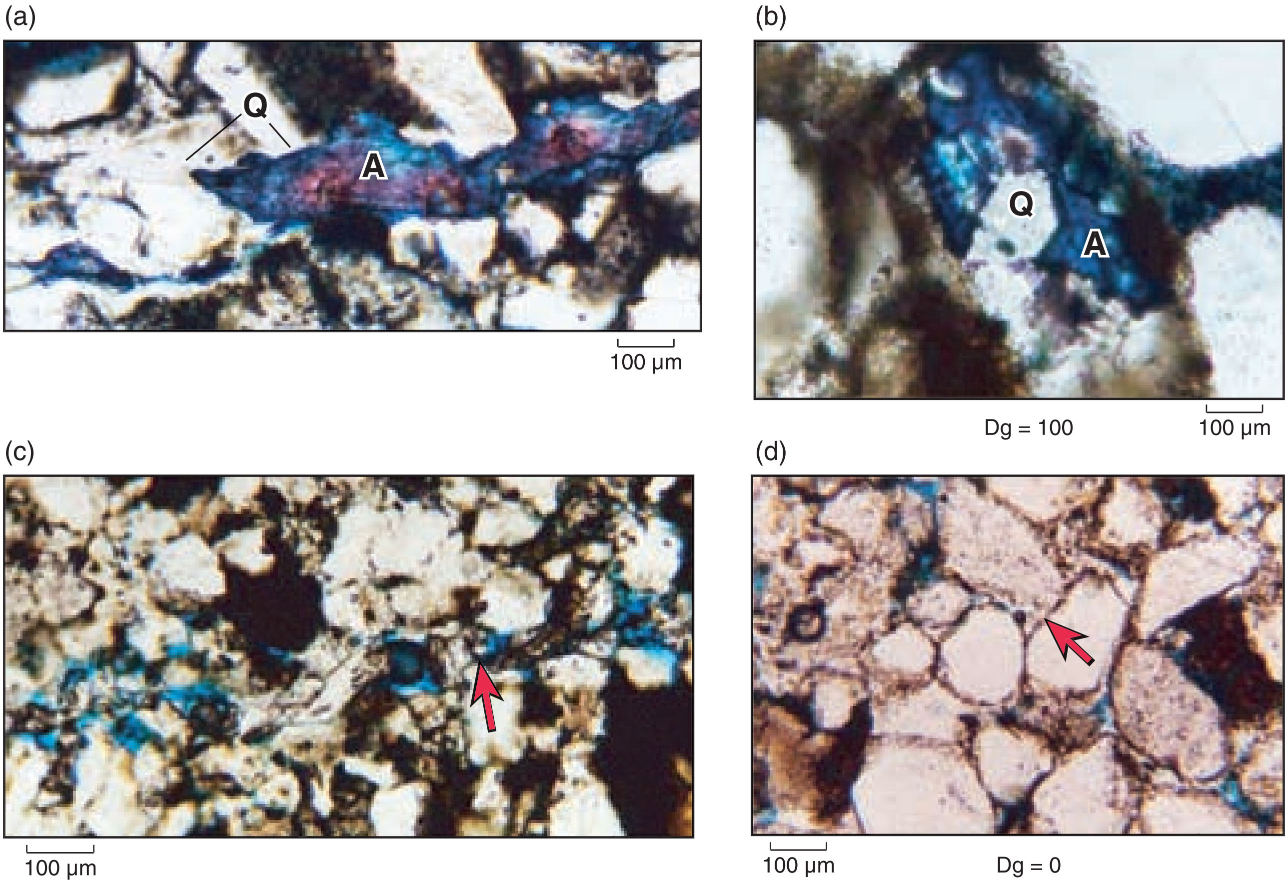


Figure 6. Fracture and host rock having shared paragenetic sequence. Permian Wolfcamp sandstone, Texas. (a) Fracture lined with quartz, Q, and sealed with ferroan dolomite, A. (b) Secondary pore lined with quartz, Q, and overlapped and filled with ferroan dolomite, A, in the same unit and depth. (c) Quartz-lined open fracture (arrow; porosity = blue). (d) Pore lined with quartz, arrow (porosity = blue). All samples are from the same well and fractures have the same strike; Paired samples from the same depths: (a, b) Dg is high; (c, d) Dg is low. Transmitted light.

walls of fractures are frequently visible, preserved under a veneer of the first cements to precipitate. Commonly, this initial phase is quartz. Similar, although in many cases less definitive, evidence of sharp fracture-cement contacts in dolomites suggests that authigenic dolomite also mostly precipitated on fresh fracture surfaces in examples that I studied. Association with crack-seal texture is compelling evidence that these cements partly precipitated while fractures opened.

Although the same early phase typically lines large fractures of a given set, late cements commonly have heterogeneous distributions, and they may be absent. In the rock mass, late cements are frequently present in small quantities (<10% whole-rock volume). Abrupt variations are common in the presence and abundance of late cements from bed to bed, formation to formation, and well to well in both fractures and rock mass. Distributions range from patchy to tabular, depending on size and shape of available pore space and cement volume. Where they occur together, late cements overlap early cements or fill voids between intact bridges (Figure 5). This pattern shows that late cements precipitated mostly in static (not opening) fractures. Large fractures of the same age and orientation may thus be sealed or open.

Paragenetic sequence, as well as fluid-inclusion and isotopic data, links fracture and host cements (e.g., Pitman and Sprunt, 1986; Laubach, 1989; Stone and Siever, 1996; Montañez, 1997) (Figure 6). Diagenetic patterns may be complex, reflecting thermal and fluid history and therefore difficult to understand or predict ahead of the bit. However, in contrast to large fractures that are difficult to sample, there is no challenge in sampling and describing polymineralic cements because these pervade the rock mass. Although many rocks contain several fracture sets formed at different times, as well as complex and, in some cases, repetitive sequences of cements, to the extent that diagenesis affects both rock and fractures, cements in the rock mass provide evidence of cements that may be in fractures.

APPLYING AND TESTING THE SURROGATE

Large fractures are the most likely to influence fluid flow on production time scales. To predict damage to fluid flow where these fractures do not intersect the wellbore, postkinematic cement is an appropriate surrogate because these cements are responsible for sealing large fractures. Herein I show how to translate this idea into a usable measurement and compare predictions in several test cases to fracture observations.

Postkinematic Cement and Degradation

What is the best way to quantify postkinematic-cement volume and how does a given amount of cement translate into fill in fractures? Once relative fracture timing is discovered from macrofracture or microfracture observations, whole-rock percentages of postkinematic cements can be obtained readily from point counts. Useful measures include percentages of postkinematic cement and ratios of postkinematic cement to a measure of rock volume into which late cements precipitated. These fracture-fill indices derive from the rock mass and do not involve fracture observation.

Figure 7 shows how surrogate use can guide geologic interpretation. In this sandstone, one fracture was sampled by core. It is lined with synkinematic quartz but sealed with postkinematic ankerite. How representative is it? The sealed fracture could be misleading because postkinematic-cement percentages overall are mostly lower than those in the depth interval from which the fracture was sampled. Low postkinematic-cement abundance is marked in the plot by left-facing flags. Samples from nearby wells demonstrate that open fractures are present where ankerite cement is rare or absent (Laubach, 1988). The sealed fracture that was sampled is probably unrepresentative of the cored interval as a whole.

Because a rock's capacity to record postkinematic-cement percentages is commonly low and also variable, cement volumes alone are problematic for use as a surrogate. For example, 15 east Texas Jurassic Cotton Valley sandstone samples have average percentages of postkinematic ankerite slightly over 3% whole-rock volume, ranging from 0 to slightly more than 9%. Porosity values are similar (average ~3%, range 0–8%). These rocks have limited capacity to record postkinematic cement. The dominant pore-filling cement in many fractured rocks is synkinematic cement, and pore space available for postkinematic cement is typically 10% or less. Whole-rock postkinematic-cement percentages might reflect differences in porosity because

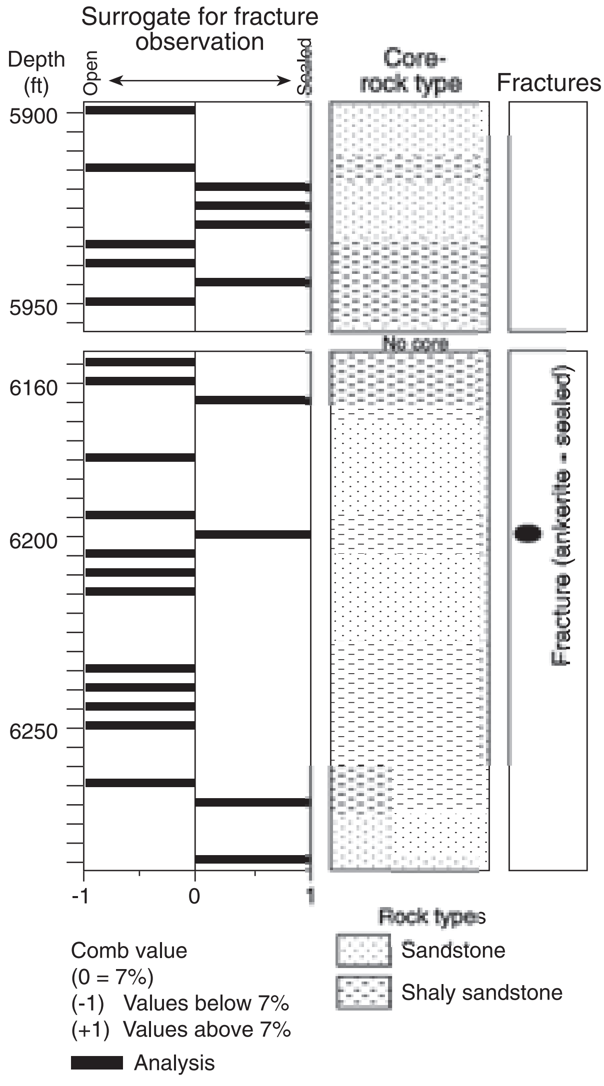


Figure 7. Postkinematic cement abundance versus depth, Jurassic Cotton Valley sandstone core. Diagram shows how the use of a surrogate can increase the amount of fracture information in a cored interval. Width of sampled fracture is about 2 mm. The comb plot marks depths having postkinematic cement above or below a specified value (in this case, 7%); left-facing comb teeth depict where samples have less than 7% ankerite. Choice of the zero value for such a plot can be selected using fracture observation or correlation with production if contrasts in production response can be equated with values of postkinematic cement.

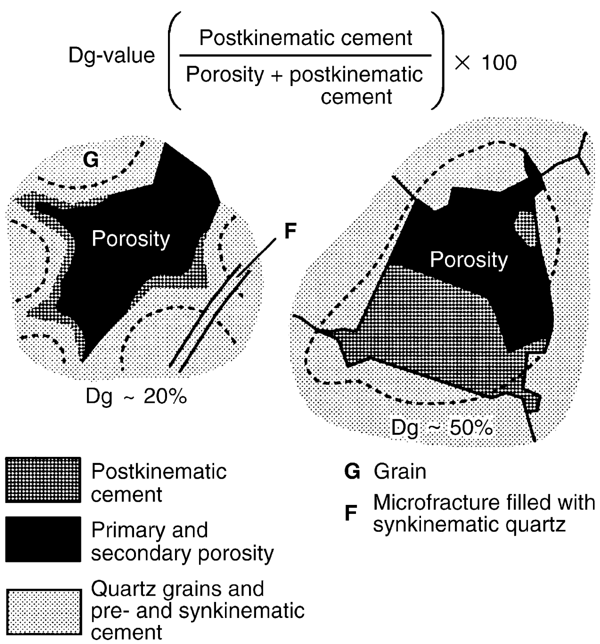


Figure 8. Degradation (Dg), a surrogate indicating likelihood of porosity destruction or retention, has values that range from 0 to 100%. Where postkinematic cement is absent, Dg is zero, quality is high, and large fractures should be open (albeit with linings and bridges of synkinematic cement), even if rock-mass porosity is small. Increasing postkinematic cement suggests that large fractures contain fill that would be absent if degradation was low. Dg is a measure of rock-mass properties that predicts fracture fill. Normalization facilitates comparison of samples having variable postfracture whole-rock volume. Diagram shows primary (left) and secondary (right) porosity partly filled with postkinematic cement. Because postkinematic cement volumes and porosity are low in many rocks, degradation is commonly a ratio of small numbers. Consequently, shifts in porosity and postkinematic cement can have large effects on degradation, amplifying signals present in rock-mass porosity that are not obvious because of scatter in porosity values caused by other factors (e.g., grain size, secondary pores, etc.).

of variations in synkinematic cement governed by extraneous factors such as, for example, grain size in sandstone, instead of contrasts in postkinematic cement that might be reflected in fracture fills.

An alternate measure is to normalize postkinematic-cement volume to space available (postfracture whole-rock volume). "Degradation index" (Dg, percent) is defined here as the ratio in the rock mass of cement that postdates fracture opening to available rock-mass porosity (postfracture void space) (Figure 8). High degradation (values near 100%) suggests sealed fractures (Figure 9). Although many samples having high degradation also have low porosity, it is not always the case, for example, where secondary porosity postdates and does not affect fracture fills (Cumella et al., 2002). However, degradation is most valuable for discriminating rocks having low porosity because of synkinematic cement and rocks having lower porosity because of traces of postkinematic cement. Only in the latter case is damage to the fracture system indicated.

Because prekinematic and synkinematic cements are voluminous, they influence rock-mass porosity more than postkinematic cements, yet traces of postkinematic cement are the phases available to damage large fractures. Rocks having contrasting degradation may thus have indistinguishable porosity. Similar values of porosity but differences in fracture damage could account for the efficacy of otherwise inexplicable porosity cutoff rules of thumb in predicting production response.

Testing the Surrogate

Degradation, a prediction of degree of fracture fill, agrees with occlusion, or observed infill in large fractures. Figure 9 compares observed large, open to sealed fractures with degradation on the basis of samples

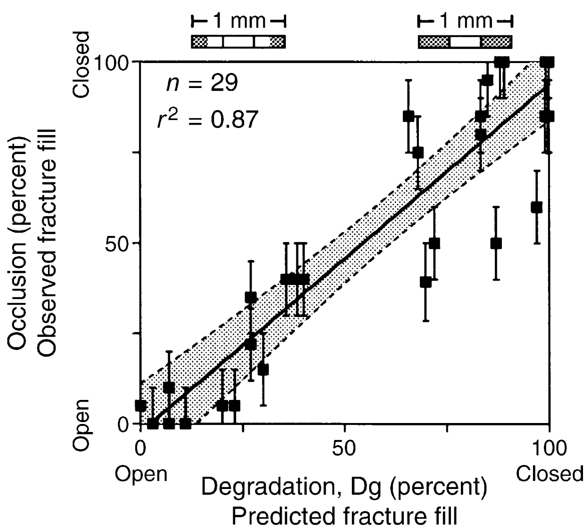


Figure 9. Fracture observations (occlusion) versus surrogate predictions (degradation). Data are from sandstones from four formations having thorough estimates of pore space lost for fractures above the emergent threshold (Wolfcamp, Weber, Cotton Valley, Lance). Scatter at intermediate Dg values and qualitative error bars mark uncertainty quantifying open pore space and postkinematic cement percentage in small fractures. Larger data sets agree with this pattern but have fewer subdivisions (open, partly open, and sealed) because of less complete fracture descriptions.

from the same depth interval, although generally not from adjacent to the fracture. High degradation correctly predicts sealed fractures, and low degradation identifies open fractures. Agreement between prediction and observation is also apparent where cores from different wells have penetrated the same fracture set (Figure 10).

Qualitatively, congruence between degradation and occlusion patterns is evident in large core suites. In eight Lower Cretaceous Travis Peak Formation wells having more than 2099 ft (639 m) of core (average 260 ft [79 m]/well, range 84 to >570 ft [25.6 to >174 m]), 118 macroscopically visible fractures were described, fewer than 0.1 fracture per foot of core (Laubach, 1989). Average kinematic aperture is only 0.1 mm. Of 118 fractures, 41 are so narrow that they are entirely filled with synkinematic quartz; these are below emergent threshold. Of the remaining fractures, 32 are open but quartz lined, and 45 contain polymineralic cements and are partly to completely sealed. Postkinematic cements are primarily ferroan dolomite and ankerite. For 251 analyses, average postkinematic-cement volume is a mere 3.4%. Comparing open, partly sealed, and filled fractures with nearby degradation estimates shows that 98% of predicted open fractures correspond to open fractures and 93% of predicted partly sealed and sealed fractures correspond to fractures having appropriate attributes. Core damage and, rarely, differences in postkinematic-cement abundance between depths containing fractures and depths of petrographic analysis can produce discrepancies between degradation and occlusion. Unsuitable macrofracture porosity descriptions lacking high-resolution aperture measurements (for example, with a comparator) also hamper quantitative comparisons for some older data sets.

Horizontal wells provide another perspective on fracture-sealing patterns. In a Cretaceous tight gas sandstone from Colorado, more than one dozen fractures range from sealed to open in about 30 ft (9 m) core cut subparallel to bedding and at a high angle to fracture strike. Postkinematic cement is uniformly low throughout this core, correctly predicting that large fractures are open. Synkinematic quartz seals closed fractures near or below emergent threshold, having apertures between 0.1 and 0.01 mm or less, and lines open fractures. However, in vertical core from adjacent wells in slightly shallower sandstones, sealed fractures are found in rocks having high degradation (Cumella et al., 2002).

High degradation correctly predicted sealed macrofractures in all four dolomites in this study. For example, Cretaceous Cupido dolomite contains several fracture sets. Synkinematic dolomite, an emergent

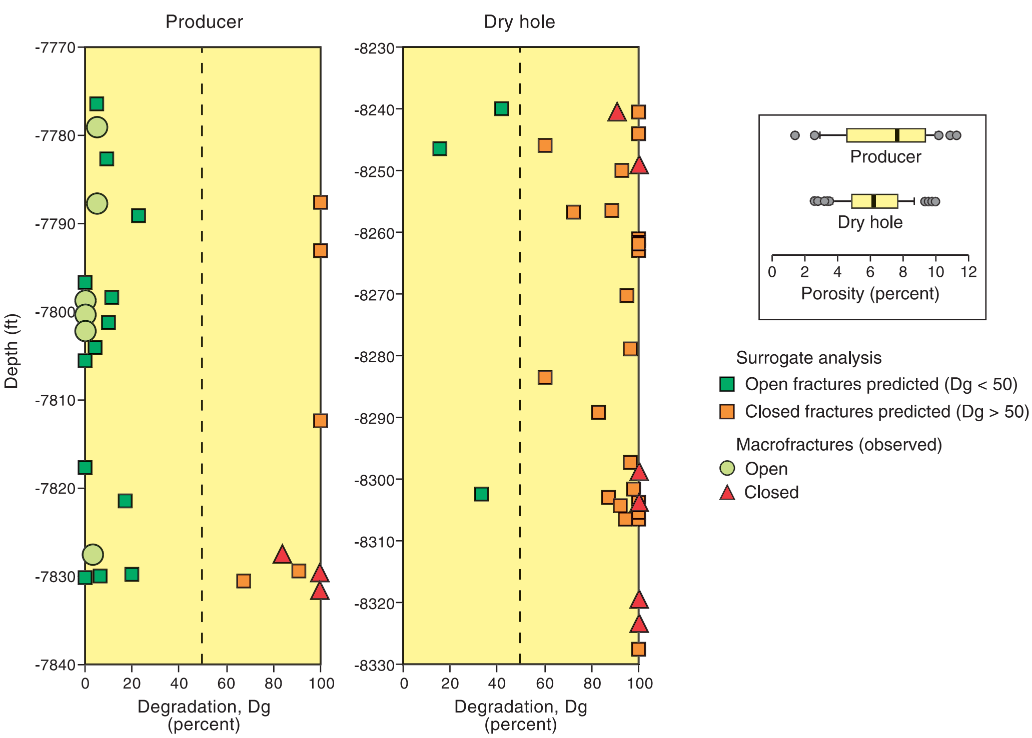


Figure 10. Fracture-quality predictions (degradation) versus depth compared with 15 fracture observations, Permian Wolfcamp sandstone, west Texas. Degradation (green and orange squares) identified depths having open and sealed fractures (green circles and red triangles, respectively). Note that the well having mostly sealed fractures is a dry hole, probably because of the absence of fracture-enhanced permeability. Wells were indistinguishable according to porosity logs. Inset shows box plot of laboratory helium porosity measurements: box, center third of data; bar, mean; circles, outliers.

threshold, and postkinematic calcite sealing large fractures are all present (Monroy et al., 2001). Similar patterns are evident in Ordovician Knox and Ellenburger (Gomez et al., 2001) and Permian Clear Fork dolomite (Stowell et al., 2002). The surrogate approach is feasible in carbonate rocks but can be challenging because of problems in discriminating pre- and postkinematic phases, which include calcite, anhydrite, and dolomite.

Well Pairs

Evidence that high degradation results in impeded fluid flow in fractures was found in six well pairs where geologic and engineering parameters are similar and effects of fractures can be isolated. Low degradation and fracture-enhanced production and the reverse are evident in well pairs from Cretaceous and Paleozoic sandstones from foreland and passive margin settings where fractures are inferred to provide intrareservoir flow pathways. Because these paired wells have similar depositional environment and stimulation, the influence of fractures on fluid flow can be isolated.

Figure 10 shows an example from Paleozoic sandstone in west Texas. Each well was cored through the same turbidite sandstone unit, and grain compositions and paragenetic sequences of cements are identical. Completion and stimulation procedures in both wells were similar. Porosity data from these wells are statistically indistinguishable, probably because synkinematic quartz cement is volumetrically dominant in both cored intervals. A slight decrease in average porosity in the well having higher average degradation values reflects slightly higher postkinematic-cement volumes relative to porosity in well B. Despite both cored intervals having approximately 10% prekinematic carbonate cement, large fractures are lined and locally bridged with quartz, which is synkinematic, judging by the presence of crack-seal textures in bridges. Postkinematic cements are ferroan dolomite, calcite, and barite.

Both wells intercepted large fractures having identical strike that formed concurrently with quartz cement. Degradation values are systematically lower in well A than in well B, suggesting that open fractures should predominate in well A, as is observed. In well A, six open fractures and three sealed fractures were accurately predicted by degradation index. In well B, six sealed fractures were correctly predicted. Well A, with low overall degradation, is a producer having probable fracture-enhanced permeability, whereas well B, with high degradation, is uneconomic because of low permeability. The surrogate thus correctly predicts both open and sealed fractures, as well as production response.

Interpreting Degradation Values

Degradation is a qualitative predictor of fracture occlusion. Because it measures abundance of postkinematic cement in rock pore space, it does not account for synkinematic cement or connectivity. Neither size-dependent filling of large fractures by postkinematic cement nor upscaling from arrays of small pores to infilling of large fractures is taken into account. Although porous rock has a finite capacity to record abundant deleterious cements, small pores might fill more readily than large fractures, so high degradation may over- or underpredict sealing in fractures of a given size.

Moreover, although these examples show that the surrogate correctly predicts sealing above a minimum fracture size, amounts of postkinematic cement required to damage a particular fracture system depend on number and sizes of fractures and how they are interconnected. The surrogate does not specify these plumbing attributes, which need to be measured separately. Degradation values are like a blood test for a factor that predicts clogged arteries. An independent measure of the arteries' capacity is needed to quantify how a specific value affects flow. Some fracture-size attributes can be extrapolated from microfracture size distributions (Marrett, 1996; Marrett et al., 1999), but fracture abundance and sizes, as well as connectivity and spatial distribution, are commonly unknown. A small amount of postkinematic cement may be sufficient to damage connectivity if connections are narrow, and a large amount may be needed to seal large fractures. Within a region or play, impact of a given degradation value should be calibrated against observed fractures or production.

Extending Scope of Fracture Data

Because small samples can be used to observe microfractures and accurately quantify cement paragenesis and volumes, the types of samples that yield fracture data are greatly expanded. In the well depicted in Figure 11, only four large fractures were sampled, yet good core coverage allows numerous degradation measurements. Degradation correctly predicted open and sealed fractures, but in addition, it provides evidence of attributes where fractures have not been sampled. By deriving surrogate predictions from core that has no fractures, we can discern the pattern of open-fracture preservation.

Sidewall cores are an economical source of data where no conventional core is available (Laubach and Doherty, 1999). Large cuttings that can be tied to depth may also be a source of fracture-quality data (S. Laubach, unpublished data, 2000). Because a wider range of samples yields predicted fracture attributes, it is feasible to construct fracture quality logs, cross sections, and maps (Figure 12) from wells having no conventional fracture data. Among other applications, these logs and maps are useful for targeting depths having favorable fracture attributes, calibrating well logs, identifying fracture sweet spots, modifying fracture patterns used in flow simulation scale-up, and testing remote-fracture detection results.

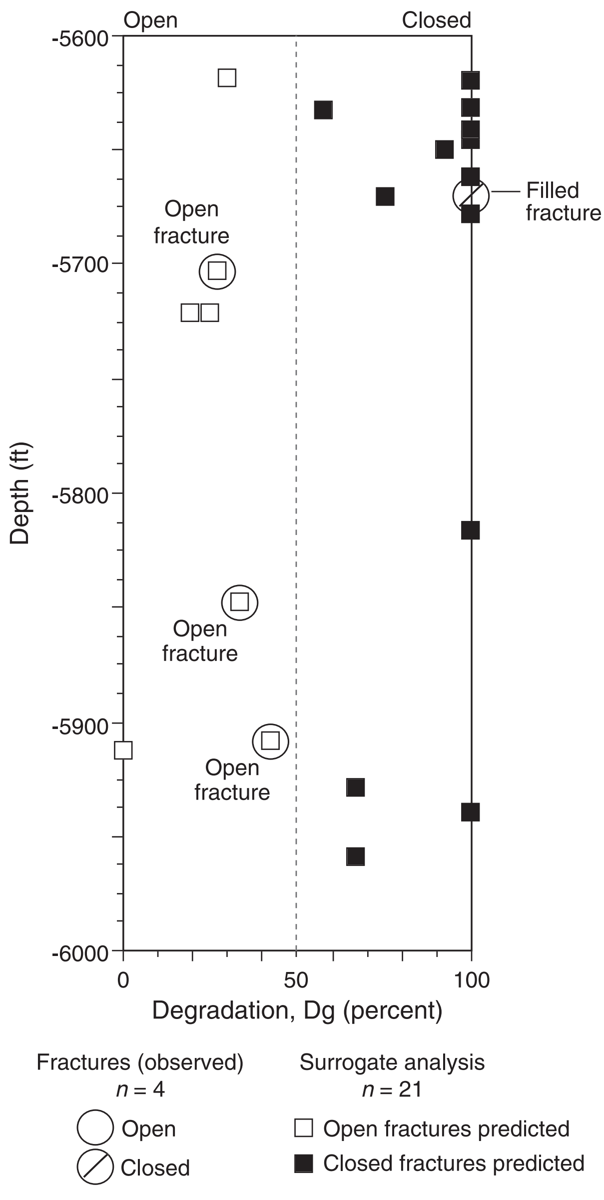


Figure 11. Predictions of open versus sealed fractures (degradation) versus depth compared with four fracture observations, Weber Sandstone, Rangeley field, Colorado. In addition to correctly predicting attributes of sampled fractures, the surrogate provides information on likely fracture attributes at depths where no large fractures were sampled by core.

IMPLICATIONS

Diagenesis patterns are readily sampled. Fractures of interest to the petroleum industry develop during burial histories in which interplay between structural and diagenetic processes is inevitable. Understanding this interplay is key to deciphering fracture attributes from limited observations. From a wide range of settings, some repeated and relatively simple preservation patterns of pore space in fractures are evident. (1) Cements that precipitate synchronously with fracture opening rarely seal large fractures but instead form thin, inconspicuous veneers and local bridges on fracture walls. These cements are found throughout a given set, and they are responsible for sealing numerous but petrographically invisible microfractures. (2) Later cements that can seal large fractures are heterogeneously distributed on a range of scales and are present in trace amounts in rock-mass pore space. These cements are commonly not associated with fracture growth.

Although any mineral phase could accompany or postdate fracture opening, this study shows that synkinematic phases are consistent with fracture in a chemical environment dominated by host-rock composition (for example, quartz in siliciclastic rocks), but postkinematic cements are not. Conditions favoring quartz, dolomite, or calcite precipitation might be causally linked to fracture growth, through, for example, pore-fluid pressure fluctuations caused by rapid cement precipitation (Laubach, 1988; Lander, 1998; Wangen, 2001), or they may merely reflect prevalence of rock-dominated chemistry through much of a rock's burial history, including times when conditions are amenable for fracture growth. Synkinematic cements, such as quartz, could merely be the most likely to precipitate through a protracted loading history (Lander and Walderhaug, 1999; Lander et al., 2002).

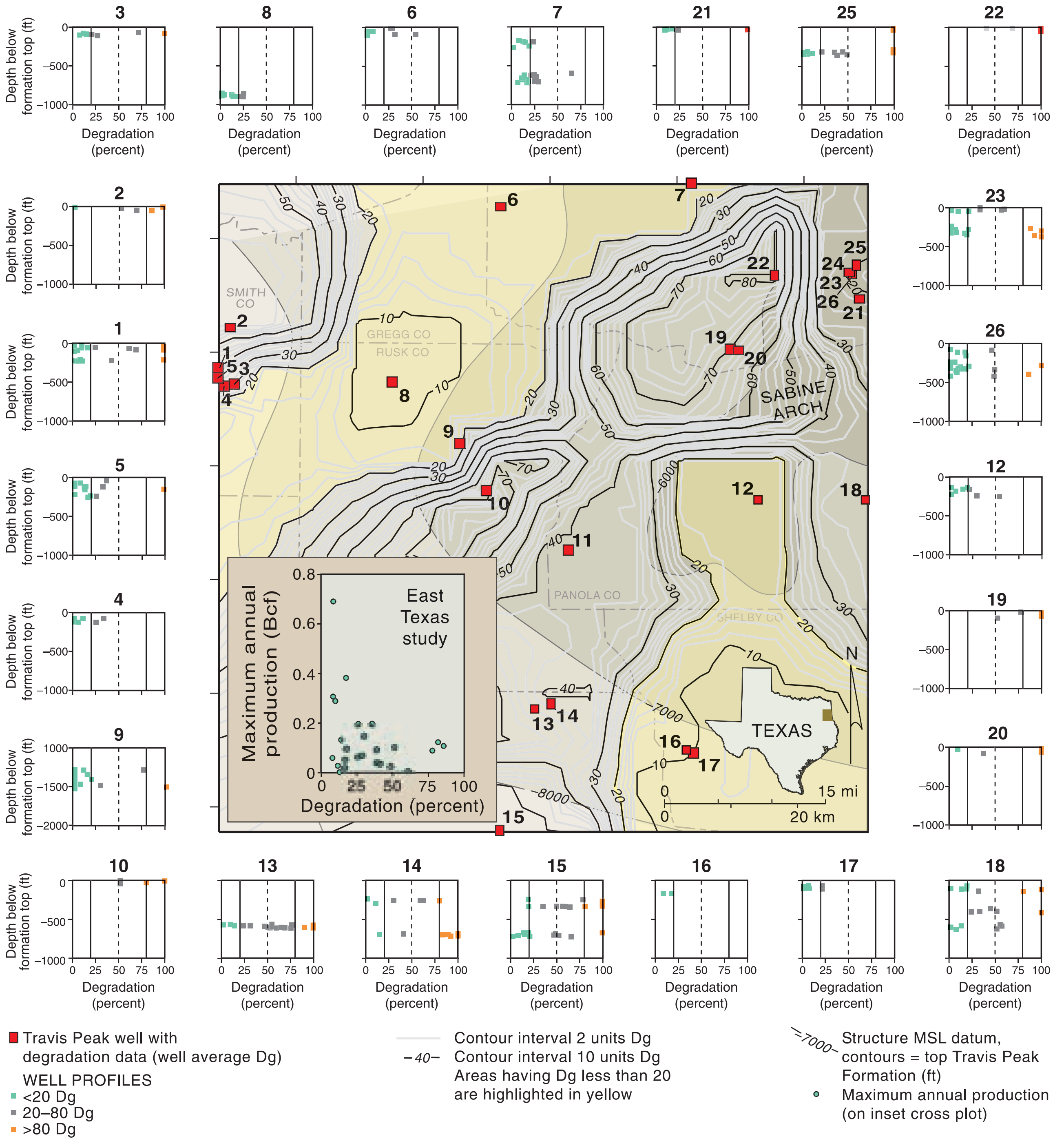


Figure 12. Map and profiles of predicted fracture quality (degradation, Dg), Cretaceous Travis Peak Formation, east Texas, demonstrating that mapping fracture quality (Dg) is possible. More than 470 point counts were used to generate Dg profiles, which are all from wells having conventional core, although such core is not required for obtaining Dg values. Note that broad Dg patterns are evident despite wide well spacing and averaging of degradation values by well that obscures Dg heterogeneity. Map is superposed on structure, top Travis Peak Formation. Inset shows a tendency for the highest maximum annual production to occur in wells having predicted open fractures (low average degradation, Dg < 20, yellow highlight on map).

Long residence at high temperature may not be adequate to accumulate sufficient cement to fill large fractures under these circumstances (Lander et al., 2002). Such conditions may typify fluid and thermal histories that many rocks have experienced for much of their history; the default is thus for large fractures to remain open. However, this process can account for numerous sealed microfractures found in association with large fractures (Laubach, 1997; Marrett et al., 1999), as well as the widespread occurrence of crack-seal textures, bridges and residual fracture porosity, and consistent synkinematic cements in many basins and tectonic settings.

For rocks confined to moderate to deep subsurface conditions in sedimentary basins, damaging cements in large opening-mode fractures mostly postdate fracture opening. Sources of elements for these cements are probably mainly derived from outside units in which they are deposited because discordant chemistry of some late-stage fracture-filling minerals implies cross-formational flow and possibly long-distance transport during subsequent diagenesis (Milliken, 2002). The largely postkinematic character of these cements suggests that fluid-transport-limited processes operated after fractures formed under conditions where loading and pore-fluid pressure conditions do not promote fracture growth. Heterogeneous cement patterns could reflect a spectrum of flow pathways, including changing hydrologic regime (for example, paleowater levels), permeable carrier beds, or flow in or near conduits such as swarms and faults, as well as precipitation localized by detrital composition. Despite occurring in mostly low volumes, these hitherto largely neglected cements could provide important clues to spatial distributions of preserved fracture porosity.

Competition among processes that create and destroy fracture porosity governs how fracture permeability changes with time. Durations of cement-precipitation episodes and the extent to which they are punctuated on scales of tens of millions of years (or less) or are more gradual remain a matter of debate. Information from fractures may help resolve that debate.

CONCLUSIONS

This paper has emphasized a practical tool for exploration or development geologists or engineers. A simple combination of easily made structural and diagenetic observations permits rapid prediction of whether fractures are open or sealed and how capable large fractures are of transmitting fluid, even when large fractures have not been sampled. The surrogate accurately predicted open and sealed fractures. Production responses by wells having differing degrees of fracture damage suggest that fractures identified by surrogates as sealed do have a detrimental effect on fluid flow and those identified as open are flow conduits.

The ability to use widely available and relatively inexpensive rock samples makes this approach practical. The essential step is discerning postkinematic cements because where they are prevalent, flow in fracture systems is impeded. Fractures that require a microscope to detect are far more common than large fractures and thus more readily sampled, and these can provide requisite fracture timing information. However, because of their propensity to seal soon after they form, microfractures must be used in conjunction with cement data derived from the rock mass. Once identified, postkinematic cement is quantified by conventional petrographic methods. Rare, large fractures can confirm inferences, increasing confidence of extrapolations to areas where only cement samples are available. Unconventional use of widely available data thus provides surrogates for evaluation of fractures, without the need to observe the fractures themselves. This surrogate predicts degree of porosity retention or closure of fractures above a specified size, defined as the emergent threshold. A convenient measure of postkinematic-cement incidence is the ratio of late cement to the space available for late-cement precipitation in the rock's mass, a ratio called the degradation index, because it measures damage to fractures as flow conduits.

Because inferences are based on site-specific observations of diagenesis and structure, the approach described herein can be used in subsurface studies without unraveling mechanical or geochemical interactions. This study does underline how important it is to understand these linked processes to improve predictions ahead of the bit.

Petroleum resources in fractured and diagenetically altered rocks are a growing target of the United States and world exploration and development. For these plays, great uncertainty stems from heterogeneous, unpredictable, and difficult-to-diagnose fracture systems that govern fluid flow. Site-specific fracture information is essential. Locating depth intervals having fractures that might contribute to fluid flow using surrogates can help our measurement of exploration risk and guide our development planning. Damaging postkinematic cements, frequently heterogeneous on a range of scales, cannot be delineated effectively using fracture observations alone. Surrogates therefore have practical value for production-fairway mapping and other applications in which identifying open fractures is essential. Results of this study can be usefully incorporated in reservoir characterization procedures anywhere fractures may contribute to production.

APPENDIX: DATA SET

Samples are from exposures to deep cores (>21,000 ft [6401 m]) in oil and gas reservoirs. Most are from depths of 6000–14,000 ft (1829–4267 m) in 21 siliciclastic formations, 4 dolomite, and 2 limestone units, where evidence of emergent threshold, syn- and postkinematic cement, bridges, and fractures sealed with postkinematic cement was observed. Cores are mostly from North and South America. In North America, data are from major producing regions, including Appalachian, Black Warrior, and Gulf Coast basins, west Texas, and the Rocky Mountain thrust belt and foreland basins. Oil and gas reservoirs are about equally represented. Most cores are from vertical wells, but there are 12 slant or horizontal cores. In the core, more than 1000 fractures and associated rock properties were examined. Measured apertures in core and outcrop range from approximately 0.0001 mm to more than 1 m (Marrett et al., 1999; Ortega et al., 2001). Lengths are typically greater than heights because fractures are confined to layers that reflect mechanical stratigraphy. Sets have preferred orientation, as well as crosscutting and abutting relations.

Rocks have mostly low to moderate porosity (0–20%) and either are deeply buried (>2 km) or have been so in the past. Sandstones range from litharenites to quartzarenites, and depositional settings range from fluvial/deltaic to deep water. Dolomites, mostly Paleozoic or Cretaceous from platform settings, have extensive authigenic dolomite and variable porosity. A spectrum of burial histories is represented, but rocks not experiencing deep burial are mostly Paleozoic. Deep or protracted burial promotes cementation, and cement volumes are typically high (>15%). More than half are from foreland basins, with the rest from passive margins and platforms or cratons or from within fold-thrust belts. Forelands include both recent, active basins (Venezuela, Colombia, Bolivia) and older, inactive foreland basins (Appalachians, west Texas, Rocky Mountains).

Envelopes on fractures made of narrow zones of disseminated cement are absent. This situation contrasts with that of some faults, which may localize a fluid environment, as well as fractures in impervious rocks such as granites, in which cement phases are localized in or near interconnected fracture systems. Moreover, although differing widely in burial history, most fracture arrays are in rocks buried to >1000-m depths, where they have remained. Consequently, rocks having exposure to recent near-surface loading and fluid conditions are underrepresented. In such rocks under cool, near-surface conditions, cements may not precipitate and fractures can remain barren (e.g., joints), undergo dissolution, or they may be filled only much later as rock and fractures undergo burial or near-surface cementation. Cement dissolution in fractures, although important in some systems, is rare or has been obscured by overprinting cements in most fractures surveyed here.

Samples are mostly from areas distant from fold hinges or faults. In folds, where sufficient evidence is available, fractures largely or entirely predate folding (Laubach and Lorenz, 1992; Olson et al., 1998; Marrett and Laubach, 2001). Although these fracture arrays are probably responses to burial and tectonic loading and pore-pressure changes, as is typical, it is impossible to uniquely specify loading paths to fracture growth. Although Paleozoic rocks are represented, many are Cretaceous and may have experienced fracture in Late Cretaceous to Holocene times. This diversity of compositions, burial histories, and settings results in differences in diagenesis and fracture history, yet patterns persist across this spectrum of geology.

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