A1

High-Angle Extension Fractures

A1a Introduction

High-angle fractures (Figures A1a.1, A1a.2) are vertical or near-vertical, and are the most common type of fracture in simple and even in some complex structural settings. Many geologists and most modelers consciously or unconsciously default to extension fractures as an assumed universal fracture type.

Figure A1a.1 High-angle extension fractures may be present in a vertical core for many feet along the core axis if the core cuts through a homogeneous lithology, and if there was enough strain energy during fracturing to create large fractures. This fracture is mineralized with calcite but the core has split along the fracture, indicating that the mineralization is weak. The calcite mineralization is white but it is obscured by drilling mud that has invaded the incompletely mineralized fracture. The core is cradled in half of the aluminum core barrel liner, which has been split lengthwise with a saw in order to remove the core from the liner. Full-diameter/unslabbed 5¼ inch vertical core, fine-grained sandstone. Uphole is towards the top of the photograph.

Figure A1a.2 Many high-angle extension fractures are relatively small and obscure, especially as exposed on the rough outer surface of a core. This calcite-mineralized fracture, highlighted by dashed lines drawn parallel to the fracture trace with a silver marker, is largely intact, indicating relatively tight mineralization. The mineralized fracture face is broken open and exposed at the thumb. The fracture is planar, but its subtle trace on the core surface appears to be irregular due to the rough core surface. The fracture has a relatively uniform width but narrows and pinches out abruptly at the top and bottom where it terminates against less calcareous layers. This fracture would have been missed if the core surface had not been cleaned while logging. Full-diameter/unslabbed four-inch vertical core, calcareous shale. Uphole is towards the top of the photo.

Atlas of Natural and Induced Fractures in Core, First Edition. John C. Lorenz and Scott P. Cooper.

Extension fractures form as sets of parallel planes and are typically strata-bound. Therefore, assuming that fluid will flow more readily through the fractures than through the matrix (not always the case), a single set of extension fractures can significantly enhance the system permeability of a reservoir, but only in the horizontal plane and only in one direction. In order to fully assess the effects of fractures on reservoir permeability, however, the detailed fracture characteristics including fracture heights, terminations, spacings, strikes, distributions with respect to lithology, width, and mineralization as it affects fracture aperture must be assessed.

Extension fracture permeability can be dynamic since fracture apertures can close as fluid pressure within the apertures is preferentially reduced over matrix pressures during reservoir production. This effect is more prominent for narrow fractures where small amounts of closure constitute a significant percentage of the fracture aperture. Fracture characterization is especially important where two or more sets of oblique-striking extension fractures are present in a reservoir since one set may be less mineralized or more optimally oriented relative to the in situ stresses, and therefore more permeable than the other(s) even if it is less well developed.

A1b Fractography of High-Angle Extension Fractures

The process of fracturing commonly creates distinct low-relief patterns or "fractography" on a fracture face, and different fractographic patterns are diagnostic of an origin in shear vs. extension. The fractography of fractures has been described since the early days of geology, but it was only with the development of materials science and studies of the breakage patterns in ceramics and glass in the laboratory that the significance of these surface markings began to be understood.

Extension fracture surfaces are commonly decorated by plumes, arrest lines, and twist hackles (Figures A1b.1–A1b.3). As the name implies, plume or plumose structure is a subtle feather-like pattern that ideally has an axis like the shaft of a feather, with low-relief branches radiating away from the axis. Some plume structures, however, are less symmetric and wander less definitively across the fracture face. In core, many plumes are less than symmetric because the core has sampled only a small part of the fracture face and a small section of the plume pattern.

Plumes are usually inferred to indicate rapid fracture propagation. Plume axes record the direction of fracture propagation and can sometimes be traced back to the point of origin of the fracture, commonly a fossil, clast, or other heterogeneity that acted to concentrate stress and initiate fracturing. In some formations plumes originate at bedding contacts, in other formations the plumes originate at inhomogeneities within beds.

Arcuate arrest lines form ridges oriented normal to the branches of the feather structure, and record interruptions in the propagation of a fracture as well as the location of the fracture tip at the time the fracture growth was interrupted (e.g., Kulander et al., 1990).

Extension fracture edges may be marked by twist hackle, commonly interpreted to indicate a change in stress conditions near the contact of the host rock with another layer, where the change in mechanical properties altered the in situ stress conditions slightly. The propagating fracture plane changed strike, splitting into segments to do so. The en echelon pattern of twist hackle exposed in a 2D plane normal to the fracture can resemble the en echelon veins and steps common to some shear fractures, and care must be taken not to infer shear from an en echelon geometry alone.

The axis of a plume structure is usually considered to have been controlled by the maximum compressive stress at the time of fracturing. However, if the fracture

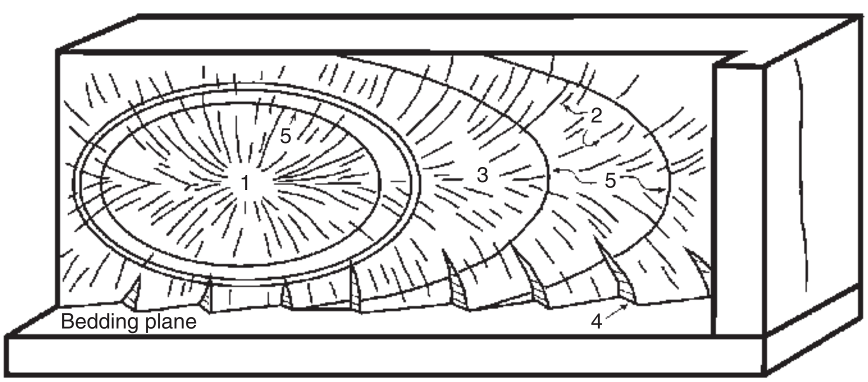

Figure A1b.1 Diagram of the ideal fractography of an extension fracture. Adapted from Kulander et al. (1990). 1 = Origin, 2 = Branches of the feather texture, 3 = Plume axis, 4 = Twist hackle, 5 = Arrest lines. Four-inch diameter core samples a relatively small segment of the fracture plane and must be examined carefully in order to recognize these elements.

Figure A1b.2 A strata-bound fracture decorated with a faint plume structure that propagated from left to right, and that broke into twist hackle in the altered stress areas near the upper and lower bedding contacts.

Figure A1b.3 Extension fracture in a sandstone showing an origin near the end of the hammer handle, possibly at the cross fracture, and an initial circular shape where the fracture radius was less than the thickness of the host bed. The fracture subsequently propagated incrementally, both left and right, pausing long enough in several places to create arcuate arrest lines. The plume pattern is normal to the arrest lines.

develops in horizontally layered strata, the axis of a strata-bound fracture commonly turns to follow horizontal bedding as the fracture grows, even if the maximum stress is vertical.

Plumes indicate extension, but not all extension fractures display plume structures. Plumes are most common in fine-grained and well-cemented rock, and they are rarer in coarse-grained rocks where the grain size exceeds the topographic relief of the plume. Plumes may not have formed where fractures propagated slowly, they are easily obscured by fracture-face mineralization, and they are often removed by fracture-face dissolution and by recrystallization during diagenesis, especially in limestones.

The small size of a fracture sample provided by a core can make it difficult to recognize extension fractures in the absence of plumes. Extension fractures can often be recognized by a lack of offset parallel to the fracture walls, easiest to determine where the fractured strata are finely bedded, but the possibility that offset was strike-slip, parallel to bedding, must also be considered where offset bedding is not obvious. Moreover, the magnitude of offset along shear fractures can be minimal, millimeter in scale, so care should be taken when examining core for offset.

A1b1 Plume Structure

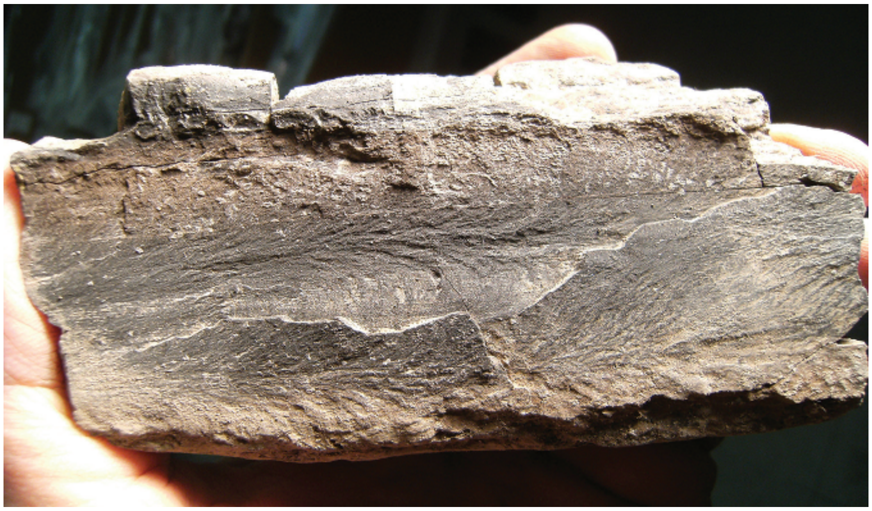

Figure A1b1.1 Plumes with horizontal axes, recording left-to-right propagation, decorate the faces of several small strata-bound, closely spaced, unmineralized extension fractures. Rough surfaces at the top and bottom of the fracture indicate the contact with the unfractured over- and underlying beds. Vertical four-inch diameter core from siltstone, uphole is towards the top of the photo.

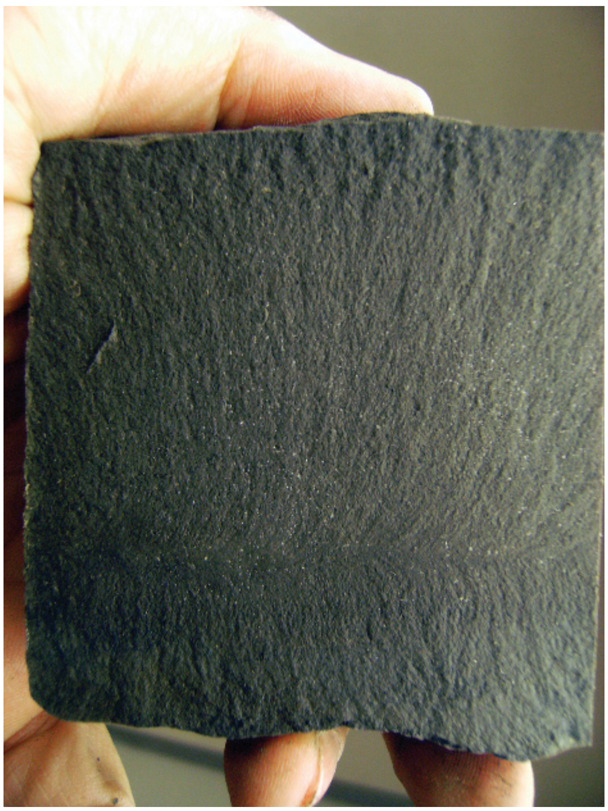

Figure A1b1.2 Plume structure on the face of a vertical, bed-normal extension fracture in shale. The plume axis is horizontal, about a quarter of the way up from the bottom edge of the core, and indicates that the fracture propagated parallel to bedding, from left to right. The plume and fracture extend the full height of a calcareous bed in a cored shale. The upper and lower contacts of the bed, and the edge of the fracture, are indicated by increasing roughness of the fracture surface near the top and bottom of the photo, probably a minor form of twist hackle. Vertical four-inch diameter core, uphole is towards the top of the photo.

Figure A1b1.3 A large-scale plume records the propagation of this fracture face from right to left across the core, which was cut from a non-calcareous shale. The plume is without a well-defined axis but propagated upward and to the left in the upper half of the cored fracture, and downward and to the left in the lower half. The fracture is lightly mineralized with calcite but the plume relief is greater than the thickness of the layer of calcite and the ornamentation is apparent through the mineralization. Vertical four-inch diameter core, uphole is towards the top of the photo.

Figure A1b1.4 This core captured part of a plume that was much larger than the core. The fracture is mineralized with a light layer of calcite. Remnants of drilling mud (tan) stain the fracture face. Vertical four-inch diameter core, uphole is towards the top of the photo.

Figure A1b1.5 A subtle plume propagated horizontally from right to left across this fracture face. The strata-bound fracture, in a non-calcareous siltstone, is covered by a layer of diagenetic clay half a millimeter thick. The impression of the plume from the missing half of the fracture is preserved on the surface of the clay. Vertical four-inch diameter core, uphole is towards the top of the photo. The stump of an unsuccessfully recovered one-inch diameter porosity/permeability plug remains in the hole cut into the core.

Figure A1b1.6 Opposing faces of an extension fracture in limestone show mirror images of the plume structure on the two surfaces. The fracture grew horizontally in this rock. The narrow fracture is lightly mineralized with calcite on both faces. Vertical four-inch diameter core, uphole is towards the top of the photo.

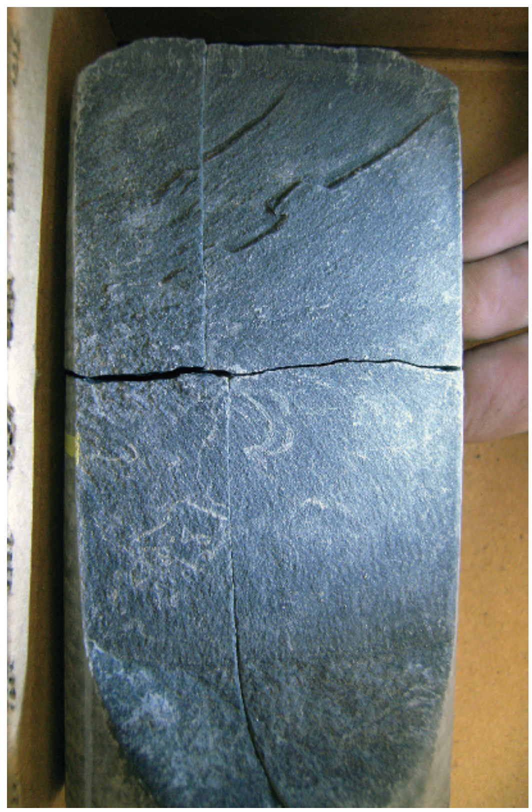

Figure A1b1.7 A plume with a horizontal axis, highlighted by oblique lighting, records the propagation of an extension fracture from left to right in a fine-grained limestone interbedded in a shale sequence. The top edge of the fracture is marked by minor twist hackle where it approaches a shale layer. The bottom edge of the natural fracture terminates at another bedding plane but without twisting. The fracture plane was extended downward along the rougher curved surface during core processing, exiting the core towards the viewer. The vertical line in the fracture face is the slabbing saw cut. Vertical three-inch diameter core, uphole is towards the top of the photo.

Figure A1b1.8 A wandering plume structure on the face of an extension fracture propagated upward, oblique to the core axis in a limestone. Plume axes parallel to the core axis suggest coring-induced fractures, but this fracture is natural as suggested by the upward vs downward growth of the plume and its asymmetry relative to the core axis. The fracture terminates at the top at a shalier unit. Vertical four-inch diameter core, uphole is towards the top of the photo.

A1b2 Twist Hackle

Figure A1b2.1 Definitive twist hackle growing out of a poorly defined left-to-right plume structure, marking the changed mechanical properties and stress conditions near the bedding contact and the upper edge of the fracture. Vertical three-inch diameter core, uphole is towards the top of the photo.

Figure A1b2.2 Two short, parallel, laterally offset, strata-bound extension fractures in a strongly bedded siliceous shale. A subtle plume structure marks the lower fracture but none is evident on the upper fracture. The upper fracture, however, is marked by well-developed, low-relief twist hackle along both the upper and lower edges. Vertical three-inch diameter core, uphole is towards the top of the photo.

Figure A1b2.3 A fracture plane in a siltstone, without an obvious plume, twisting in the upper half of the core into hackles where the homogeneous rock changes to bedded rock. The twist hackles suggest different mechanical properties and slightly oblique stress regimes in the two zones. Vertical four-inch diameter core, uphole is towards the top of the photo.

Figure A1b2.4 Opposing faces of a vertical extension fracture in oil-stained sandstone that show twist hackle transitioning upward into a more planar extension fracture. The fracture face is not marked by plume structure since the sandstone is poorly cemented and not mechanically prone to the formation of plumes. Vertical three-inch diameter core, uphole is towards the top of the photo.

A1b3 Arrest Lines

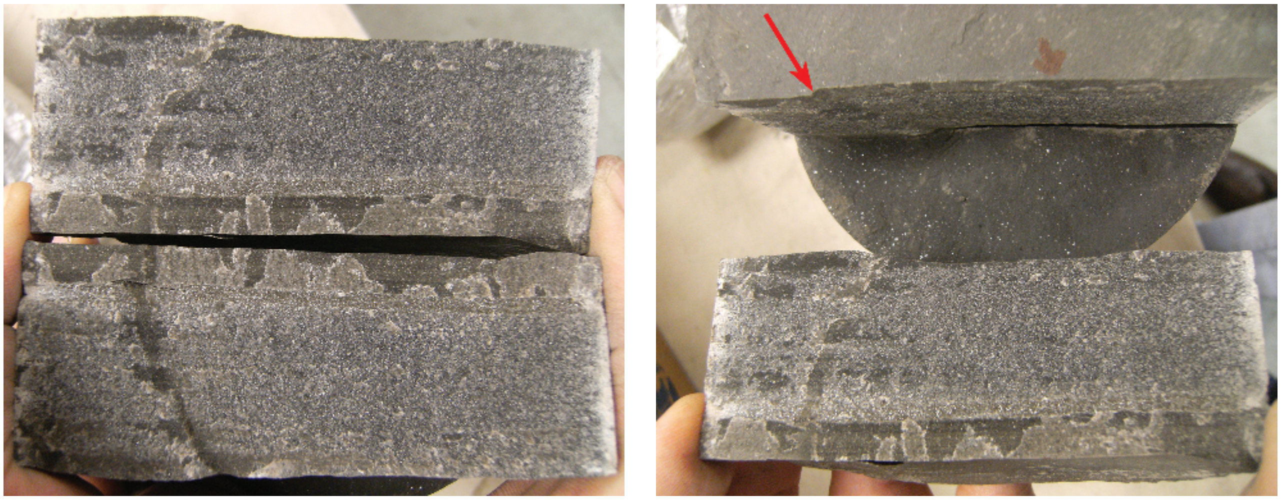

Figure A1b3.1 Two views of an arrest line on a calcite-mineralized fracture face in shale. The left photo shows the opposing, calcite-mineralized faces of an extension fracture (opened in butterfly fashion along a horizontal axis) to show the arcuate rib of the arrest line. Note the complimentary patterns of mineralization on the two faces, adhering to one or the other face but not both. The right photo shows one face of this fracture plane edge-on, looking downhole to highlight the low-amplitude relief in the fracture face at the rib (*red arrow*), with the opposing face turned parallel to the plane of the photo. Vertical four-inch diameter core, uphole is towards the top of the left photo, and facing the viewer in the right photo.

Figure A1b3.2 Two views of a calcite-mineralized composite extension fracture in shale. The arcuate edge of the original fracture cuts approximately down the middle of the core, separating the planar surface of the original fracture (to the right in both photos) from the twist hackle surface marking a later extension of the fracture. Drilling mud obscures the fracture face. Twist hackles and the change in strike indicate a changed stress regime at the time of fracture extension. Vertical four-inch diameter core, uphole is towards the top of both photos.

A1c Extension Fracture Dimensions

Height, width, length, and spacing are some of the more important fracture parameters for estimating and modeling the influence of fracture permeability on a reservoir.

Fracture *widths* can be measured in intact cores and even if the core has broken open along a fracture, its width can at least be estimated. One train of thought suggests that fracture widths in core are inaccurate due to the expansion of a core after it has been cut from the rock and released from the in situ confining stresses. However, anelastic strain recovery techniques, developed to measure stress-release expansion in order to calculate in situ stresses (e.g., Teufel, 1983; Warpinski et al., 1993), suggest that lateral core expansion, and thus associated changes in fracture widths in intact core, are of the order of a few hundreds of microstrains (a few hundred parts per million) and are negligible. In fact, the thermal *contraction* of a core as it cools from reservoir to surface temperatures commonly has a greater effect on core diameter.

The *spacings* of high-angle fractures can sometimes be estimated from vertical cores, (e.g., Narr, 1996) but spacing is more reliably assessed in core from deviated wells where actual spacings can often be measured.

Measurements of the *heights* of high-angle extension fractures can be problematic in any core; full fracture height will be captured by vertical cores only if the fracture plane is parallel to the core axis, and will be almost impossible to assess from horizontal cores where the maximum measurable heights are limited by the core diameter.

Similarly, it is virtually impossible to obtain fracture *lengths* from the one-dimensional data acquired from either vertical or horizontal wells. Lateral fracture edges are occasionally captured by cores, but useful data on fracture lengths are best gathered from outcrops.

Extension fracture heights, lengths, and spacings are illustrated in this section of the atlas, along with vertical and lateral fracture terminations. Effective fracture widths are strongly influenced by mineralization and so they are addressed in the Mineralization section. Fracture strikes are also important and some are illustrated here, but strikes are addressed more completely later in the volume.

Where a robust set of core measurements for extension fracture dimensions can be obtained, the data for heights, widths, and spacings (and in outcrop, the fracture lengths) typically have lognormal distributions with a wide range of values. It is probably inaccurate to use single values for any of these dimensions as inputs for fracture models. The lognormal distributions include numerous short ("short" in terms of both height and length), narrow, and closely spaced fractures, with increasingly fewer taller, longer, wider, and more widely spaced fractures.

Similar parameters for shear fractures measured in cores are typically more irregularly distributed since cores capture such a small sampling of these less predictable fracture systems.

A1c1 Extension Fracture Heights and Vertical Terminations

Extension fracture height measurements are commonly limited by bedding, being controlled as much by the sedimentology of a formation, i.e., the differences in the mechanical properties of adjacent beds, as by the stresses that caused fracturing. Another consideration for height measurements is that for many taller fractures, the measured heights are commonly only minima since only part of a fracture height can be measured if it is inclined relative to the core axis and exits the side of the core before terminating (Figure A1c1.1). Taller fractures, whether extension or shear fractures, commonly exit the side of a core before terminating: if a core is four inches in diameter and contains a four foot tall fracture that is inclined 5° to the core axis, the fracture may exit the core top and bottom on opposite sides of the core. Measurable height is a minimum even if one of the two vertical fracture terminations is present in the core. Nevertheless, a core-based fracture-height data set (Figures A1c1.2, A1c1.3) is still useful as representative of the lower end of the range of fracture heights in a system, and even truncated data sets provide at least minimum values that can be used to estimate the true range of fracture heights.

It is also useful to log the thickness of the bed that hosts fractures and the location and nature of the fracture terminations in order to describe the effect of fractures on vertical system permeability. Cross-plots typically show a strong correlation between extension fracture heights and bed thickness where fracture height is controlled by mechanical stratigraphy. In contrast, extension fractures may cut indiscriminately across bedding where formations have a low degree of mechanical contrast across bedding. In these formations one should log both the locations of fracture terminations and the number and types of beds crossed by fractures.

Vertical fracture terminations, top and bottom, can usually be assigned to a few generalized categories including the following:

Known Terminations

- Termination at a lithologic, geomechanical boundary, suggesting a difference in the strain response of the two lithologies. Fracture terminations at boundaries may be abrupt, tapering, or splayed, but they suggest

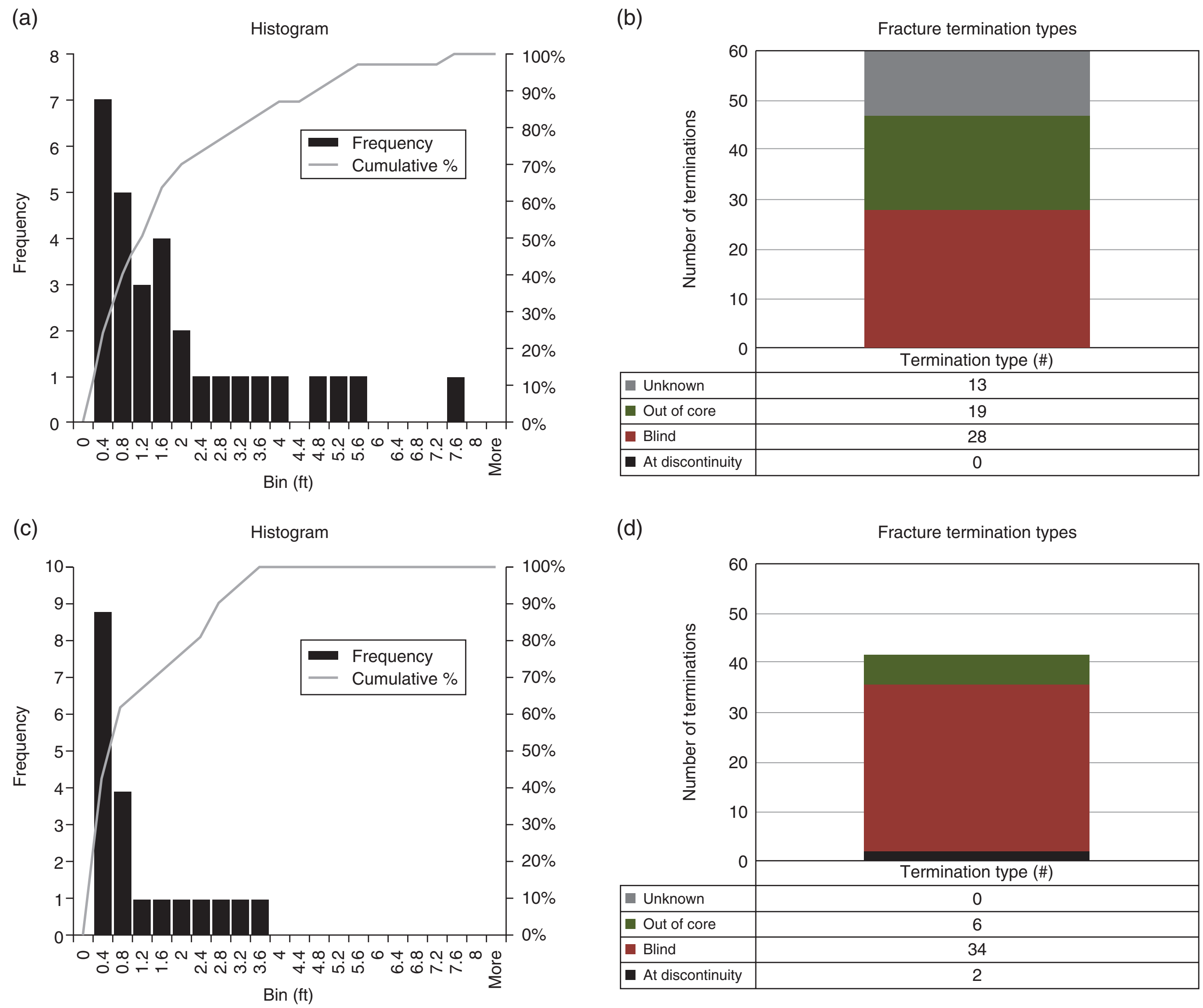

Figure A1c1.1 Histograms of the distributions of high-angle extension fracture heights and their terminations in cores from two vertical wells in the same poorly bedded marine shale formation. Top: fracture heights range from 0.1 to 7.60 ft, averaging 1.85 ft (n = 30 fractures with 60 terminations). Bottom: fracture heights range from 0.1 to 3.3 ft, averaging 1.12 ft (n = 21 fractures with 42 terminations). Most of these fractures terminate blindly within homogeneous rock, few terminate at bedding planes.

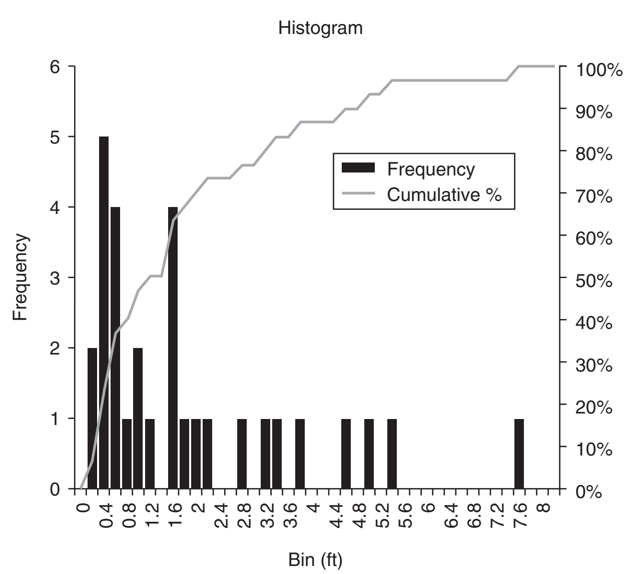

Figure A1c1.2 Height distribution of the same high-angle extension fracture data set used in Figure A1c1.1 upper left, but plotted here with 0.2 ft height bins rather than 0.4 ft bins. Height distributions that fall off abruptly to the left, with fewer smaller fractures, can be hidden if a relatively large bin size is chosen for the plot or if the data set is small. Fracture heights range from 0.1 to 7.60 ft, averaging 1.85 ft (n = 30 fractures).

Figure A1c1.3 Two overlapping, narrow, calcite-mineralized, high-angle extension fractures with dips parallel to the core axis so that the full heights can be measured and logged. Vertical four-inch sandstone core, uphole is towards the top of the photo.

that the unstimulated fracture-controlled vertical permeability may also be vertically limited.

- Termination at a stylolite, where the fracture formed after the stylolite which acted as a mechanical boundary to arrest fracture propagation. Alternatively, postfracturing stylolite-related dissolution may have shortened the fracture.
- Blind terminations within an apparently homogeneous lithology, indicating that the strain at the time of fracturing was insufficient to propagate the fracture to a bedding contact.

Figure A1c1.4 Even thin shale layers can provide enough mechanical contrast to arrest the propagation of extension fractures, suggesting that the energy required to form this type of fracture is relatively low. Vertical four-inch diameter limestone core, uphole is towards the top of the photo.

Unknown Terminations

- Out of core, i.e., the fracture exits the side of a core or sometimes out the very top or bottom of a core before terminating.
- Unknown, which includes fracture terminations that cannot be pinpointed but that probably occur within missing core pieces or within rubble zones.

Vertical extension fractures commonly terminate against an adjacent, more ductile lithology (Figures A1c1.4–A1c1.8), where strain that was accommodated in brittle fashion in the fractured layer was accommodated by ductal flow in the non-fractured layer. This type of termination is one of the common although not universally applicable criteria for identifying extension fractures.

Extension fractures may also terminate blindly within an apparently homogeneous lithology (Figures A1c1.9, A1c1.10). In these cases, the stress that was driving fracture propagation was insufficient to extend the fracture to the bed boundary.

Extension fractures also commonly terminate at stylolites. It is not always obvious whether the stylolite predates fracturing and provided a mechanical contrast against which the fracture terminated, or whether

Figure A1c1.5 Mechanical properties can change over geologic time due to diagenesis and changes in pore pressures. Some clay-rich lithologies that are presently relatively ductile were, under different conditions, the more fracture-prone strata in a heterogeneous sequence. In this example, a calcite-mineralized vertical extension fracture in a shale tapers towards its termination against a limestone layer. At the time of fracturing, the shale was more susceptible to fracturing than the limestone. Slab from a vertical three-inch diameter core, uphole is towards the top of the photo.

Figure A1c1.6 A near-vertical, calcite-mineralized fracture exits the core downward before reaching its termination, and terminates upward, with twist hackle, against a lithologic boundary. The upward decrease in the thickness of the calcite mineralization corresponds to a narrowing of the fracture. Vertical four-inch diameter limestone core, uphole is towards the top of the photo.

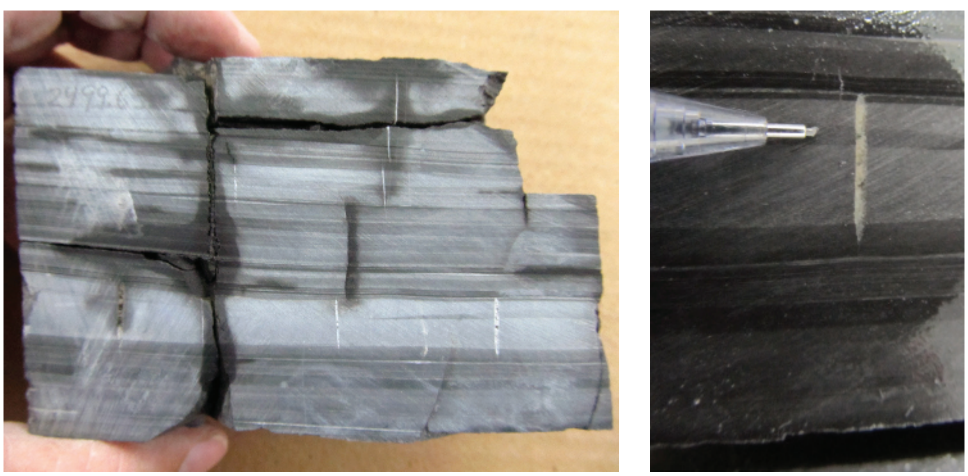

Figure A1c1.7 Short, calcite-mineralized, strata-bound fractures that are confined to brittle limestone layers and that terminate abruptly against the interbedded ductile shales. Slab from a vertical four-inch diameter core, uphole is towards the top of both photos.

Figure A1c1.8 A strata-bound, calcite-cemented vertical extension fracture in a gray dolomite terminates abruptly, without tapering, at a contact with an adjacent limestone. Vertical four-inch diameter core, uphole is towards the top of the photo.

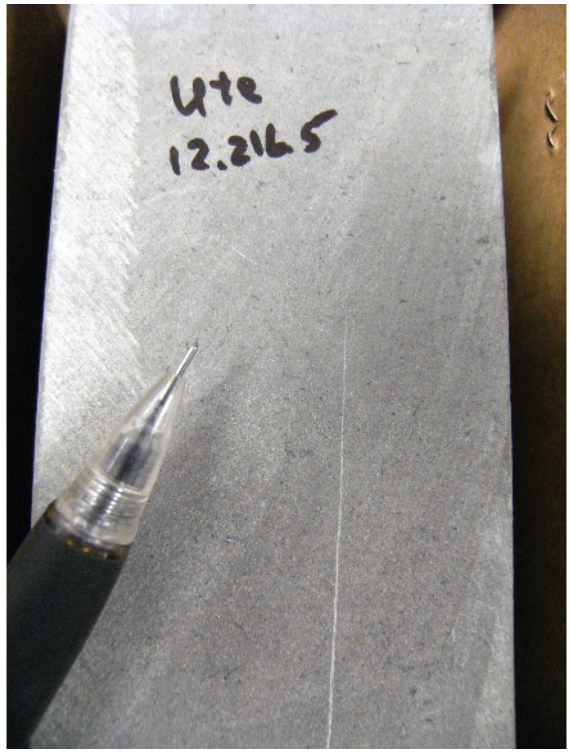

Figure A1c1.9 Some lithologic changes are gradual, as in this upward transition from fine-grained sandstone to siltstone. The gradual narrowing and termination of this calcite-mineralized, high-angle extension fracture reflect this gradual change in lithology. Slab from a vertical four-inch diameter core, uphole is towards the top of the photo.

Figure A1c1.10 An irregular high-angle extension fracture that terminates blindly, i.e., for no mechanical reason, in a relatively homogeneous, cross-bedded, anhydrite-cemented, eolian sandstone. Vertical, 2.5-inch diameter core, uphole is towards the top of the photo.

fracturing was first and the fractures were truncated as the rock dissolved along the stylolite.

Other fractures exit the sides of a core before terminating (Figures A1c1.11–A1c1.13), sampling only a fraction of the total fracture height.

Some extension fractures terminate blindly but overlap with similar, parallel fracture segments (Figures A1c1.14–A1c1.17). In some examples the overlapping fracture tips hook towards each other, suggesting that two fractures propagated towards each other in nearly the same plane. Other fracture pairs show no such interaction, and some are in fact segments of the same fracture, joining together into a single plane in the third dimension. Given the limited volume of a core sample, it can be unclear whether such fracture segments form a single permeability conduit or whether they are separate fractures and the fracture-controlled permeability is discontinuous. If they are single conduits, the en echelon segments should be measured as a single fracture height.

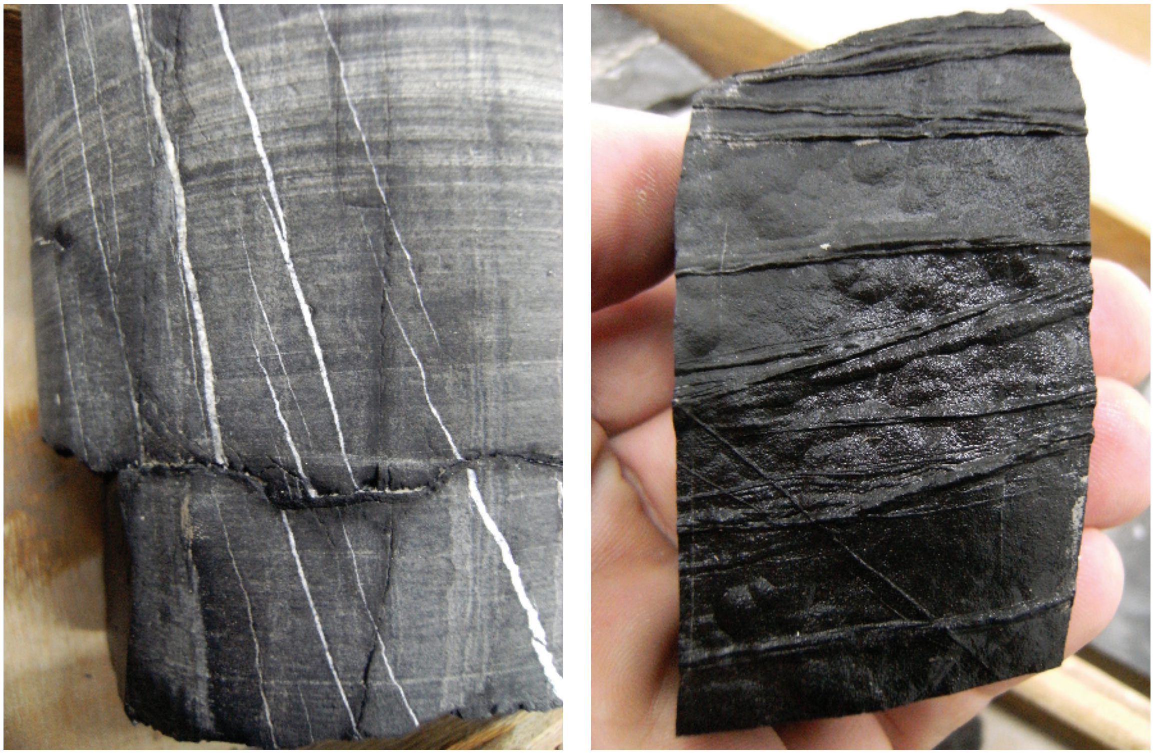

Figure A1c1.11 Left: high-angle, calcite-mineralized extension fractures in limestone terminate at the insoluble clay residue along an irregular, stylolitized shale parting. Right: plan view of a stylolitized shale bedding plane in the same core, showing muddy ridges that project into the dissolved ends of the fractures where they terminate against the shale parting, suggesting that dissolution/stylolite formation postdated fracturing. Fracture-filling calcite is commonly more soluble than a host limestone, and clays along the parting conformed to linear dissolution embayments along the fractures. Vertical four-inch diameter core, uphole is towards the top of the left photo, and away from the viewer in the right photo.

Figure A1c1.12 Full fracture height cannot be measured where the fracture exits the core top or bottom before terminating. In the example on the left, the location and type of termination at the base of a calcite-mineralized extension fracture are unknown since the fracture exits the side of the core downward (the fracture is highlighted by the dashed line marked on the core surface beside the fracture trace). In the right photo it is the upper termination that is unknown. Even though truncated, minimum heights can and should be measured. Vertical, four-inch diameter limestone (left) and shale (right) cores; uphole is toward the tops of both photos. The core on the left was also oriented relative to north, as indicated by the scribe groove immediately to the left of the black line. The red–black line pair in this photo is the most common convention for marking the in situ up orientation of a core, with "red on the right looking uphole."

Figure A1c1.13 One face of a high-angle extension fracture skims the edge of this core. A small but important data set can be recorded from this example, including parameters such as the presence of fracturing, a minimum fracture height and width, and the fact that the fracture is mineralized with calcite but that the mineralization is weaker than the host rock. Fracture strike might also be addressed if this fracture plane can be related to the strike of other induced or natural fractures. Vertical, four-inch diameter limestone core; uphole, as marked by both the red–black line pair and the uphole arrows, is towards the top of the photo.

Figure A1c1.15 En echelon segments that hook towards each other suggest separate fractures that propagated towards each other. When traced across the end of the core, these two fractures consist of separate, parallel planes. Vertical, three-inch diameter shale core; uphole is towards the top of the photo.

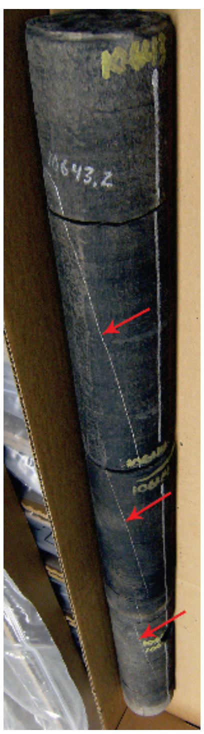

Figure A1c1.14 Three en echelon extension fractures in a calcareous shale. Limited vertical fracture-controlled permeability is suggested by fractures that overlap but do not join in the third dimension, at least not within the volume of the core. Vertical, three-inch diameter core; top of the core is towards the top of the photo.

Figure A1c1.16 Some overlapping en echelon offsets occur at mechanical discontinuities such as variations in lithology. Here, the propagation of a fracture in shale was inhibited by thin limestone beds, but equal strain across the formation created a new fracture that propagated in a parallel, offset plane. Slabs of vertical, four-inch core, uphole is towards the top of the photo.

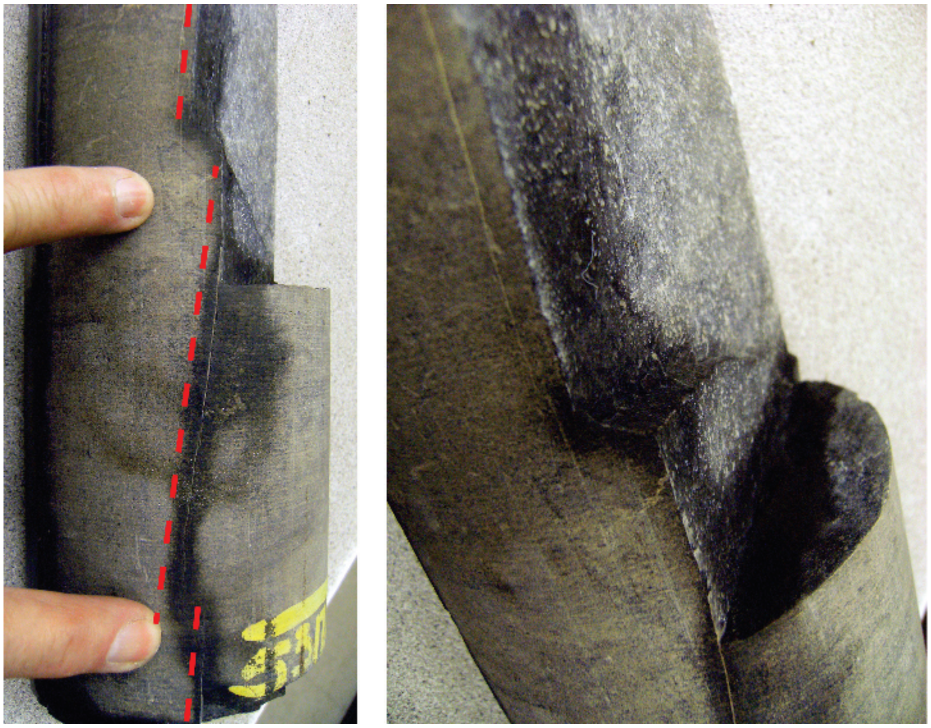

Figure A1c1.17 Two views of an en echelon fracture pattern that is only the surficial expression of a single fracture. Left: the surface of the core shows two offsets (at the fingertips) of a calcite-mineralized, high-angle extension fracture system that might suggest three separate fractures with three measurable heights, and discontinuous vertical fracture-controlled permeability. Right: same fracture system viewed oblique to the fracture face, showing that the fracture planes that appear to be separate on the core surface join in the third dimension. This suggests that the en echelon pattern may be twist hackle at the edge of the larger extension fracture. En echelon patterns can also form in shear, and the full 3D geometry of the fracture should be investigated before making an interpretation. Vertical, four-inch diameter limestone core; top of the core is towards the top of the photos.

A1c2 Extension Fracture Lengths and Lateral Terminations

Except for the smallest fractures (Figures A1c2.1–A1c2.4), horizontal fracture lengths cannot be assessed with vertical core. However, where extension fracture lengths can be measured in outcrop (e.g., Lorenz and Laubach, 1994), they commonly have lognormal distributions similar to other fracture parameters. Unfortunately, the dimensions of outcrops that expose bedding planes and that therefore might be useful for

Figure A1c2.1 Short, limited-length, poorly mineralized, high-angle extension fractures in a shaley limestone. Left: Oil bled from the fractures onto the surface of the core. Right: The fractures are only a few centimeters long and a few centimeters tall. Numerically this zone forms a spike in plots showing fracture frequency by depth, but the fractures are parallel and poorly interconnected. Vertical, four-inch diameter core; uphole is towards the top of the photo on the left, and the view is downhole on the right.

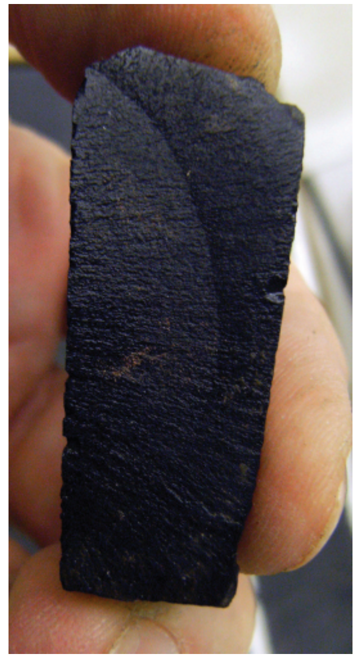

Figure A1c2.2 A circular, calcite-mineralized extension fracture in a poorly bedded shale. The fracture is only about 0.1 mm wide, but its prominent intersection with the slab face inaccurately suggests that it is an important contributor to permeability. It is part of a suite of scattered similar fractures in the shale core, terminating blindly top and bottom rather than at bedding planes. Limited observations suggest that the fractures of this suite are parallel and nearly circular. The photo on the left displays the opposing faces of the fracture, covered with drilling mud. The photo on the right shows one of the fracture faces after the mud has been washed off. It is still wet, obscuring the thin layer of calcite cement. Slabs of four-inch vertical core; uphole is towards the top of both photos.

Figure A1c2.3 Opposing faces of a small, circular, calcite-mineralized, high-angle extension fracture, exposed in butterfly fashion. Secondary induced fracturing has extended the fracture plane beyond the mineralized natural fracture edges, into freshly broken rock (lighter gray areas), along a plane that is slightly oblique to the original mineralized fracture. Four-inch diameter vertical shale core; uphole is towards the top of the photo.

measuring fracture lengths are commonly smaller than fracture lengths. Few outcrops provide large enough areas to capture one or both of the lateral terminations of a significant number of fractures, and there are few published data sets from such pavements. Where fracturing is well developed, the tips of closely spaced extension fractures may overlap and, as they do in vertical exposures, the two fracture segments may merge in the third dimension. Extension fracture lengths may be effectively unlimited where a system of parallel extension fractures

Figure A1c2.4 A calcite-mineralized high-angle extension fracture face in shale. Mineralization, terminating along an arcuate front within the core, defines the lateral limit of the fracture prior to breakage of the core. The thumb is resting on a second, parallel, and slightly offset mineralized fracture plane. The two fracture planes are separated laterally by a slab of rock a few millimeters thick. Vertical three-inch core; uphole is towards the top of the photo.

is well developed, creating elliptical and highly anisotropic reservoir drainage.

High-angle extension fractures that are not strata-bound are commonly circular or slightly oval in shape when viewed normal to the fracture face. However, once their heights reach the mechanical bedding-plane limit, extension fractures grow primarily by extending parallel to bedding and fracture lengths may be significantly larger than fracture heights. Since length is governed by strain whereas height is controlled by bedding thickness, cross-plots show no relationship between the two parameters.

The lateral terminations of extension fractures are occasionally found in outcrops and less frequently in core. Lateral terminations can be recognized by an arcuate fracture front and locally by a limit of mineralization. Sometimes the front separates the natural fracture surface from a rougher, unmineralized, induced fracture that extends outward from the natural fracture. The lateral edges of high-angle extension fractures can also be marked by twist hackle.

A1c3 Extension Fracture Spacings

Lateral fracture spacing is one of the more important yet also one of the more difficult parameters to obtain when trying to assess fracture contributions to reservoir porosity and permeability. As with the length and width, extension fracture spacing populations commonly have lognormal distributions that consist of numerous closely spaced fractures and increasingly smaller populations of wider spacings (Figures A1c3.1–A1c3.2). Vertical core is a poor mechanism for sampling the lateral spacings of high-angle fractures (Figure A1c3.3), but cores can and do commonly capture spacings that are less than the core diameter, indicating that fracture spacing can be quite close. Such spacing measurements typically represent only the low end of a lognormal spacing distribution.

Several examples of closely spaced mineralized extension fractures within a core diameter are illustrated. The available spacing measurements can be treated statistically (e.g., minimum, maximum, and average) but in fact, these statistics may not be representative of the total spacing population since spacings wider than core diameter are not included.

Narr (1996) offered a method for obtaining a number for the lateral spacing of high-angle fractures from vertical core data, with certain constraints. Narr's two deceptively simple formulae for fracture spacing are:

- Spacing = (average aperture × core diameter × ft of fracture-prone core), divided by (the sum of apertures × sum of fracture heights)
- Spacing = (core diameter × ft of fracture-prone core), divided by (the sum of fracture heights).

The required conditions for the application of these formulae are that:

- a single set of parallel fractures is being measured (as in Figures A1c3.4, A1c3.5)
- all fractures are oriented normal to bedding and bedding is oriented normal to the core axis
- fracture height is significantly greater than the core diameter
- a representative sample of the fracture population has been captured by the core
- fracture apertures are consistent

A spacing calculated from these formulae is a single number and does not define the more common range of spacings. Nevertheless, if the conditions are met, Narr's formulae can provide a spacing value where none existed.

If the lateral fracture spacing cannot be calculated from vertical core, spacing estimates fall back on experience in comparing fracture intensities in vertical wells to data from horizontal wells in the same formation (e.g., Lorenz and Hill, 1994). In general, we have found that a formation probably contains enough fractures to significantly affect a reservoir if *any* vertical fractures are captured by 10 ft of vertical core. Conversely, the formation *cannot* be assumed to be unfractured if there are no fractures in the core.

Experience also suggests that 1 foot of cumulative vertical fracture height per 10 feet of vertical four-inch diameter core marks the minimum ratio for a significant fracture intensity in many reservoirs. This proxy for fracture development commonly translates into an average spacing of about 3 feet, but that average occurs within a range of a few inches to a few tens of feet.

Cores from deviated wells (Figures A1c3.6, A1c3.7) do a much better job of sampling the lateral spacing of high-angle fractures, but even those wells must have azimuths that cut across or at least oblique rather than parallel to the fracture strikes in order to acquire a statistically valid sample of the spacing population. Raw fracture spacing measurements along the axis of a horizontal core should be geometrically corrected (the "Terzaghi correction") to get true fracture spacings normal to the fracture planes. If this is not done, closely spaced fractures that strike nearly parallel to the axis of the core may appear to be less well developed than a set of more widely spaced fractures that strike normal to the core axis.

Core from inclined wells can also offer reliable fracture spacing measurements where two or more parallel fractures are present in the same piece of core. Where there are few mechanical bedding discontinuities and the fractures can therefore be extrapolated vertically with a degree of confidence, reasonable spacing measurements can be obtained by measuring the distance between fractures along the core, making it the hypotenuse of a triangle, and then geometrically calculating the distance between the two fractures normal to the fracture planes.

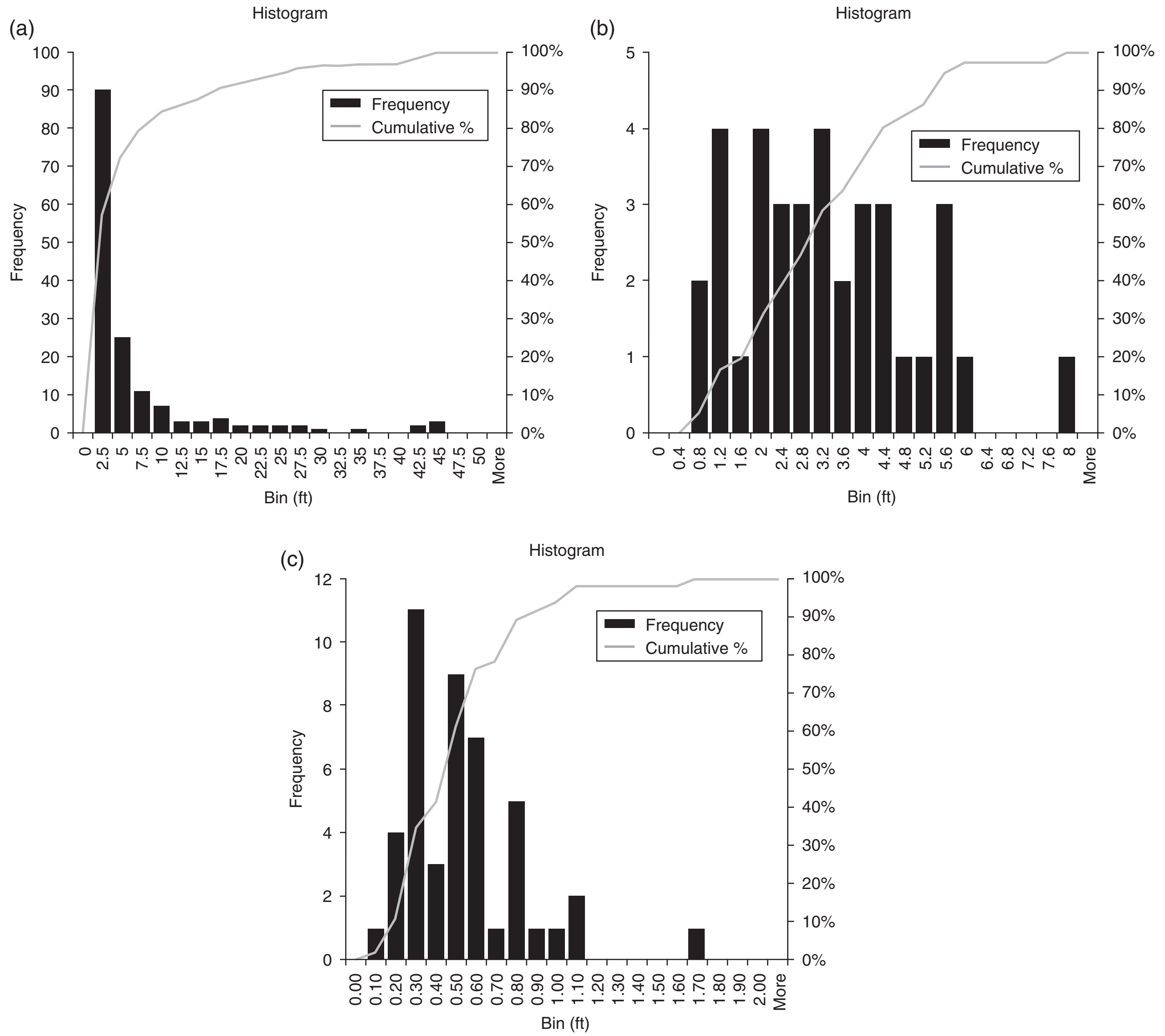

Figure A1c3.1 Histograms of the spacings of high-angle extension fractures in horizontal cores cut from three different formations. Upper left: data from a four-inch core cut from a calcareous, deep marine shale (n = 158). Spacings in this core range from 0.01 to 43.77 ft and average 5.54 ft, histogram bin size 2.5ft. Upper right: data from a four-inch core cut from a deep marine, fine-grained sandstone (n = 36). Spacings range from 0.46 to 7.64 ft, averaging 3.06 ft, histogram bin size 0.4 ft. Bottom: data from a four-inch core cut from a deep marine, clay-rich shale; the plotted fractures are confined to a calcareous, 2.5 inch/6.3 cm thick bed within the shale that was cored parallel to bedding (n = 46). The spacings in this bed range from 0.1 to 1.67 ft and average 0.52 ft, histogram bin size 0.10 ft. The drop-off in frequency to the left that is shown in two of these histograms is common, but can be lost depending on the bin size of the plots.

Figure A1c3.2 Photo showing the spacing patterns for two sets of bed-normal extension fractures on the inclined upper bedding surface (dipping uniformly at about 20° towards the viewer) of a marine sandstone. The fractures extending top to bottom of the photo have a regular distribution whereas the more closely spaced fractures extending across the photo have a lognormal spacing pattern. The fact that there are two distinct spacing patterns in this one sandstone demonstrates that the rule of thumb that spacing is proportional to bed thickness is only useful as a first approximation in the absence of other data; bed thickness is only one of several controls on fracture spacing, and not typically the dominant one.

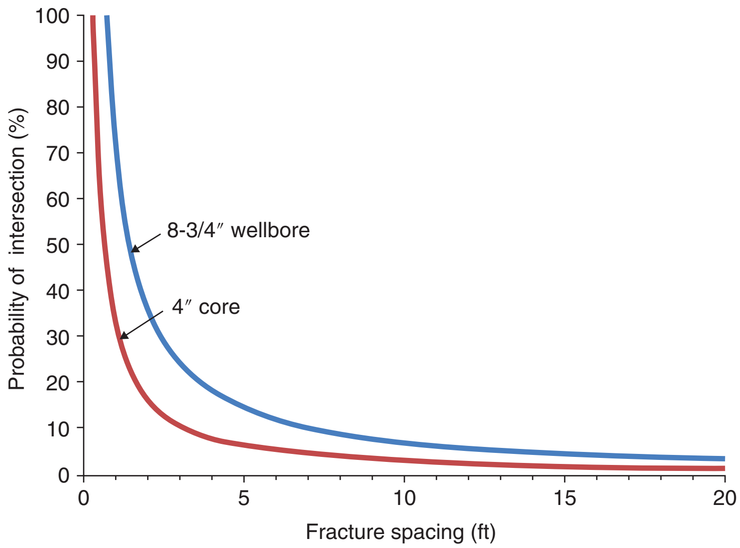

Figure A1c3.3 The probability of intersecting a vertical fracture with a vertical wellbore or a vertical core is low until fractures are closely spaced. A four-inch diameter core has only a 50% chance of capturing a fracture if the fractures have an average eight-inch spacing (from Lorenz, 1992).

Figure A1c3.4 Two views of closely spaced, strata-bound, parallel, unmineralized, high-angle extension fractures. Left: fractures are parallel to the white lines, and are confined to thin siliceous shale beds bounded by thinner clayey shale beds. Right: same piece of core, looking from the top down and showing the two closely spaced fractures in the upper layer of siliceous shale. The presence of this many fractures suggests that despite the small sample size, the core captured a representative population of both spacings and heights, and that the reservoir is intensely fractured. Vertical 3.5-inch core; uphole is towards the top of the photo (left) and towards the viewer (right).

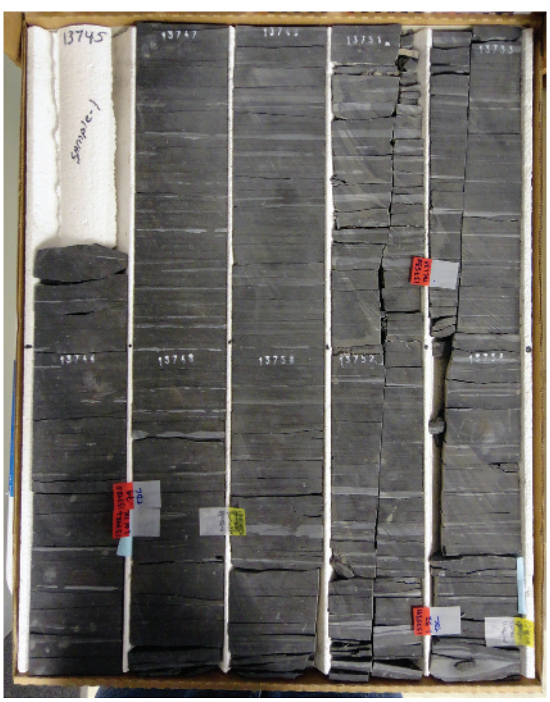

Figure A1c3.5 A near-vertical extension fracture that extends from the base of the middle row of core slabs, through the fourth row, and out of the core in the fifth/last row of slabs on the right. The mineralized fracture is at least four feet (1.3 m) tall and cuts indiscriminately across the poorly developed bedding in this shale formation. A similar fracture is present in the next box of core slabs. The fractures have parallel dip angles and are assumed to have parallel strikes although that cannot be definitively determined since the core cannot be locked together. If they have parallel strikes and extend vertically far enough to overlap, as is probable, then the spacing between them can be calculated using basic geometry, and the two fractures are separated by only 1.4 ft of rock.

Figure A1c3.6 High-angle extension fractures in a near-horizontal core, in a glauconitic limestone near the contact with an underlying shale. Three parallel natural fractures are located at the tips of the blue pencil, the white pen, and the white toothbrush handle (the toothbrush is used for cleaning the core). The flashlight and gray pencil lying parallel to the core were used for stabilizing the core pieces for the photograph. The bed-normal natural fractures are obscured by various saw cuts and induced breaks in the core. If this spacing were typical of the reservoir, a vertical core would have about a 75% chance of capturing one of these three fractures. However, fractures are more widely spaced, of the order of 10 ft, in the middle of the limestone, reducing the probability of fracture intersection to about 3%. Butts of four-inch core; uphole is towards the right of the photo.

Figure A1c3.7 The spacings of high-angle extension fractures can be measured directly in many horizontal cores. The scribe-line groove next to the red line on the core surface indicates that this sandstone core was mechanically oriented relative to stratigraphic up, and the fractures were determined to be vertical, corroborated by their orientation normal to bedding. Bedding planes may be horizontal, but there can still be a 180° ambiguity as to top vs. bottom of the bedding. That ambiguity was resolved for this core with the orientation survey. Fracture spacing normal to the fracture planes, as opposed to their spacings along the core axis, can be measured directly. Note that the "uphole" core orientation line pair has non-standard colors: red is on the right looking uphole as usual, but a white line replaces the more common black line in the pair. In horizontal cores, "uphole" refers to the direction towards the heel of the well and then upward to the surface. Two red–white line pairs were marked on this core so that both the slabs and butts would be marked after slabbing, but there can be confusion if the pairs are drawn too close together. Horizontal four-inch diameter core; uphole is to the left.

A1d Extension Fracture Variations and Lithologic Influences

The ideal extension fracture is planar, with parallel opposing faces and a reasonably uniform width except where it pinches out and terminates. However, the host lithology influences the characteristics of a fracture, and the same stress system that generates planar and systematic fractures in a uniform, fine-grained lithology may form rough and irregular fractures in the interbedded coarse-grained lithologies.

Extension fractures are commonly more intensely developed in the brittle strata in a formation and may even be restricted to those units. For example, sandstones are typically more heavily fractured than interbedded muddy shales, and dolomites are typically more heavily fractured than interbedded limestones. However, this is not a universal relationship; the mechanical properties of a rock are a primary control on fracture intensity, but geologic systems are not static. Mechanical properties change with diagenesis, cementation, compaction, and temperature. Confining stresses and pore pressures change with burial depth, also affecting the mechanical properties of a rock, while fracture development changes with strain magnitude and rate.

The effects of these variables on fracturing can be quantified in laboratory experiments where one or two parameters are changed at a time, but in nature these controlling parameters are poorly constrained. Moreover, in core we are presented merely with the results of several of nature's superimposed experiments. Natural fracturing was controlled by the stress conditions present in the formation and the mechanical properties of the rock at the time of fracturing, not by the present-day stresses and rock properties.

In some sandstone formations, shale partings only a few centimeters thick have arrested the propagation of meter-tall extension fractures. Under other conditions, however, extension fractures, driven by a high in situ stress anisotropy or reacting to low mechanical contrasts in the different layers, crossed bedding boundaries, disregarding the geomechanical differences caused by layering. It is also possible to find well-developed extension fracture systems in thick shale units since elevated pore pressures can change even clay-rich shales, commonly considered to be relatively ductile, into brittle and fracture-prone strata.

Fracturing in a heterogeneous formation may contain entirely different fracture sets in the different layers (Figure A1d.1), all formed under the same stress system, due to varying mechanical properties of the layers (e.g., Lorenz et al., 2002). Elsewhere, unrelated fracture sets have been superimposed on a given layer, reflecting different stress conditions and mechanical properties in the layer at different times in its history. Numerous outcrop examples show multiple, unrelated sets of extension fractures, with different intensities and different strikes, in the same layer. A single layer of coarse-grained sandstone of the Permian Abo sandstone in central New Mexico contains both a set of dip-slip conjugate shear fractures formed under one set of conditions and, striking at right angles to the shear fractures, a set of high-angle extension fractures formed under significantly different conditions.

Many extension fractures are not marked by plume structures. Interpretations of these as extension fractures rely on other features that are common to extension fractures such as terminations at minor bedding contrasts and an absence of evidence for shear.

A1d1 High-Angle Extension Fractures in Limestone

Extension fractures in limestone are as variable as the lithologies that fall into the category of "limestone." Fine-grained micrites commonly host narrow extension fractures marked by plume structure (Figure A1d1.1), but extension fractures are likely to be rougher and more irregular in vuggy (Figure A1d1.2) and coarser-grained (Figure A1d1.3) limestones.

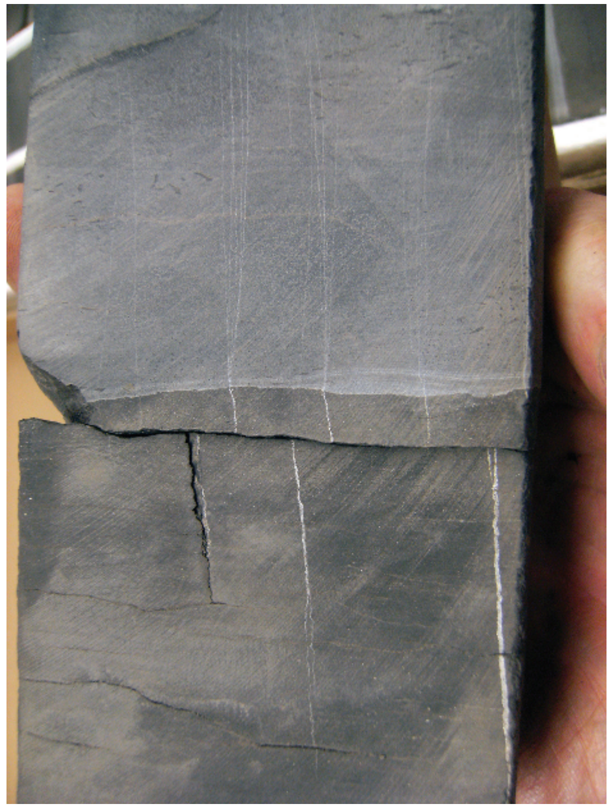

Figure A1d.1 Multiple narrow, calcite-mineralized, high-angle extension fractures in a limestone accommodated the same strain that was taken up by a smaller number of wider fractures in the underlying calcareous shale. (The apparent offset at the horizontal plane below the lithologic contact is due to differences in the orientations of the slab planes above and below the offset, and is not real.) Vertical three-inch diameter core; uphole is towards the top of the photo.

A1d2 High-Angle Extension Fractures in Dolomite

Extension fractures in dolomites are commonly rough and irregular (Figures A1d2.1–A1d2.4) because dolomites tend to be coarse-grained and are commonly vuggy. The fracture faces are rarely marked by plume structure since the the surface relief on a plume is typically less than dolomite grain size. The diagenesis, dissolution, and reprecipitation associated with dolomites typically result in irregular and wide fracture apertures with irregular mineralization.

A1d3 High-Angle Extension Fractures in Shale

High-angle extension fractures in cored shales range from a few centimeters to tens of feet tall. Short fractures are common where the fractures are bounded by strong mechanical contrasts between thin beds of different shaley lithologies, but short fractures can also occur within thicker-bedded shales where minimal strain did not propagate tall fractures to the bedding boundaries. Likewise,

Figure A1d1.1 The plume structure commonly associated with extension fracturing can be formed in many lithologies, including limestone as shown here. Plume structure may be inhibited in coarse-grained lithologies such as conglomerates and crystalline dolomites, but can form easily in these strata if the grains do not offer significant mechanical contrasts or if the stress differential was high enough to drive fractures indiscriminately across the grain boundaries. Vertical, four-inch diameter core; uphole is towards the top of the photo.

Figure A1d1.2 Two rough, parallel, high-angle extension fractures in a vuggy limestone, striking oblique to the slab surface (angling into the plane of the photo towards the left). The oblique strike exaggerates the fracture width and irregularity. Fracture dimensions on a slab plane are apparent dimensions unless the fracture strikes normal to the slab surface. Top and bottom fracture terminations are blind within a homogeneous lithology. Slab from a four-inch diameter core; uphole is towards the top of the photo.

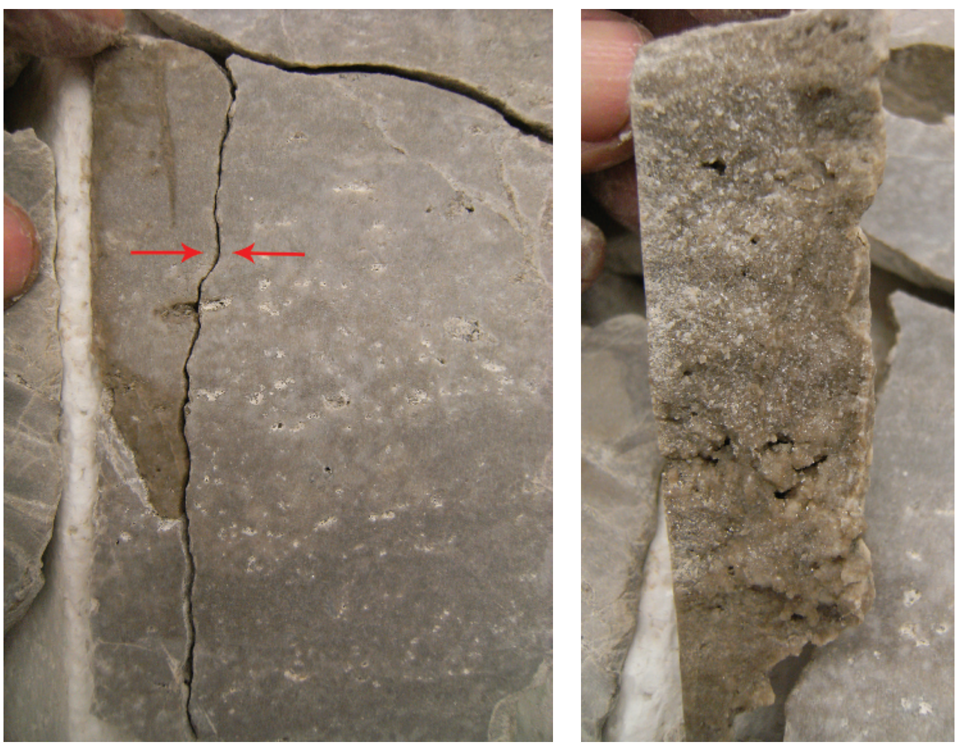

Figure A1d1.3 Two views of a rough-surfaced, high-angle extension fracture (between the two arrows in the left photo) in a vuggy, coarse-grained limestone. The photo on the right shows the fracture face, with subtle crystalline calcite mineralization. Plume structure is unlikely to have developed on such irregular fractures in coarse-grained lithologies, but plumes are also easily removed by dissolution in soluble lithologies. Slab of a four-inch, vertical core; uphole is towards the top of both photos.

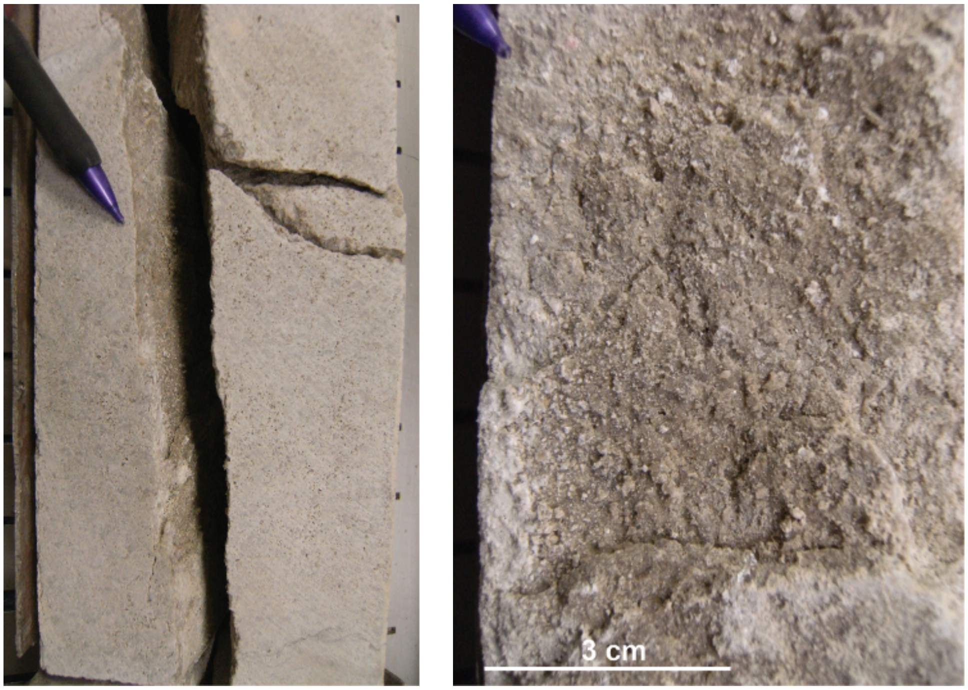

Figure A1d2.1 Two views of an extension fracture in a coarsely crystalline dolomite. Fractures in dolomites tend to be irregular and to have rough surfaces, due to propagation around the dolomite rhombs and the typically multiphase diagenetic history of these rocks. Fracture faces may be sparsely mineralized with isolated knobs and crystals of dolomite (right). The apparent width of the fracture on the left is due only to the way the broken fracture is lying in the box; actual width is on the order of a few millimeters. Vertical three-inch diameter core; uphole is towards the top of both photos.

Figure A1d2.2 An irregularly planar extension fracture in a dolomite. If the fracture is irregular in only one plane, i.e., if horizontal cross-sections across this core were to show linear sections of the fracture at any given depth despite this irregularity in the vertical plane shown here, it would be plausibly interpreted as a strike-slip shear fracture, especially if the surface was marked by shear indicators. However, the fracture is likely to be an extension fracture if the fracture surface is irregular in cross-sections oriented in any direction. This core has broken open along the poorly mineralized fracture plane. Butts of vertical four-inch core; up-section is towards the top of the photo.

Figure A1d2.3 Left: a tall high-angle extension fracture in a coarsely crystalline dolomite has a rough, irregular plane. The core has broken open along the incompletely mineralized fracture plane. The green line between the red–black uphole/downhole orientation lines is a Master Orientation Line useful for assessing fracture strikes relative to each other in continuous intervals of core. Right: scattered millimeter-scale dolomite crystals are present on the faces of a fracture from the same formation and fracture system. Some of the irregularity of this fracture is due to postfracturing dissolution. The dolomite crystals were precipitated after dissolution. Vertical four-inch diameter core: uphole is towards the top of both photos.

extension fractures may be narrow (Figure A1d3.1) or wide (Figure A1d3.2), depending on the amount of strain that each fracture had to accommodate. Extension fractures in shales are commonly marked by plume structure (Figure A1d3.3), although it may be subtle and is easily obscured by mineralization.

Most shale fractures are mineralized to some degree, but recent studies (e.g., Landry et al., 2015) suggest that even mineralized, low-permeability fractures in a shale can have higher permeability than the typically nanodarcy scale permeability of a hosting shale. Fractures in shales provide large surface areas for the diffusion of fluid or gas from the matrix into the fracture, and, hopefully, to a wellbore.

Tall fractures (Figures A1d3.4, A1d3.5) are common in thickly bedded shales where the horizontal mechanical

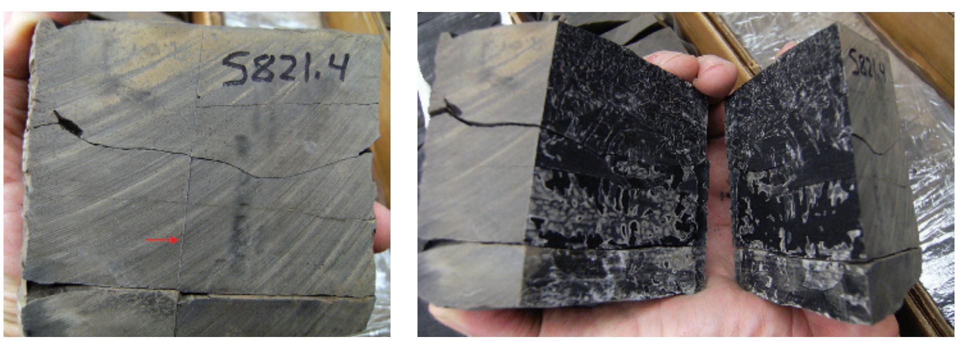

Figure A1d3.1 Two views of a short, narrow, calcite-mineralized, high-angle extension fracture in a shale core. Left: the fracture (arrow) cuts the slab face. (The arcuate pattern sweeping from upper right to lower left across the slab is scarring from the slab saw.) Right: the two faces of the fracture are mineralized with a layer of calcite that is 0.01 mm thick. The single layer of calcite adheres irregularly to the opposing fracture faces, resulting in what only appear to be unmineralized patches on each face. Butts from a vertical, three-inch diameter core; uphole is towards the top of both photos.

Figure A1d3.2 Two views of a tall high-angle extension fracture in shale. The fracture is approximately 3 mm wide. The photo on the right shows the face of the fracture on the piece of core indicated by the arrow in the photo on the left. In contrast to the fracture shown in the previous photo, both fracture faces are incompletely mineralized with calcite that grew from the walls into the open aperture. Irregular mineralization indicates that this fracture creates an important conduit to fluid flow, with permeability significantly greater than that of the matrix of the host rock. Slabs of vertical, four-inch diameter core; uphole is towards the top of the photo.

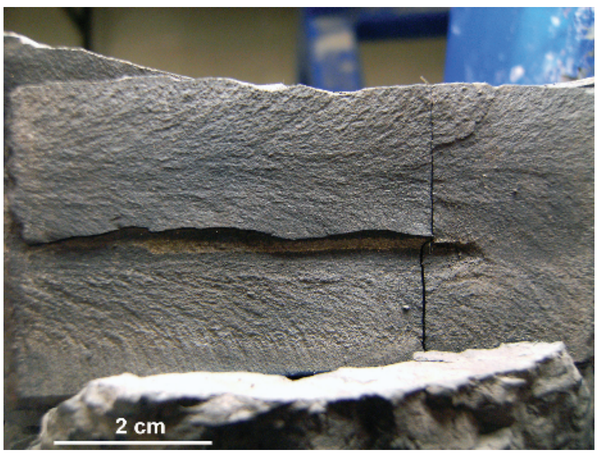

Figure A1d3.3 Plume structure, recording horizontal propagation of a short, strata-bound, high-angle extension fracture follows bedding in a thinly bedded shale where the different layers provide strong mechanical contrasts. Fracturing is confined to the more siliceous beds in the formation. Vertical three-inch diameter core; uphole is towards the top of the photo.

bedding contrasts are both minimal and far apart. Short fractures are typical of heterogeneous shale formations where they may be confined to the shaley beds (Figure A1d3.6) or to the more calcareous or more siliceous beds (Figure A1d3.7). Some shale formations contain two fracture sets, one in the muddier beds and another with a different strike in the more brittle lithologies. Tall extension fractures can also cut across bedding and multiple lithologies if the driving stress anisotropy was high and/or the mechanical contrast between beds was low (Figure A1d3.8).

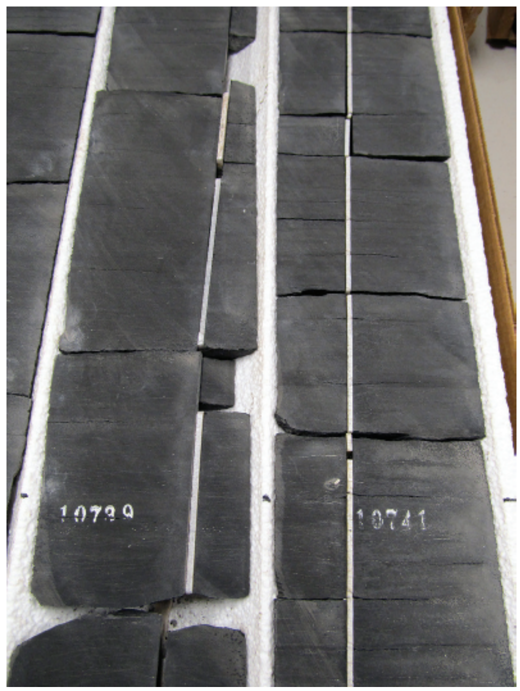

Figure A1d3.4 A mineralized, 4 mm wide, high-angle extension fracture in poorly bedded shale extends for several feet nearly parallel to the core axis. The fracture walls are smooth and fracture width is uniform, but the aperture remaining between crystalline calcite that lines the wall is less regular. Calcite mineralization adheres weakly to the fracture walls so the core breaks easily along the fracture plane. Gaps that show in the mineralization are areas where the layer of calcite has become detached from both walls and is missing. The mineralization is the same color and has the same texture as the styrofoam bed on which the slabs are lying. Slabs of vertical, four-inch diameter core; uphole is towards the top of the photo.

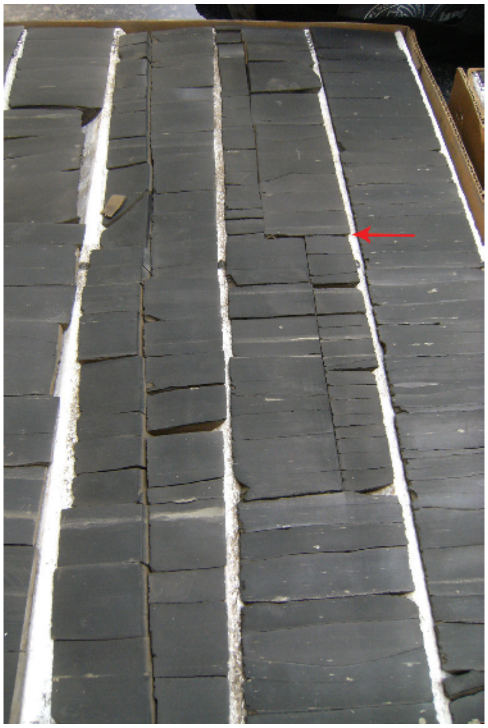

Figure A1d3.5 A tall, calcite-mineralized fracture in bedded shale can be traced for about four feet in core slabs. The offset in the fracture at the arrow is spurious, due only to a change in the slab-plane orientation. Reassembly of the slabs and butts shows that the fracture consists of a single continuous plane that has about 50% more height than is apparent in the slabs shown here, and that it exits the sides of the core before terminating so that its full height is greater still. Calcite mineralization is of the order of 0.2 mm thick. Slabs of four-inch vertical core; uphole is towards the top of the photo.

Figure A1d3.6 Two incompletely mineralized, high-angle extension fractures that are confined to shale units interbedded with shell-hash limestones. At the time of fracturing, the shale was more susceptible to brittle deformation than the limestone. Slabs of vertical, four-inch diameter core; uphole is towards the top of the photo.

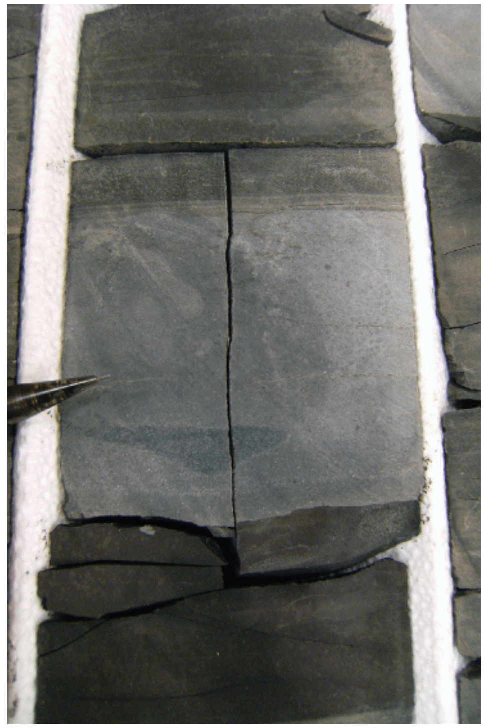

Figure A1d3.7 A calcite-mineralized, vertical extension fracture that is confined to a limestone interbedded with shale. This fracture extends a short distance into the confining shales, but most such fractures terminate at the bedding contact. In contrast to the previous example, the limestone was more susceptible to fracturing than the adjacent shale. Slabs of vertical, four-inch diameter core; uphole is towards the top of the photo.

Figure A1d3.8 A relatively wide (2 mm), incompletely mineralized, near-vertical extension fracture that extends indiscriminately across shale and limestone beds. The fracture surfaces are slightly rougher in the limestone but otherwise there is little difference in fracture characteristics in the two lithologies. Mineralization consists of two layers of calcite attached to the fracture faces and growing inward, with euhedral crystal faces marking a medial, unmineralized aperture. Slabs of vertical, 3.5-inch diameter core; uphole is towards the top of the photo.

A1d4 Narrow Extension Fractures

Some high-angle extension fracture sets consist of very narrow (0.01 mm or less), parallel to subparallel, mineralized fractures (Figures A1d4.1–A1d4.3). Such narrow fractures can occur either singly or in bundles, and are most common in fine-grained, micritic limestones and homogeneous calcareous shales although they have also been found in sandstones (Figure A1d4.4). These very narrow fractures can be too small and too tightly cemented to create significant mechanical discontinuities in the rock, particularly where they are filled with finely crystalline calcite that has geomechanical properties that are similar to those of the limestone host rock. Younger fractures, including induced fractures, can cut at shallow angles across such fractures with no apparent interaction.

When a rock is strained to the point of fracture multiple times, fractures may repeatedly open and heal with mineralization ("crack-seal"), or they may open incrementally without concurrent mineralization. Narrow fractures may also form once and heal with mineralization that is as strong as or stronger than the matrix rock,

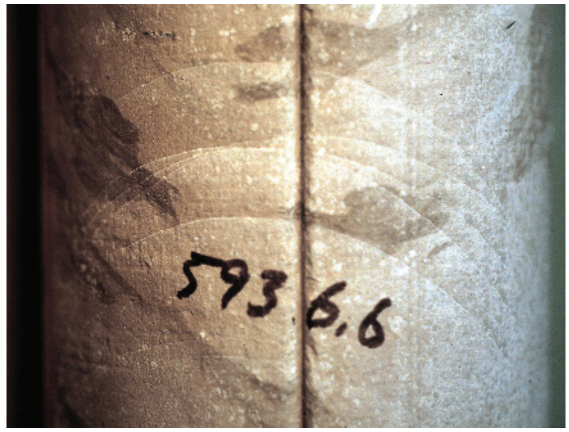

Figure A1d4.1 Five narrow, near-parallel, calcite-mineralized, high-angle extension fractures in a dense chalk cut from an inclined wellbore. The three middle fractures are slightly oblique to each other and cut across one another without apparent interference, suggesting the mineralized fracture plane had mechanical properties nearly identical to those of the host rock. The groove down the center of the photo is a core-orientation scribe line. The core is $2^{3/8}$ inches in diameter and was cut from a wellbore that is inclined about 45° from the vertical. Uphole is towards the top of the photo, and the bedding contact below the depth marking defines horizontal.

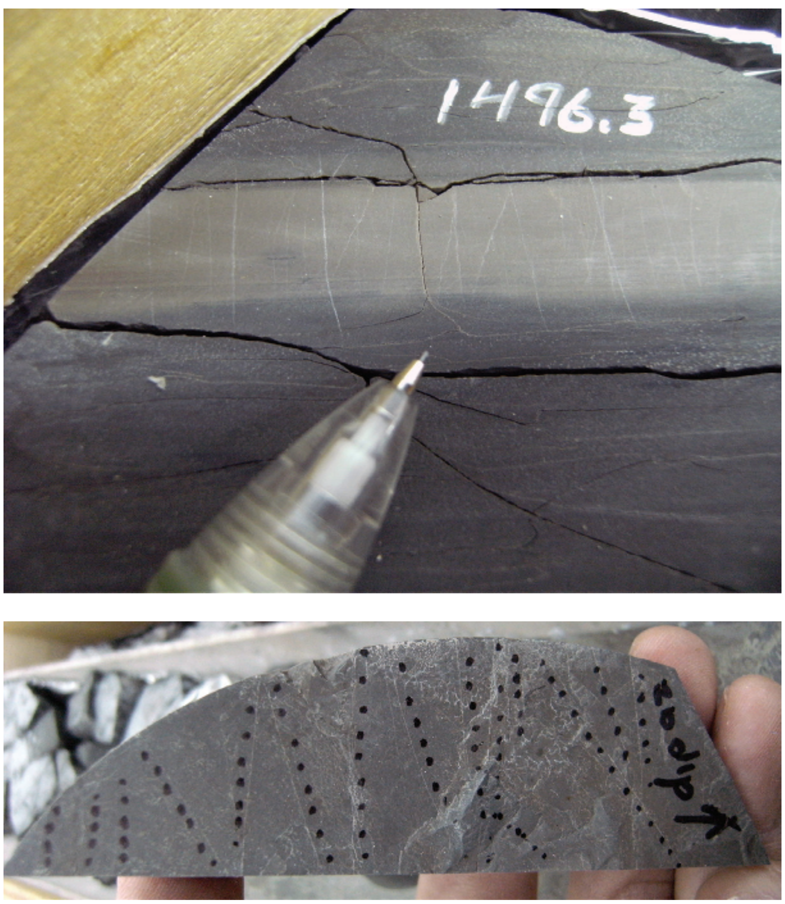

Figure A1d4.2 Two sets of narrow, calcite-mineralized, strata-bound fractures in a narrow limestone band interbedded in a shale formation, cut from inclined strata in a vertical hole. Top: some fractures are inclined relative to the core axis but are normal to the tilted bedding and probably formed prior to tilting. Other fractures are vertical, parallel to the core axis, and oblique to bedding, and probably formed after tilting. Bottom: the same fracture system in core cut a few feet deeper in the hole, showing two strikes for the superimposed, narrow, calcite-mineralized fractures (next to the dotted lines). If the bedding dip azimuth ("dip az") is known, as from an image log, the actual fracture strikes can be reconstructed. The four-inch core is vertical but bedding is inclined; the top photo shows the slabbed surface on the core butts, uphole is towards the upper right corner of the photo. The bottom photo shows the end of the slab and the view is downhole.

Figure A1d4.3 Two sets of narrow, intersecting, calcite-mineralized, high-angle extension fractures exposed on the end of a core cut from a calcareous shale. The single fracture cutting upper right to lower left predates the other fractures since they terminate against it. Examination of the slab face alone, or even of the slab in three dimensions, would not have revealed the second fracture set; the second fracture set is apparent only in the butt section of the core. Butts of a vertical, four-inch diameter core; uphole is towards the viewer.

so that each successive stress event creates new, subparallel fractures rather than reopening earlier fractures. This is especially common in low-porosity, fine-grained carbonates where the relatively soluble matrix provides ready material for rapid mineralization of fractures.

Narrow fractures in clay- or organic-rich micrites may be bundled, with successive narrow fractures forming immediately adjacent and parallel to each other rather than reopening the initial fracture. Where postfracturing dissolution has occurred, dissolution is concentrated along the fracture bundles if the calcite mineralization is more soluble than the host rock.

A1d5 Irregular High-Angle Extension Fractures

Some high-angle extension fractures are quite irregular, often as a result of the interaction between the propagating fracture and significant lithologic heterogeneity (Figures A1d5.1, A1d5.2), although heterogeneous lithologies may also contain quite planar fractures (Figure A1d5.3). Irregular fracturing may also occur within a setting where high pore pressure has created a low stress differential so that the fracture strikes are

Figure A1d4.4 Bundled, narrow, high-angle extension fractures in a deeply buried sandstone. Thin sections (location marked by the yellow rectangle) show fractures both cutting through grains and following grain margins. Slab face of a vertical four-inch diameter core; uphole is towards the top of the photo.

Figure A1d5.1 Some extension fractures found in coarse-grained rock such as in this bioclastic limestone are irregular, the fracture planes having propagated around rather than through the clasts. Vertical three-inch diameter core; uphole is to the top of the photo.

Figure A1d5.2 A calcite-mineralized fracture cuts irregularly through a thinly laminated silt-shale lithology. Poor planarity is a function of lithologic heterogeneity probably combined with a low stress differential during fracturing. Vertical, two-inch diameter core; uphole is towards the top of the photo.

Figure A1d5.3 Extension fractures can be planar even in coarse-grained rock such as this pea-gravel conglomerate, if the rock was well cemented, if the clasts had mechanical properties that are similar to those of the matrix material, and/or if the stress differential that drove fracturing was high. Vertical four-inch diameter core; uphole is towards the viewer.

Figure A1d5.4 High-angle extension fractures can also be irregular in structurally complex settings. This oil-stained extension fracture in a limestone is from a faulted anticline. Complex fractures such as this may be related to local structural complications. Vertical, four-inch diameter core; uphole is towards the top of the photo.

Figure A1d5.5 Irregular, oil-filled, high-angle extension fractures in a bedded limestone. This fracture pattern begins to resemble the non-systematic fracture system hypothesized by Gretener and Feng (1985) for fracturing under conditions of high pore pressure that cause the stress differential to be very low and fracture strikes to be poorly constrained. This type of fracture system is rare. Many fracture systems have been suggested to have been caused by pore pressure that exceeds the minimum in situ compressive stress, but the dependent relationship between pore pressure and effective stress does not support such a mechanism for systematic fracture sets. Vertical four-inch diameter core; uphole is towards the top of the photo.

poorly constrained, or in structurally complex areas (Figures A1d5.4, A1d5.5) where the strata have been subjected to multiple stress events. Since these fractures are poorly planar and have no obvious fractographic markings, their interpretation as extension fractures rests on a lack of evidence for shear offset, and on terminations at minor mechanical discontinuities.

A1e High-Angle Extension Fracture Intersections

When two or more intersecting extension fracture sets occur in a reservoir, fracture-related permeability enhancement may be greatest along the best-developed set (which is not necessarily the oldest set), along the least mineralized set (which is not necessarily the best-developed set), or along the set that is parallel to the maximum compressive stress. Thus it is important to characterize natural fractures and to measure their strikes both relative to each other and relative to stress-controlled induced fractures. Complete fracture characterizations and ultimately an understanding of the fracture–stress interactions must be developed from the limited data provided by a core in order to understand a fracture-controlled permeability system.

Although core is a miniscule sampling of a reservoir, examples of intersecting fracture sets in a core are not uncommon. However, fracture intersections are easily missed if only 2D core photos or core-slab surfaces are studied; none of the following examples of fracture intersections come from exposures on slab surfaces since a full 3D understanding of fractures is required in order to measure relative fracture strikes. It is important to use all the core, butts and slabs together, during a core fracture study, and to examine all surfaces of the core. This increases the sample size and significantly improves the probability of finding all of the fracture sets captured by the core, and of measuring their relative strikes. The use of core slabs only for a fracture study is akin to using only 30% of an image log.

Fracture systems with multiple strikes can be created by strike-slip conjugate shear pairs formed during a single stress event, but they can also be the result of superimposed extension-fracture sets. It is important to interpret the origin of intersecting fracture geometries correctly since conjugate shears and superimposed extension fractures have different strikes relative to the in situ stresses, resulting in either fracture closure or shear during production, with different effects on fracture permeabilities. An advantage of core over image logs is that it is usually easier to tell the difference between shear and extension fractures in a core where the fracture face can often be examined and where fracture details can be observed in three dimensions.

Where intersecting fractures consist of superimposed extension fractures but the fractures cannot be oriented, the two sets may be distinguishable by differences in characteristics such as heights, host lithologies, and type/color/completeness of mineralization. However, the fractures of some unrelated, intersecting sets have similar characteristics, and can therefore only be distinguished by strike. Piecing long core sections together on a work table and comparing strikes is often the only way to determine whether a suite of natural fractures in a core consists of one or two fracture sets.

A1e1 Obvious Intersections

Fractures that intersect within a piece of core are not uncommon (Figures A1e1.1, A1e1.2). The butt ends of cores are commonly the best places to look for and

Figure A1e1.1 Two similar, narrow, calcite-mineralized high-angle extension fractures in a muddy shale core, intersecting at a 70° angle. Other than strike, the only obvious distinction between the two fractures is that one dips nearly parallel to the core axis and the other has an 80° dip. The formation is heavily fractured and other intersections occur in the core, but the two fractures are nearly identical. Vertical four-inch diameter core; uphole is towards the top of the photo. The wider white marking on the left side of the core is a service company orientation mark.

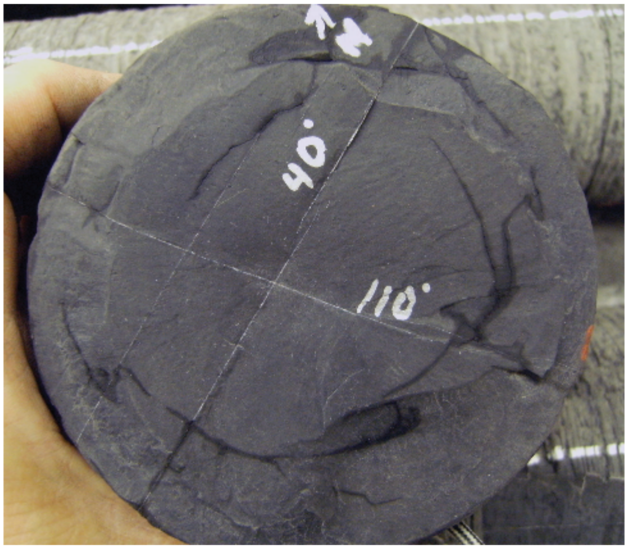

Figure A1e1.2 Intersecting, calcite-mineralized, high-angle extension fractures exposed on the end of a vertical shale core, same core and formation as the previous photo. The core is oriented so we know its in situ position, as marked by the "N" arrow, and we can reconstruct the true fracture strikes, 40–220° (two fractures) and 110–290° (one fracture). The fractures appear to be mutually cross-cutting but close examination of the mineralization shows that one cuts across the other and is younger (see the next photo). Vertical four-inch diameter core; view is downhole.

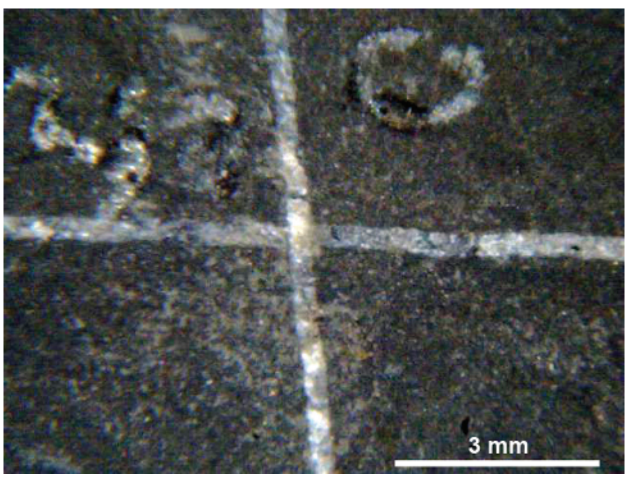

Figure A1e1.3 Close-up of intersecting, calcite-mineralized, vertical extension fractures on the end of a vertical shale core (from the same core shown in the previous photo) showing that the mineralization of the fracture oriented top to bottom in the photo cuts across and postdates the mineralization of the left-to-right fracture. Vertical four-inch diameter core; view is downhole.

document intersections (Figures A1e1.2–A1e1.5). Intersecting fractures may have similar or distinctly different characteristics such as aperture and mineralization (Figure A1e1.6).

Figure A1e1.4 Intersecting, unmineralized, closely spaced, high-angle extension fractures on the end of a vertical limestone core, with local oil stain. The older fracture set is planar and through-going, and has consistent strikes. Younger, oblique fractures are less planar and terminate or are offset at the through-going fractures. Abutting relationships indicate that the fracture set cutting across the photo top to bottom is younger than the left-to-right fracture set. The top-to-bottom fracture set might be interpreted to have been offset by shear along the left-to-right set, but neither the magnitudes nor the senses of offset are consistent, and none of the fracture faces are marked by shear indicators. The top-to-bottom set propagated to and terminated against discontinuities provided by the earlier left-to-right set. Vertical four-inch diameter core. The circled dot indicates that the view is downhole.

Figure A1e1.5 Four calcite-mineralized but incompletely filled fractures with at least three distinct strikes in core cut from a limestone. The relative ages of the fractures are unclear. Water has wicked into the aperture of the lower left fracture indicating significant remnant fracture porosity. Vertical, four-inch diameter core. The circled X indicates that the view is uphole.

A1e2 Less Obvious Intersections

Only one set of a pair of intersecting fractures may be exposed on a slab face (Figure A1e2.1), and intersections may not be obvious from the two-dimensional views provided by photographs (Figure A1e2.2). Incomplete

Figure A1e1.6 Intersecting high-angle extension fractures ("NF") as exposed on the end and slab face of a vertical core. The larger fracture has an irregular width and aperture, suggesting dissolution and indicating good potential for fluid flow. Dissolution-enhanced fractures in this core are oriented at a characteristic angle to the narrower fractures, and the two sets can be distinguished even where they do not intersect. The two planes of exposure, on the slab surface and on the end of the core, illustrate the difference between the true and apparent widths of the larger fracture. Slab from a vertical four-inch diameter core; uphole is towards the top of the photo.

Figure A1e2.1 Fragments of two high-angle extension fractures (planes marked A and B) in the butts of a core cut from dolomite. Only one of the fractures intersects the slab plane. Vertical three-inch diameter core; uphole is towards the top of the photo and away from the viewer.

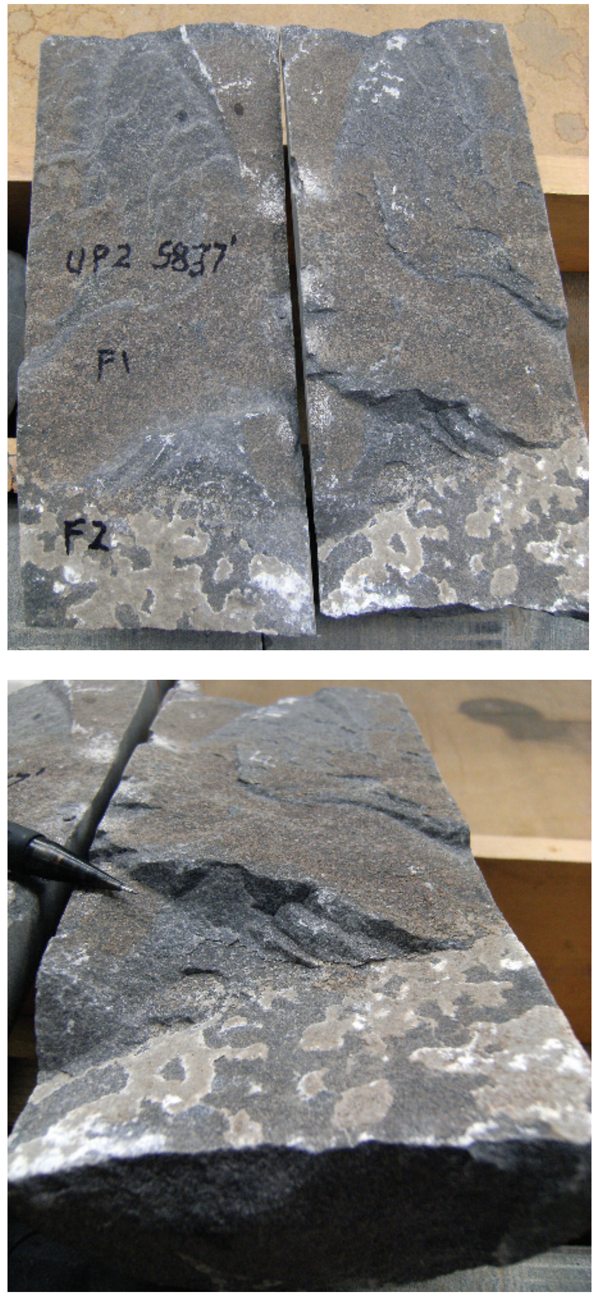

Figure A1e2.2 Two views of fractures in a limestone core. Top: the core is split along a mineralized fracture plane with both faces exposed, showing two types of mineralization. A dirty gray calcite with a crystalline habit covers the upper 80% of the fracture face and shows that significant in situ permeability exists along the fracture. White, amorphous calcite partially occludes the lower part of the fracture. Not apparent from this photo is the fact that the different types of mineralization occur on different, oblique fracture planes, as indicated by the end-on view (bottom) showing that this surface is composed of two fractures with non-parallel strikes. Note that only about 50% of the opposing faces of the lower fracture are covered with the white mineralization, but that the patches of amorphous calcite are mirror images of each other and that the fracture is in fact almost fully occluded. Vertical four-inch diameter core; uphole is towards the top of both photos.

fracture characterizations may be made using core photos, but their limitations must be recognized. Some fracture intersections, and their relative ages, are apparent from steps where one fracture intersected a previous fracture (Figure A1e2.3).

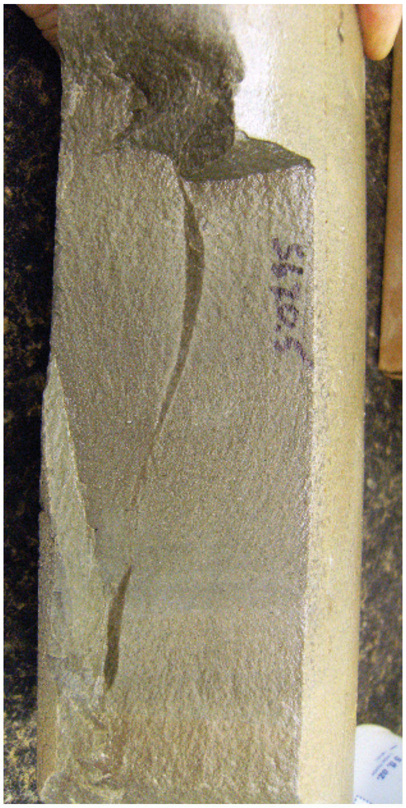

Figure A1e2.3 A faint plume on the surface of a vertical extension fracture (parallel to the plane of the photograph) did not propagate cleanly across the oblique, older natural fracture that it intersected (dark, oblique plane along the middle of the core). In some places the younger, plumed fracture has stepped laterally in order to cross this pre-existing mechanical inhomogeneity in the rock, which strikes inward and to the left from the plane of the photo. Vertical four-inch diameter core; uphole is towards the top of the photo.

A1e3 Projected Intersections

Fractures with different strikes may not intersect within a core volume, but can easily be projected to an inferred intersection in the nearby rock (Figures A1e3.1, A1e3.2).

Figure A1e3.1 Two calcite-mineralized vertical extension fractures skim the edge of a limestone core. The fractures intersect at an 80° angle but they have similar characteristics, and the two sets are indistinguishable where they do not occur together in this unoriented core. The importance of recognizing the presence of one versus two fracture sets is that two sets form an interconnected permeability network whereas a single extension fracture set forms a poorly connected network with highly anisotropic drainage and permeability. Vertical 4.5-inch diameter core; uphole is towards the top of the photo.

Figure A1e3.2 Fracture planes in horizontal cores can also be extended beyond the core volume to projected intersections. Here two sets of high-angle extension fractures in a horizontal core have strikes that intersect at nearly 90°, but the intersections are not captured within the core. The silver line marks the high or dorsal side of the core. A quick, conceptual image of the reservoir fracture system, consisting of a network of closely spaced, high-angle fractures with 90° intersections, can be developed from this core. Horizontal three-inch diameter core; uphole is to the left of the photograph.

Figure A1f.1 Left: edge-on view of two vertical, calcite-mineralized extension fractures (arrows) at the left and right edges of this piece of slabbed sandstone core cut from a deviated well. The wellbore deviation angle was 60° from vertical (wellbore deviation is typically expressed in degrees from vertical, unlike geologic dip angles which are given in degrees from horizontal), and the core is pictured in its in situ position. The unoriented core can be rotated around its axis (*red dashed line*) but the fractures, known to be vertical from nearby vertical cores, are only vertical in one rotational position. The wellbore deviation azimuth is approximately north, therefore these are approximately east-west striking fractures. Right: the face of one of the vertical, calcite-mineralized fractures on the end of the core piece shown in the left-hand photo; calcite partially obscures a plume structure. Deviated, four-inch diameter core: uphole is towards the upper left of the left photo, and away from the viewer in the right photo; stratigraphic up is towards the top of both photos.

A1f High-Angle Extension Fractures in Deviated Core

In contrast to vertical cores, cores from deviated wellbores usually cut across rather than along individual high-angle extension fractures. Deviated cores therefore typically provide smaller samples of individual fractures but have the potential to sample a larger number of fractures. Fracture frequency must be assessed carefully since deviated cores will capture numerous samples of the fractures that strike normal or nearly normal to the wellbore deviation azimuth yet may sample few or none of the fractures striking nearly parallel to that azimuth even if they are more closely spaced.

A deviated core typically provides more and better information on fracture spacings (Figures A1f.1, A1f.2) than vertical cores. On the other hand, a deviated core is less likely to capture the vertical terminations of high-angle extension fractures (Figures A1f.3, A1f.4).

Deviated core commonly affords an opportunity to determine fracture strikes without orienting the core, provided that stratigraphic up in the core can be determined and the wellbore deviation azimuth is known. However, stratigraphic up is no longer equivalent to the obvious "uphole" direction as it is in vertical core, so stratigraphic up in core from a deviated well is not always obvious.

Figure A1f.2 Three obscure, closely spaced, calcite-mineralized vertical extension fractures (between the pairs of black arrows) in a horizontal sandstone core. The groove across the center of the photograph is a scribe line created by the core orientation shoe. The service company used a non-standard red–white line pair for uphole annotation, but the red line is still "red on the right looking uphole" so the heel of the well is towards the left in this photo. Fracture strikes can be measured if the core high side is known and if the wellbore deviation azimuth is known from the wellbore deviation survey. The ridges on the surface of the core are created by the rotating core bit and are normal to bedding. Horizontal, four-inch diameter core; uphole is towards the left, and stratigraphic up is out the side of the core, towards the viewer.

Figure A1f.3 A calcite-mineralized vertical fracture in a piece of unslabbed sandstone core cut from a wellbore that is deviated at about 50° from the vertical. The core has been propped up into its in situ position. There is only one position of rotation around the central core axis (indicated by the red dashed line) at which the bedding (arrow) is horizontal and the fracture is vertical. Fracture strike can then be physically measured using the wellbore deviation azimuth. If bedding is absent or not horizontal, and/or if the fractures are not vertical, the problem becomes more complicated. Deviated, four-inch diameter core; uphole is towards the upper left corner of the photo, stratigraphic up is towards the top of the photo.

Figure A1f.4 Face-on (top) and oblique (bottom) views of a vertical extension fracture that cuts across the axis of a horizontal core. The fracture face above the dotted line has an aged appearance and is more planar than the conchoidal, fresh surface below the dotted line. The upper part of the face is a natural fracture that has been subjected to dissolution; it terminates downward at a bedding plane marked by the dotted line. When the core broke during processing and handling, the natural fracture plane was extended downward as an induced fracture. Horizontal, four-inch diameter core; view is uphole, towards the heel of the deviated well, and stratigraphic up is towards the top of both photos.

Whereas fracture dips can easily be measured in a vertical core, both the dip and strike of a fracture in a deviated core may be unconstrained. Nevertheless, if bedding is arguably horizontal in the formation and can be recognized in the core, there are only two rotational positions around the long axis of the horizontal core where bedding will be horizontal, limiting the number of possible fracture orientations to two.

If the core is inclined relative to bedding and one can tell whether the core is cutting up-section or down-section, then core orientation relative to up can be determined. Moreover, the wellbore deviation survey, which provides an azimuth for the wellbore through the cored interval as well as the deviation of that axis from vertical, can then be used to determine fracture strikes and dips.

For example, if a horizontal wellbore has an azimuth of N60°E and the cored strata are horizontally bedded, a bed-normal fracture that strikes at right angles to the core axis is vertical and has a NNW-SSE strike. If the top of bedding is ambiguous and the fracture is oriented at a 60° angle to the core axis, however, the bed-normal fracture can be reconstructed to have either a NNE-SSW strike or an E-W strike, depending on which side of the horizontal bedding is up. If bedding is not horizontal or cannot be recognized in the core, then the determination of fracture dip and strike in core cut from a deviated wellbore requires that the core be oriented.

When a horizontal core is oriented, the position of the principle scribe line is given in reference to vertical "up", rather than to north as in a vertical core. In the deviated core orientation report, the position of the principle scribe line on the core is given in degrees clockwise from the high side of the core while looking downhole.

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