Natural fractures in the Spraberry Formation, Midland basin, Texas: The effects of mechanical stratigraphy on fracture variability and reservoir behavior

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ABSTRACT

Horizontal cores from sandstone-siltstone reservoirs in the Spraberry Formation (Midland basin, west Texas) have documented two systems of dramatically different yet dynamically compatible natural fractures, in reservoirs separated vertically by only 145 ft (44 m). Each system is capable of producing a different degree of the northeast-trending permeability anisotropy recognized in Spraberry reservoirs. One fracture system consists of two vertical fracture sets with an apparent conjugate geometry (striking north-northeast and east-northeast). The other system consists of evenly spaced, northeast-striking vertical fractures, nearly bisecting the acute angle of the first system. Although lithologically similar, differences in quartz-overgrowth and clay content in the layers resulted in a yield strength of the lower bed that is only half of that of the upper layer, producing different fracture systems in the two reservoirs despite their proximity. Such differences in the mechanical properties, due to variations in diagenetic and depositional histories of the strata, are probably widespread within the formation. They have the potential to cause significant vertical and lateral variation in the Spraberry fracture system across the basin. Low present-day in-situ stresses in the reservoirs allow the fractures to open, to become more conductive, and even to propagate, under very low injection pressures.

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INTRODUCTION

Background

Large reserves of oil were discovered in the Spraberry Formation in the Midland basin of west Texas in 1949, and the area of Spraberry production (Figure 1) now covers approximately 25,000 mi^2 (64,000 km^2), comprising one of the largest plays in the world. Spraberry reservoirs occur at depths of approximately 7000–8000 ft (2130–2440 m), consisting of interbedded, fine-grained sandstones, siltstones, and organic-rich shales nearly 1000 ft (300 m) thick. These Spraberry strata were deposited in a deep-marine environment during the Leonardian stage of the Permian Period and are commonly interpreted as the deposits of turbidity currents (e.g., Guevara, 1988; Tyler and Gholston, 1988).

The Spraberry play has had a cumulative production of about 740 million bbl of oil, but oil recovery percentages and the daily production rates of individual wells are low. As of January, 1999, daily production across the entire play was 62,000 bbl of oil and 25 mcf of gas. This is an average of only 7 bbl of oil per day recovered from each of 8900 producing wells, and the estimated ultimate recovery of oil from the play is only 10–15% of the 6–10 billion bbl of oil originally in place. Spraberry reservoirs are underpressured, averaging only 800–900 psi (5.4–6.1 MPa); matrix porosities range from 6 to 15%, and restored-state matrix permeabilities are typically less than 10 md.

All areas of the Spraberry trend have indications of extensive natural fracturing despite minimal local faulting and folding within a relatively stable geologic setting. Fracturing and a generally northeasterly trending, fracture-controlled permeability anisotropy were inferred from well tests and well interference patterns early in the history of the Spraberry play (e.g., Elkins, 1953; Elkins and Skov, 1960; Schechter et al., 1996a, b) The presence of fracturing was corroborated using limited amounts of core, including one deviated core (Wilkinson, 1953), but the data necessary for a three-dimensional characterization of this important fracture system, and for prediction of its variability and its effects on the reservoir plumbing system, were lacking. Many of the fractures logged and reported from the early vertical cores would, in fact, now be classified as coring-induced structures (e.g., Lorenz, 1995).

Four in. (10 cm) diameter core would have only a 10–20% probability of intersecting a natural fracture in Spraberry strata, given fracture spacing demonstrated by horizontal cores taken during this project and the low probability of intersecting vertical natural fractures with vertical cores (e.g., Lorenz, 1992). Thus it is not surprising that few vertical Spraberry cores contain fractures that are unarguably natural, although coring-induced and hydraulically induced petal and petal-centerline fractures are exceptionally well developed. Moreover, examination of vertical cores during the course of this project suggested that natural fractures in the Spraberry Formation are commonly extended by hydraulic processes

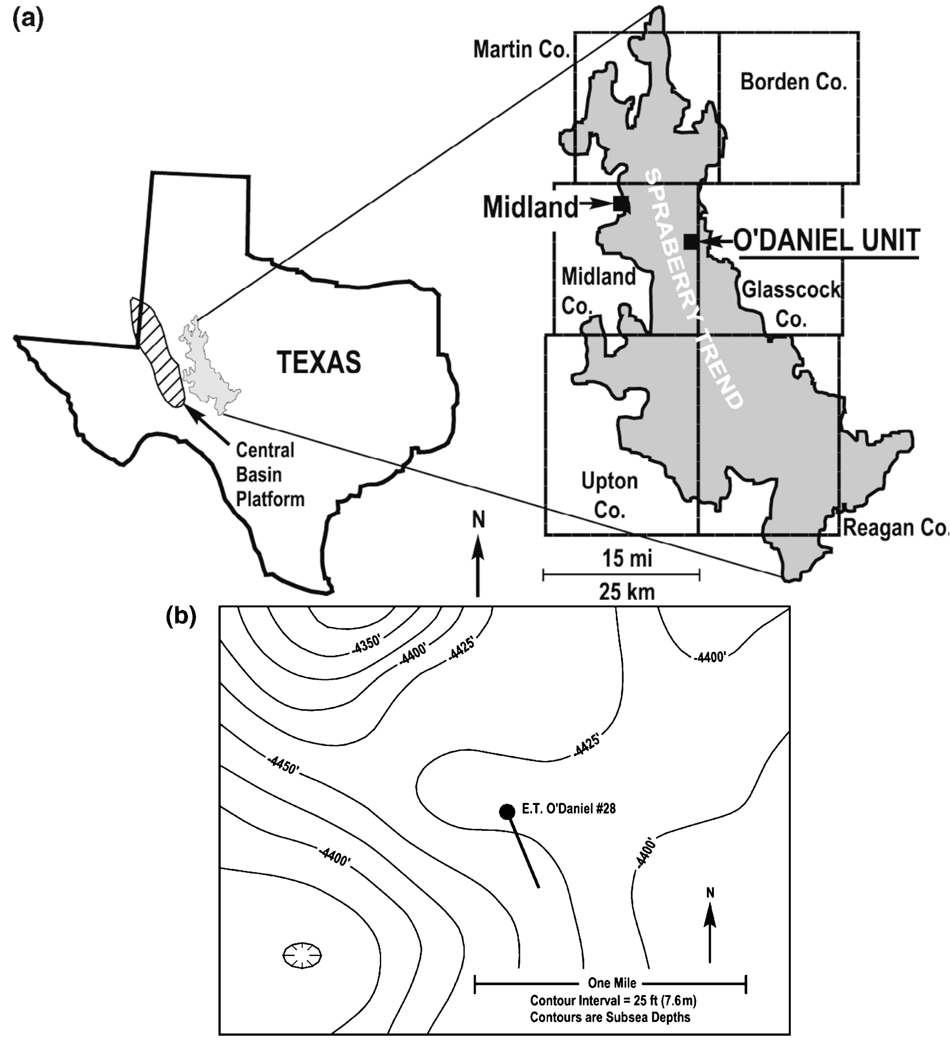


Figure 1. (a) Location map, showing the Spraberry trend of west Texas. (b) Structure contour map on top of the Spraberry Formation in the O'Daniel unit area, Midland basin, west Texas. Heavy line is the azimuth of the two horizontal side tracks of the Parker and Parsley 28 E. T. O'Daniel well. Structure contours are in feet relative to mean sea level.

associated with drilling and coring, obscuring the differentiation between natural and induced fractures and complicating fracture interpretations.

The early well tests and observations of interference commonly gave erratic results and led to an inconsistent picture of the fracture characteristics and their effects across the field. Horizontal permeability anisotropy due to fracturing was calculated to average 13:1 but locally ranged up to 1000:1 (Elkins and Skov, 1960). Early production data indicated a generally northeast trend to this maximum horizontal reservoir permeability, and this direction was assumed to be the average fracture strike, but the reported permeability axes were also variable, ranging from 036 to 076° (e.g., Elkins and Skov, 1963). The descriptions presented here suggest that natural fractures are not uniformly distributed or oriented within Spraberry strata, helping to explain some of this variability.

Northeastward-directed Laramide compressive stress has been suggested to be the source of much, if not all, of the minimal, post-Permian structural deformation and fracturing in the Permian basin (e.g., Hills, 1970; Calhoun and Webster, 1983; Price and Henry, 1985; Erdlac, 1993; Winfree, 1994, 1995). The reported present-day stresses, significant in terms of fracture conductivity, are still generally aligned with this trend (Avasthi et al., 1991; Nolen-Hoeksmema et al., 1992; D. Holcomb, 1997, personal communication), although local variations occur over structures.

Spraberry Project

A proposal to conduct experiments designed to improve recovery from Spraberry reservoirs was funded by the National Petroleum Technology Office of the

U.S. Department of Energy in 1995. This was a cost-sharing proposal, submitted to the Department of Energy's Class Reservoir program by (1) the Petroleum Recovery Research Center of the New Mexico Institute of Mining and Technology, and (2) Pioneer Natural Resources (then Parker and Parsley, Inc.). The ultimate goal of the project has been to assess the economic feasibility of CO_2 flooding in Spraberry reservoirs, by characterizing natural fractures in the formation with horizontal cores and by testing cored reservoir samples in the laboratory for the suitability of CO_2 flooding (Schechter et al., 1996a).

Nineteen horizontal core runs, recovering a total of 395 ft (134 m) of core, were cut in 1996 from two subparallel, horizontal sidetracks kicked out from the wellbore of the existing Parker and Parsley 28 E. T. O'Daniel well, located in the E. T. O'Daniel unit, Midland County, Texas (McDonald et al., 1997). The upper sidetrack had an azimuth of 158°, and the lower sidetrack azimuth was 165°. Wellbore deviations from vertical varied by core run but were within 0–4° of horizontal. The targets of these wellbores were two 10–15 ft (3–4.6 m) thick, fine-grained sandstone to siltstone units (referred to hereafter as "sandstones" for simplicity), designated the 1U and 5U reservoirs and located within a sandier part of the formation (Figure 2). These reservoirs are separated vertically from each other at this site by 145 ft (44 m) of interbedded sandstone, siltstone, and shale. Although the two main reservoirs were targeted for coring, postdrilling analysis suggested the cores were in fact cut within and across thinner, 3–4 ft– (1 to 1.2 m) thick sandstones immediately above the main 1U and 5U reservoirs. Several of the cores ramped into the immediately overlying and underlying shale beds or missed the sandstone units entirely. This, inadvertently, allowed for a comparison of fracture distributions by lithology. The cores were pieced together immediately after recovery using published procedures (e.g., Lorenz and Hill, 1992) and analyzed for natural fractures before being slabbed, plugged, or sampled.

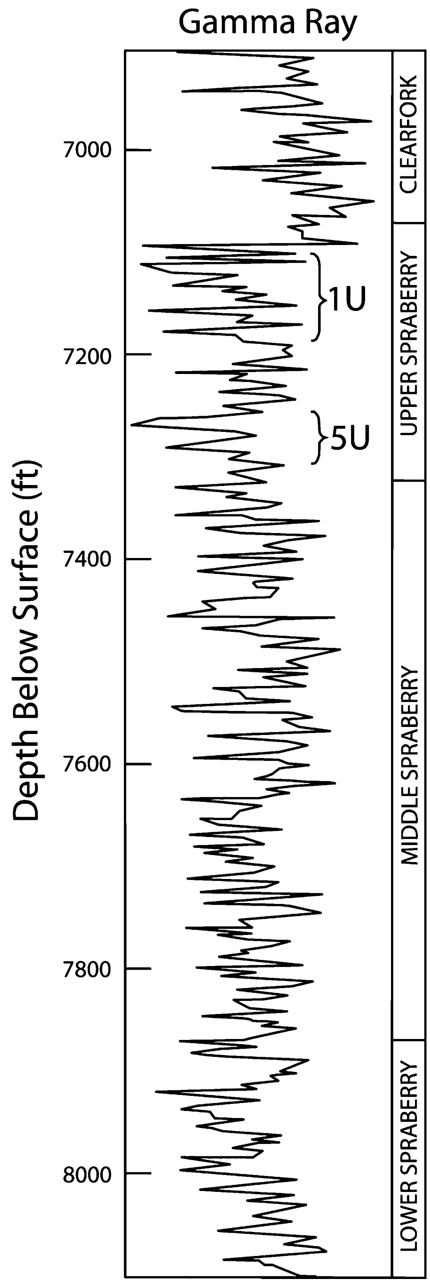


Figure 2. Stratigraphic column/gamma-ray profile through the Spraberry Formation in the O'Daniel unit, Midland basin, west Texas. The 1U and 5U intervals are the main producing reservoir units of the Spraberry trend. The horizontal cores were taken from the thinner sandstones near the tops of the 1U and 5U intervals.

NATURAL FRACTURE DESCRIPTIONS

The data set of 102 natural fractures obtained from the horizontal cores has provided a unique characterization of the local subsurface Spraberry fracture system. Short, preliminary reports of the natural fracture data have been presented previously (Lorenz, 1997a, b; Montgomery et al., 2000), but the data set (Tables 1, 2) and an analysis are presented here.

The cored natural fractures are all within a few degrees of vertical and range in strike from 020 to 085° (Figure 3). The most important finding has been that a significant difference exists, despite stratigraphic

Table 1. Natural Fractures in Horizontal Core from the 1U Unit, Spraberry Formation, Parker and Parsley 28 E. T. O'Daniel Well*

Measured Depth (ft)	Strike	% of Aperture Filled with Barite (visual estimate)
7339.1**	70°	0
7345.5	70°	0
7352.5	70°	0
7356.3†	70°	0
7360.5	50°	50
7365.1	40°	50
7366.9	40°	80
7369.5	45°	10
7372.6	40°	20
7375.3	45°	80
7381.3	45°	70
7382.5	45°	85
7385.6	45°	0
7386.4	40°	50
7389.8	45°	80
7394.3	40°	95
7402.7	45°	100
7406.8	45°	95
7408.9	45°	80
7412.0	40°	100
7414.4	45°	100
7416.6	60°	0
7419.6	40°	0
7422.2	45°	0
7425.9	40°	0
7663.3	80°	0
7666.7	40°	0
7667.9	45°	95
7673.7	45°	90
7678.1	45°	70
7678.6	60°	0
7682.9	45°	90
7688.4	40°	95
7690.7	45°	70
7693.0	40°	80
7694.0	35°	80
7699.8	40°	10
7701.2	45°	20
7702.4	45°	10
7706.4	40°	20
7710.9	40°	80
7715.9	40°	95
7717.6	80°	0
7719.4	80°	0
7721.5	85°	0
7722.3	45°	30

*Drilled intervals between cores, from 7399.0 to 7401.0 ft, and from 7429.7 to 7662.5 ft MD.
**Faint plumose marking.
†Multiple, intertwining fracture planes.

proximity and lithologic similarity of the host strata, between the fracture populations of the two cored intervals.

Three fracture sets are defined in following sections. The strikes of two of the fracture populations overlap, creating a degree of ambiguity in differentiating fracture populations that cannot be completely resolved with this limited data set and clouding the discussions on fracture origins. A combination of fracture strikes, mineralization, surface characteristics, and stratigraphic location have been used in the groupings made during this study.

Mineralized Spraberry fractures are unquestionably natural, but the macroscopically unmineralized natural fractures in both the upper and lower cores are less obviously so. These planar features do not resemble any of the geometries of coring-induced fractures reported from vertical or deviated core (e.g., Kulander et al., 1990; Lorenz, 1999a). In addition, these fractures (described in following sections as unmineralized) have faces that display a different color and a smoother, aged texture compared to freshly broken core surfaces. Geometry, surface textures, and microscopic to patchy macroscopic fracture-surface coatings of barite, quartz, and dolomite (Cather and Lorenz, 1998) show that these are natural and not artificial fractures related to coring and handling.

Upper (1U) Core

Evenly spaced, barite-mineralized, northeast-striking extension fractures dominate the upper cored interval (the nominal 1U reservoir unit in Figure 4). Of the total population of 46 natural fractures cored in this interval (Table 1), 36 define a group with a narrow range of northeasterly strikes (Figure 4a). The average fracture strike within this set is 043°, and the standard

Table 2. Natural Fractures in Horizontal Core from the 5U Unit, Spraberry Formation, Parker and Parsley 28 E. T. O'Daniel Well*

Measured Depth (ft)	Strike
7587.2	30°
7589.9	75°
7590.0	40°
7590.1	75°
7592.4**	60°
7593.6†	25°
7597.1	65°
7597.6†	25°
7598.0**	40°
7599.7†	25°
7599.9	45°
7600.2	25°
7600.9	50°
7601.2	40°
7601.4	45°
7602.2	65°
7602.3	70°
7603.0	25°
7603.9	70°
7605.3	70°
7606.1††	70°
7607.2	25°
7608.7	70°
7611.1††	25°
7615.3	30°
7617.4	60°
7624.3†	35°
7628.0	20°
7838.5	35°
7839.4	70°
7842.0	45°
7843.6	40°
7845.0	60°
7847.4	30°
7848.8	70°
7851.9††	25°
7856.0	65°
7857.9††	35°
7858.0	35°
7865.4	30°
7865.6†	30°
7869.0	70°
7872.5	75°
7872.6	30°
7877.2	75°
7889.5	75°

Table 2. Continued

Measured Depth (ft)	Strike
7890.9	75°
7892.4	75°
7894.4**	75°
7895.9	75°
7897.8	25°
7897.8	75°
7900.0	75°
7905.3	70°
7915.2	70°
7925.1	70°

*Drilled intervals between cores, from 7628.2 to 7838.0 ft MD.
**Steps suggesting left-lateral shear.
†Steps suggesting right-lateral shear.
††Multiple, intertwining fracture planes.

deviation is only 2.8°. Thirty of these 36 fractures display obvious crystalline barite mineralization up to several millimeters thick (Figure 5); the other six show

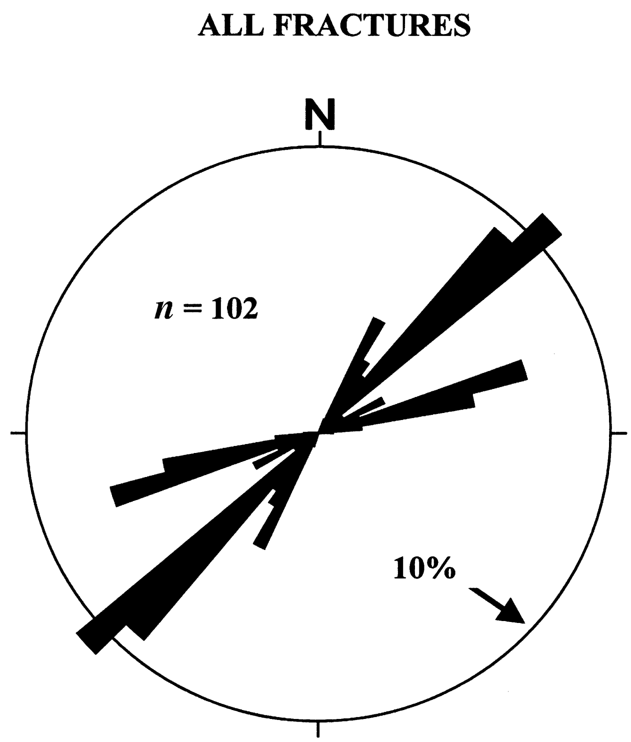


Figure 3. Rose diagram of all 102 natural fracture strikes in all horizontal cores from the Parker and Parsley 28 E. T. O'Daniel well. Outer ring = 10% of the fracture population plotted. The average and standard deviation strike values for the three sets are 043 and 2.8° (set 1), 033 and 8.0° (set 2), and 070 and 4.9° (set 3), respectively. The 95% confidence arcs are not shown because they would imply a knowledge of the strike probability density functions. The raw data (Tables 1, 2) and relevant statistics (average and standard deviation) are provided in the text.

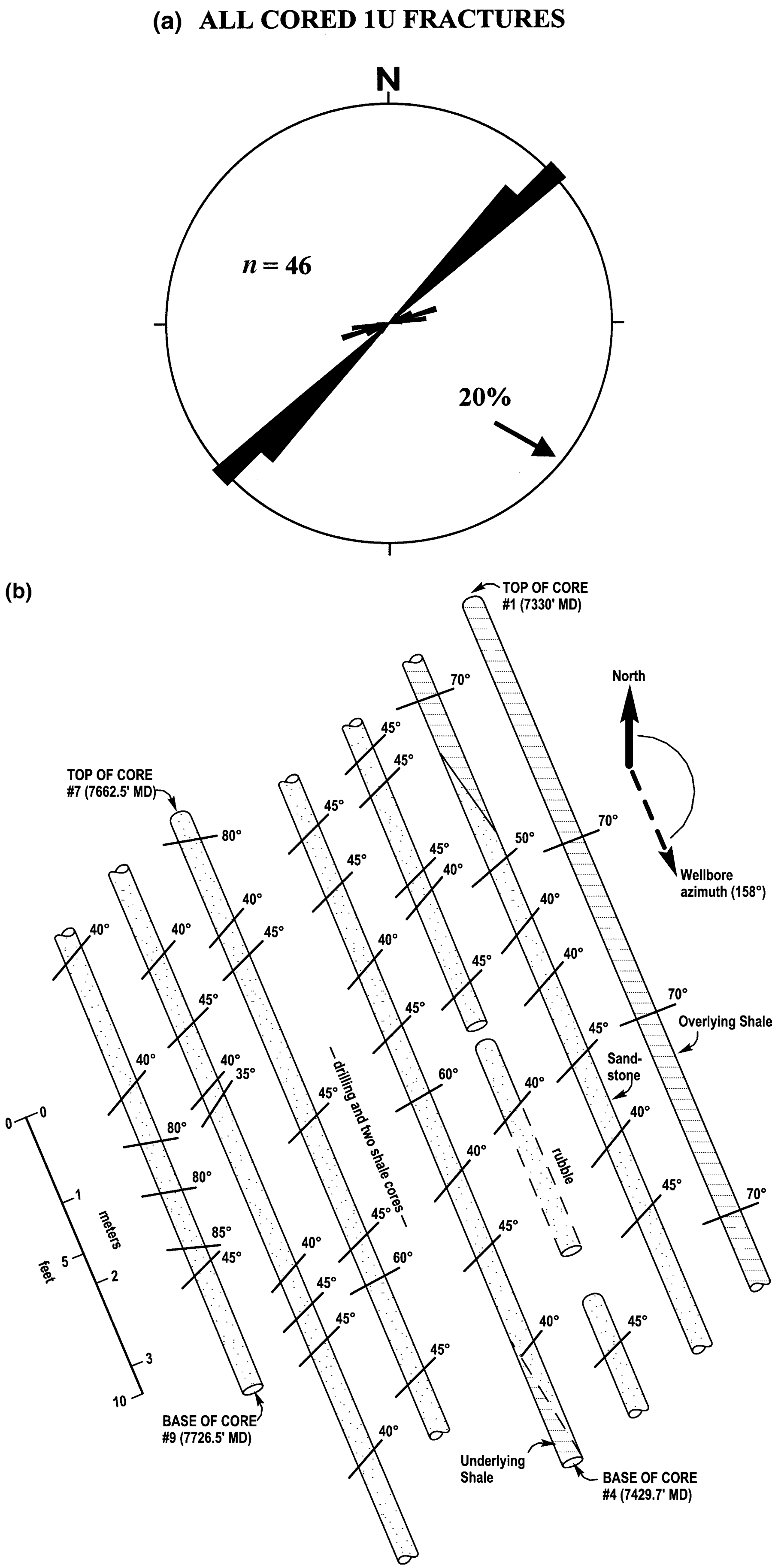


Figure 4. (a) Rose diagram of all 46 natural fracture strikes found in cores from the upper (1U) cored interval. Outer ring = 20% of the fracture population plotted. (b) Plan-view presentation of the cores taken from the upper (1U) interval showing natural fracture strikes and their positions relative to the cored lithologies. Two unfractured cores taken from the shale underlying the reservoir are noted but not portrayed. All data are presented in plan view except the bedding contacts, which are drawn as viewed from the side of the core, that is, as if the viewer were standing to the left of the core bar with the core in the horizontal position, downhole to the right, and looking toward the east-northeast, (i.e., for bedding only, top of core = right edge of the core). As depicted, the diameter of the 2 5/8 in. (6.7 cm) core is exaggerated about 5 times relative to its length.

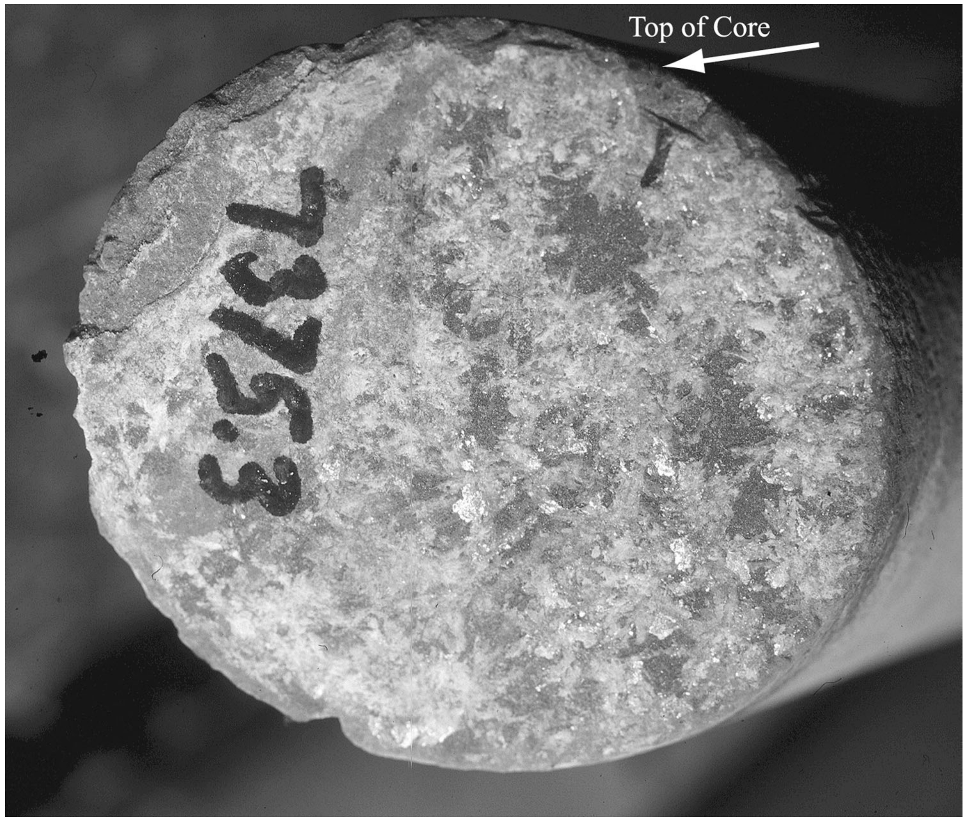


Figure 5. Photograph of the barite-mineralized, set 1 fracture (strike 45°) at 7375.3 ft MD in the 1U interval. Core diameter is 2 5/8 in. (6.7 cm).

local traces of mineralization, visible under the microscope. A few of the fracture surfaces show plumose structure, but most are planar and apparently unornamented. These northeast-striking fractures are called set 1 fractures in the following discussions.

The other fractures in the 1U reservoir are macroscopically unmineralized and represent populations distinct from set 1. Four of these fractures, striking consistently 070°, are present in the shale unit overlying the reservoir sandstone and are similar to the ten fractures having 070–075° strikes found in the shale overlying the other, 5U, reservoir. Four subparallel fractures that have a similar orientation (striking 080–085°) are present in the 1U sandstone. These east-northeasterly striking fractures probably belong to set 3, described in the following section.

Lower (5U) Core

In contrast to the fractures found in the 1U interval, the 56 natural fractures cored in the lower sandstone (the nominal 5U reservoir) have more widely dispersed strikes, ranging between 020 and 085° but grouped within two trends (Table 1; Figure 6). Half of the natural fractures in this core form a group with strikes between 020 and 050° (Figure 7), and these north-northeasterly striking fractures are designated as set 2. About a third of the set 2 fractures have strikes within the range of the set 1 fractures from the 1U core (Figure 8), but lack conspicuous barite mineralization. The average strike of fractures within set 2 is 033°, and the standard deviation is a relatively large 8°.

Most fractures from the 5U reservoir appear to be unmineralized, even under examination using a hand lens. Minute crystals of quartz, dolomite, and barite, however, are present on all of these surfaces when viewed under the microscope (Cather and Lorenz, 1998), and local millimeter-scale patches of quartz and barite are present on some of the fracture faces.

Five of the set 2 fractures display distinctive en echelon steps, indicative of formation in right-lateral horizontal shear (e.g., Petit, 1987; Wibberly et al., 2000). One of the set 2 fractures has similar but left-lateral shear indications (Figure 9). The en echelon steps are without slickensides or slickenlines, indicating an origin in primary shear rather than reactivation of an extension fracture in later shear. Three more fractures consist of multiple (two to three), subparallel to anastamosed fracture planes, also suggestive of shear but without indicating the sense of shear (the rock was

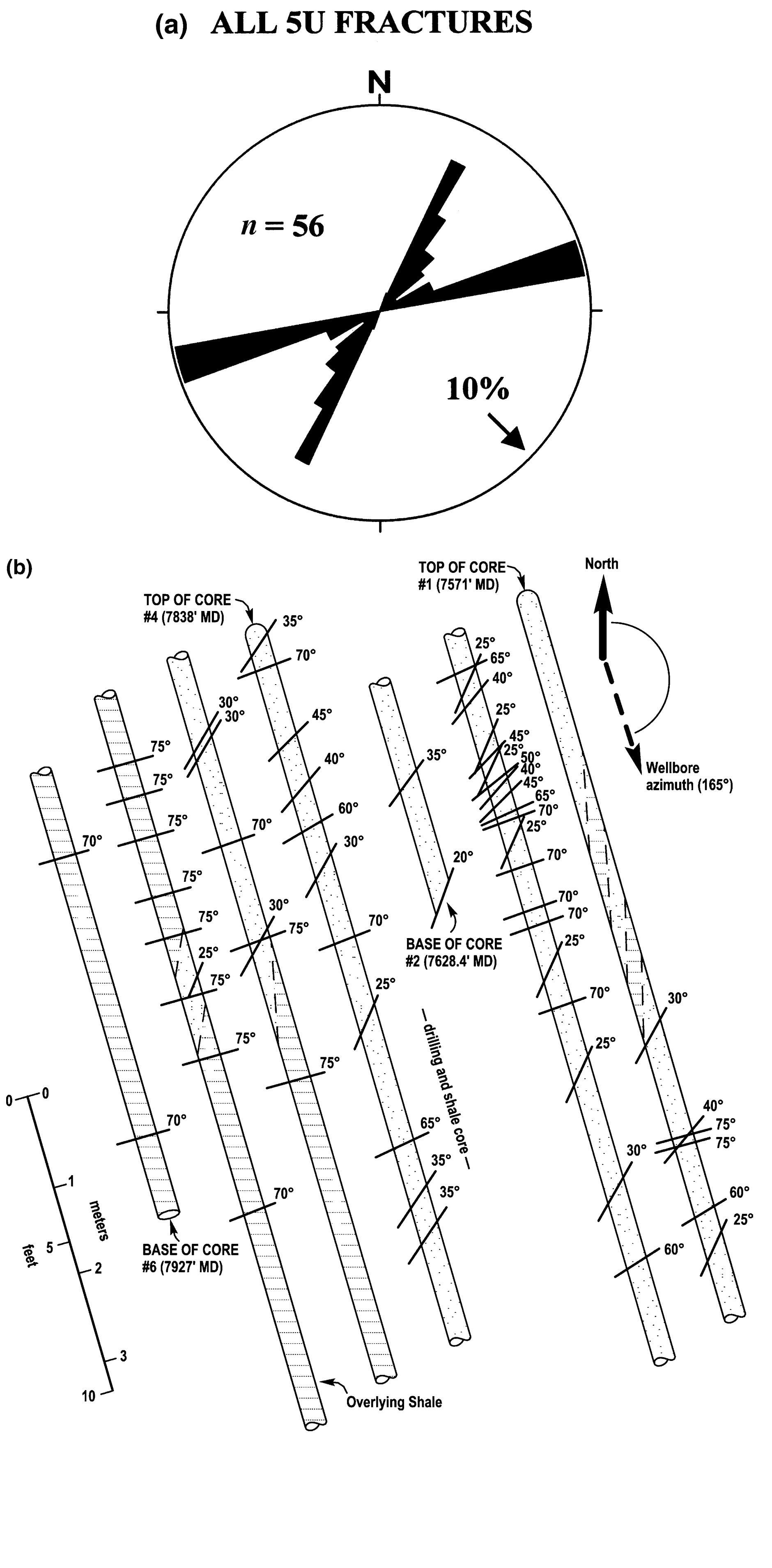


Figure 6. (a) Rose diagram of all 56 natural fracture strikes found in cores from the lower (5U) cored interval. Outer ring = 10% of the total fracture population plotted. (b) Plan-view presentation of the cores taken from the lower (5U) interval showing natural fracture strikes and their positions relative to the cored lithologies. Two unfractured cores taken from the shale underlying the reservoir are noted but not portrayed. All data are presented in plan view except the bedding contacts, which are drawn as viewed from the side of the core, that is, as if the viewer were standing to the left of the core bar, downhole to the right, with the core in the horizontal position and looking toward the east-northeast, (i.e., for bedding only, top of core = right edge of the core). As depicted, the diameter of the 2 5/8 in. (6.7 cm) core is exaggerated about 5 times relative to its length.

Figure 7. Photograph showing three fracture planes cutting core from the lower (5U) interval. Core has been laid out in plan view, that is, with the top of core (line drawn along the axis of the core) toward the viewer. Figure 9 is a photograph of an end-on view of the fracture in the upper right of this photograph. Core diameter is 2 5/8 in. (6.7 cm).

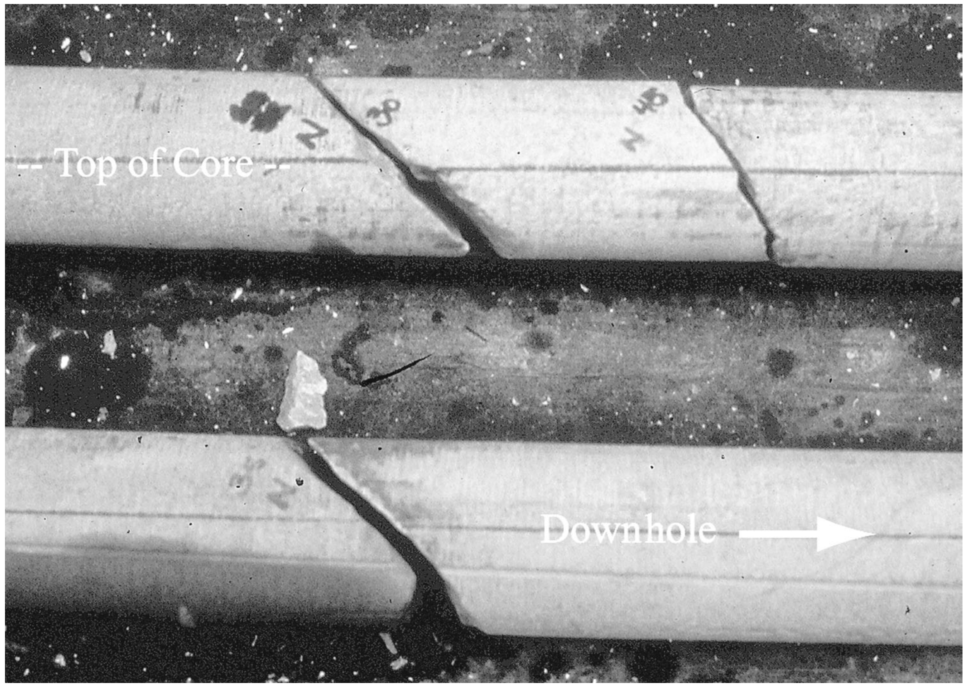
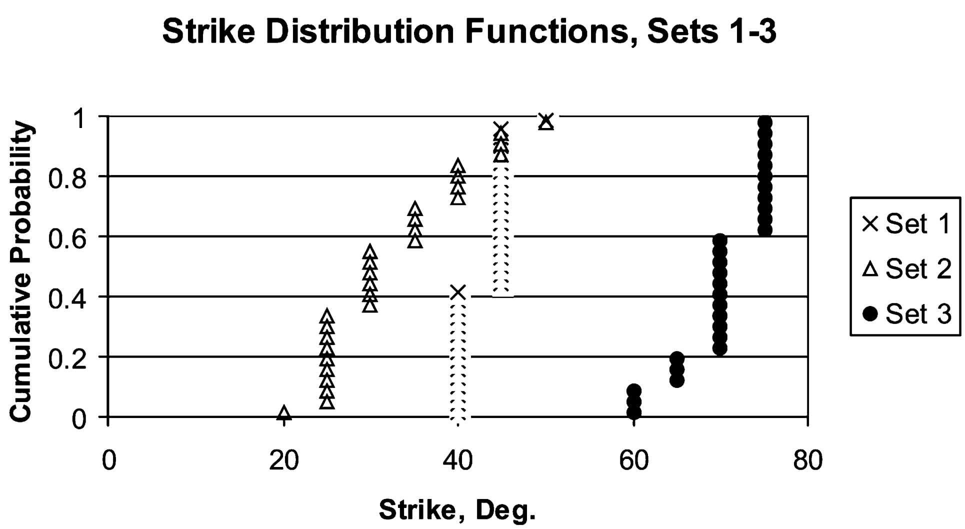


Figure 8. Cumulative probability plot of strikes within the three fracture sets in the Spraberry cores. The strikes of fractures in set 2 have a broader range and smaller average than set 1, and the uppermost 30% of set 1 fractures have strikes similar to those in set 2. Set 3 strikes are clearly different from the other two sets.



not broken open to examine the fracture surfaces more closely).

The other half of the fracture population in the 5U core comprises set 3, forming a distinct lobe with strikes from 060 to 085° on the rose diagram (Figure 6a). These include fractures found in the shale that overlies the 5U sandstone, as well as fractures in the 5U sandstone itself. The average and standard deviation of strikes for set 3 fractures are 070 and 4.9°, respectively. These fractures are predominantly planar, unornamented, and macroscopically unmineralized (Figure 10), but five show features suggesting shear: three display left-lateral en echelon steps, and two are compound, anastamosed fractures.

Only one example of the intersections between the set 2 and set 3 fractures was cored. In this instance, a fracture with a strike of 025° appears to terminate against a fracture with a 075° strike (at 7897.8 ft measured depth [MD]), suggesting that the former may be younger.

Fracture Distributions

Set 1 fractures dominate the sandstone reservoir facies of the 1U interval, whereas the fractures of sets 2 and 3 dominate the 5U reservoir facies. A few fractures with the east-northeast set 3 orientation occur in the 1U sandstone, however, and it is also possible that

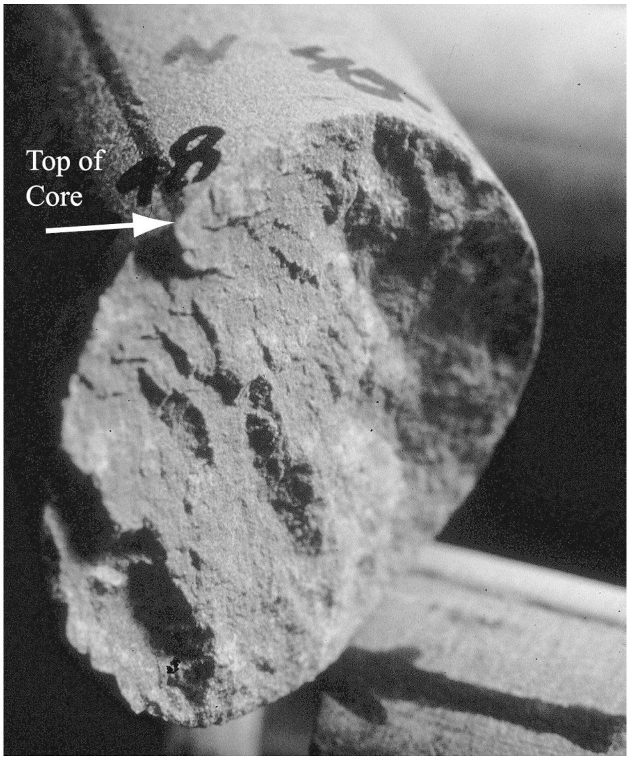


Figure 9. Photograph of steps on a set 2 fracture face suggestive of an origin in shear, at 7598.0 ft MD (strike 40°), from core in the lower (5U) interval. Core diameter is 2 5/8 in. (6.7 cm).

Figure 10. Photograph of a macroscopically "unmineralized" fracture surface, at 7678.6 ft MD in the upper (1U) core. Core diameter is 2 5/8 in. (6.7 cm).

some northeast-striking set 1 fractures are present but indistinguishable from set 2 fractures in the 5U sandstone.

Set 3 fractures are the only ones found both outside of and within the reservoir sandstone facies, being widely and evenly spaced (about 10 ft [3 m]) within the black, calcareous shales overlying both reservoirs. However, no natural fractures are present within the 80 ft (24 m) of horizontal core taken from the shales immediately below the two reservoirs (these cores are not depicted on Figures 4b, 6b).

The Spraberry fracture-spacing characteristics are examined statistically in the Appendix. In brief, set 1 fractures are regularly and closely spaced: corrected spacing normal to the average fracture strike ranges from just less than 1 to 5.8 ft (0.30 to 1.77 m) and averages 2.9 ft (0.88 m). In contrast, spacings of the fractures in sets 2 and 3 are more irregular, ranging, in the sandstones, from inches to 9.9 ft (centimeters to 3.02 m). Spacings range up to 14 ft (3.96 m) if the set 3 spacings in the shales are considered. The spacings of set 1 fractures define an approximately lognormal distribution, whereas the spacings of sets 2 and 3 are neither lognormal nor exponential, both being closest to a generalized Pareto distribution. None of the three populations exhibits power-law (fractal) behavior. Close fracture spacing and the apparent absence of swarming behavior (see Appendix) suggest that the fracture system is well developed and "saturated" in the sense of Wu and Pollard (1995).

Mechanical Properties

The cored 1U and 5U beds are lithologically similar at the macroscopic scale, but laboratory measurements and petrographic examinations demonstrate a significant difference in their composition and mechanical strengths. This difference becomes important when attempting to explain the observed fracture systems. The average mechanical yield strength of the upper, 1U sandstone as measured by triaxial tests is nearly twice that of the 5U sandstone (38,000 psi [262.5 MPa] and 22,000 psi [150.2 MPa], respectively) (Sterling, 2000) (Figure 11). The difference in yield strength results from subtle differences in the clay and quartz contents of the two units. Petrographic analysis indicates that the average total clay content of the lower unit is 10%, whereas it is only about half that (6%) in the stronger, upper unit. The additional clay in the lower unit is detrital, occurring as diffuse clay laminae. In addition, euhedral quartz overgrowths on sand grains are better developed in

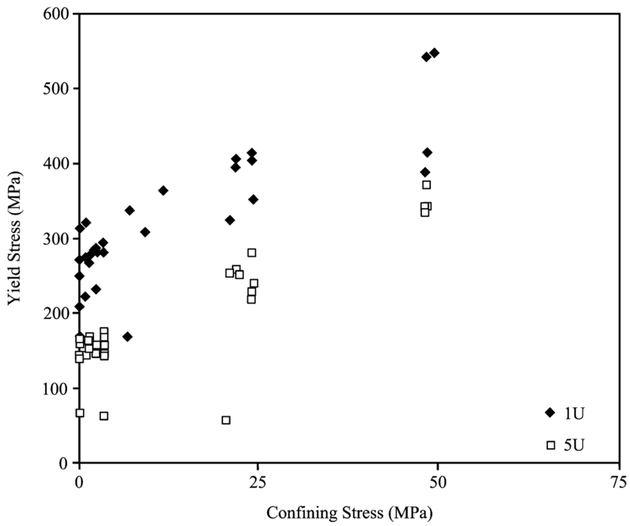


Figure 11. Comparison of the yield strengths for different confining stresses for 56 samples of the upper (1U) and lower (5U) Spraberry sandstone units. The 5U unit is a significantly weaker sandstone at all confining stresses. (Figure modified from Sterling, 2000.)

the strong upper unit, where they comprise an average of 7% of the rock volume, compared to only 3% of the rock volume in the lower unit. Lower clay content and better cementation by quartz overgrowths would strengthen a rock mechanically, providing the most likely explanation for the observed difference in strength.

DISCUSSION: POSSIBLE ORIGIN(S) OF THREE FRACTURE SETS

An understanding of the fracture origins would be useful for inferring the possible distributions of the fracture sets beyond the O'Daniel site, but the reasons for the difference between the two fracture systems are not obvious. Possible reasons for fracture-system dissimilarities include differences in stress and strain undergone by the two beds, differences in the pore pressures within the beds at the time of fracturing, differences in bed thicknesses, and/or differences in the mechanical properties of the two units.

Reconstructions of the bed thickness (based on the geometric relationships between bedding dip, deviation angle, and lengths of the wellbores that slant at low angles across the beds) indicate that both of the sandstones are 3–4 ft (1–1.2 m) thick. Although bed thickness variations would have more influence on fracture spacing than fracture type, similar thicknesses of the beds eliminate this variability from consideration. Moreover, minimal structure, homogeneity of the Spraberry Formation, and the stratigraphic proximity of the 1U and 5U beds argue against significant differences in the local strain magnitudes, stress differential, or formation pore pressures between the two beds.

The difference in mechanical properties between the two beds is the only known factor that might account for the difference in fracture systems. It has another advantage in that it is one of the few factors that satisfies a less obvious requirement for a plausible explanation for the fracture differences. A plausible explanation not only must address the formation of three different fracture sets but also must suggest why fractures of set 1 did not also form in abundance in the 5U sandstone, and, equally, why the 5U fracture system is not pervasive in the 1U bed. Differences in mechanical properties are offered as the underlying factor, but in the following discussions it should be kept in mind that the fracture data from the horizontal Spraberry cores comprise an excellent yet relatively small and one-dimensional sampling of the subsurface fracture population.

Three separate fracture sets may form in several ways. End members of the spectrum of possibilities are (1) three fracture sets may result from three separate, sequential fracturing events, and (2) three fracture sets may form contemporaneously as parts of an integrated fracture system.

Interpretation as Fracturing by Separate Events

As described, each of the cored fracture sets has a characteristic suite of spacing distributions, distributions with respect to lithology, strikes, and mineralization, suggesting that perhaps they formed sequentially in response to different strain events. This could be supported by initial statistical interpretations of the spacing distributions (see Appendix) and the few data suggestive of relative age relationships. For instance, the presence of more complete mineralization in the northeast-striking fractures of set 1 could be interpreted to mean that set 1 formed and was mineralized prior to the formation of the other two sets. Likewise, it could be inferred that set 3 fractures formed prior to the fractures of set 2 from the one cored fracture-abutting relationship.

Reconstructions of the tectonic history of the basin, however, indicate that there have been few tectonic events affecting the Permian basin and the Spraberry strata since deposition. The only significant post-Permian tectonic event has been the Laramide orogeny, which consisted of Late Cretaceous–Eocene, basement-involved thrusting several hundred kilometers to the west (e.g., Winfree, 1994, 1995). This was followed by or was possibly contemporaneous with gentle uplift and tilting of the strata and broad folding over basement faults (e.g., Ewing, 1991). Strains and stresses associated with the Laramide orogeny are most likely to have been controlling factors in fracturing of the Spraberry Formation if only because there are few other candidates, but this association is reinforced by parallelism between the inferred northeast-directed Laramide compression and the strikes of Spraberry fractures. Multiple fracturing events during and after Laramide deformation, each event accounting for one of the three fracture sets, would seem unlikely in this simple structural setting. More important, it should have imposed all three fracture sets onto both reservoir units.

Interpretation as an Integrated Fracture System

An alternative interpretation of the Spraberry fracture data set is that the significant difference in mechanical properties between the fractured layers accommodated the contemporaneous formation of three fracture sets during one strain event. Given the simple tectonic setting, a simple model is preferable to a complicated one.

The overall geometry of the composite Spraberry fracture strikes is similar to, though not identical with, that of a conjugate shear or conjugate hybrid fracture pair (i.e., sets 2 and 3), with an associated (set 1) extension-fracture system (compare Figure 12a vs. 12b). The strike of the latter lies within the acute angle defined by the strikes of the former, although it does not perfectly bisect that angle. Geometry by itself is insufficient to prove an origin as a contemporaneous conjugate pair (e.g., Pollard and Aydin, 1988), although some support for formation as a conjugate shear pair is provided by the few anastamosed and stepped fracture planes. All but one of these fractures even show the proper indications of right-lateral or left-lateral shear (e.g., Petit, 1987; Lorenz, 1997d; Wibberly et al., 2000) for their orientation within the proposed conjugate pattern.

The relatively small conjugate angles of intersection, and the dominantly planar (extension) fracture surfaces, suggest that if the set 2 and set 3 fractures formed contemporaneously, they may belong to the

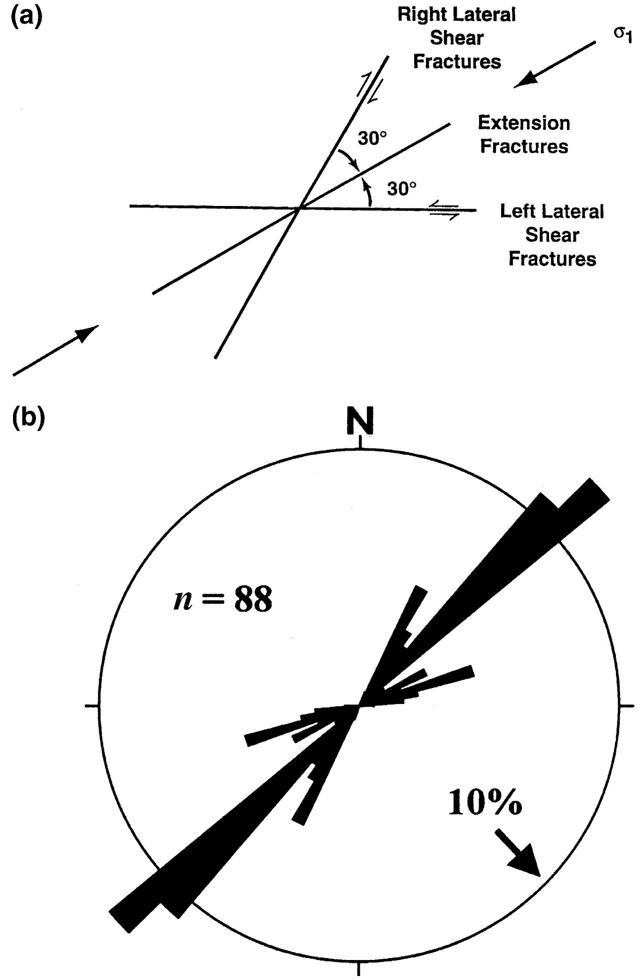


Figure 12. (a) Plan-view pattern of an ideal conjugate pair with an extension fracture bisecting the acute angle. (b) Rose diagram of the 88 1U and 5U fractures that occur in the reservoir sandstones. Outer ring = 10% of the total fracture population plotted.

elusive fracture category Hancock (1986) has called "conjugate hybrid fractures." Hybrid fractures also form conjugate patterns and can be associated with related extension fractures, but the dihedral intersection angles of hybrid fractures are typically less than the 60° that is associated with ideal conjugate shear pairs. Hancock (1986) indicated that the normal stress across such fractures can be less than zero for dihedral angles of less than 45°, possibly explaining an absence of shear indicators on most set 2 and set 3 fracture faces. Unfortunately, published characterizations of hybrid fracture characteristics and patterns, which could be used for comparison, are uncommon.

Support for the integrated fracture formation interpretation is found in the northeast-trending in-situ, present-day maximum horizontal compressive stress at the O'Daniel site. This trend (055°) (D. Holcomb, 1997, personal communication) lies neatly within the acute set 2/set 3 conjugate angle and subparallel to the average strike of set 1 extension fractures. Whether or not this is a remnant Laramide stress, this is the orientation that would be expected if a horizontal compressive stress formed an integrated extension/conjugate fracture system. It would be less convoluted to have fractured all of the strata at once under this stress configuration than to have formed the various fracture sets under sequentially different stress orientations that coincidently wound up with an orientation as the apparent acute-angle bisector. The similar, generalized Pareto fracture-spacing distributions of sets 2 and 3 (see Appendix) also suggest that fracture sets 2 and 3 are related.

Discussion

To make the interpretation of an integrated conjugate-and-extension fracture system work, there must be a reason for the formation of conjugate fractures in one bed and extension fractures in another within the same stress/strain setting. Theoretical considerations (e.g., Griggs and Handin, 1960; Hancock, 1986) suggest that weak rock may fail in a conjugate pattern under the same stress conditions that create subparallel extension fractures in stronger rock. Thus the factor-of-two difference in the yield strength of the two Spraberry units (Figure 11) offers mechanical stratigraphy as a basis for this system. Such differences in rock properties can have dramatic effects on fracture characteristics, in the extreme allowing extensive fracturing in some layers while leaving others entirely unfractured (e.g., Lorenz, 1997e). In the Spraberry case, a conjugate shear or hybrid fracture pair formed in one layer, and an extension fracture set, with a strike that approximates the bisector of the acute conjugate angle, formed in a nearly adjacent layer. Hancock (1986) called this a "dynamically compatible" fracture pattern. Extension fractures in one bed of the Spraberry Formation may be equivalent to and transition into conjugate shear and/or hybrid fractures in another layer, or even laterally in the same layer, depending on variations in mechanical strength of the rock.

One way to assess the plausibility of this model would be to determine whether the amounts of strain accommodated by the two fracture systems are equivalent. The average spacing of set 1 extension fractures is about 3 ft (~1 m) and the average aperture is on the order of 0.01 in. (0.25 mm), thus the average strain in the 1U bed is about 0.025%. To get 0.025% lateral strain within a bed containing inclined shear fractures with the average orientations and spacings of the fractures of sets 2 and 3, the average shear offset would be roughly 0.04 mm. This is a plausibly small amount of offset, and although the actual offsets are indeterminable on set 2 and set 3 fractures even where en echelon indications of shear are present, it allows but does not prove a simultaneous origin of the three fracture sets. Likewise, the apparently random placement of the set 2 and set 3 fractures relative to each other (Appendix) suggests that neither set was developed prior to the other, that is, that neither set created a preexisting heterogeneity in the rock that influenced the placement of a younger set. This favors, but again does not prove, a conjugate origin for the set 2 and set 3 fractures.

Microfractures illuminated by cathodoluminescence under the microscope have been suggested to be related to larger scale fracture characteristics (e.g., Laubach, 1997) and might be expected to shed light on the origins of the larger Spraberry macrofractures. Three samples of sandstones from the upper (1U) horizontal core were analyzed for microfracturing using cathodoluminescence techniques (S. E. Laubach, 1997, personal communication). One sample, located midway between two mineralized fractures spaced 5.5 ft (1.67 m) apart and having strikes of 040 and 045°, had a vector mean microfracture strike measured by cathodoluminescence of 025°. Two analyses from a second sample located immediately adjacent to a fracture with a 045° strike had vector mean microfracture strikes of 019 and 347°. Three analyses of the third sample, located midway between two fractures with 080 and 040° strikes and spaced 4.4 ft (1.34 m) apart, had vector mean microfracture strikes of 025, 042, and 032°. The reported average strike of 025° ± 010° for all microfractures would appear to be best aligned with the strikes of the set 2 fractures in the 5U sandstone, rather than with the set 1 fractures that dominate the 1U interval from which the cathodoluminescence samples were taken.

The primary shortcomings of the integrated conjugate-and-extension fracture interpretation would appear to be the somewhat less than ideal conjugate geometry of the 1U and 5U fracture strikes and the dissimilarities in the set 2 and set 3 distributions with respect to lithology (i.e., set 3 is present in the shales, but set 2 is not). The fact that only 21% of the set 2 and set 3 fractures indicate shear is of interest but is not problematic if these fractures originated conjugate hybrid fracture pairs, which Hancock (1986) suggested could have a conjugate geometry and contemporaneous formation while forming in extension.

The difference between the amount of mineralization in fractures of set 1 vs. fractures of sets 2 and 3, suggested in a previous section as a possible indicator of the relative ages of fracturing, could instead be related to differences in fluid flow capacities of the two systems. Interconnected conjugate fractures should have had better conductivity within the reservoirs, allowing for easy mineralization or, equally, for its dissolution. A system of poorly connected, subparallel extension fractures, however, may have become a relatively closed system early on during mineralization, minimizing subsequent fluid flow and preserving the mineralization.

Given the small sampling of the fracture population and the tendency for geologic phenomena not to conform to the ideal, we are comfortable with offering the dynamically compatible fracture model as a working hypothesis for interpreting the Spraberry fracture system. Regardless, the model of fracture origin itself is not as important as the fact that significant variability is present in the subsurface fracture system of the Spraberry Formation.

IMPLICATIONS FOR RESERVOIRS

Natural fractures create a horizontal permeability anisotropy of up to 1000:1 in Spraberry reservoirs, typically along a northeast-southwest trend but with local, previously unexplained variations (Elkins and Skov, 1960). For example, the Humble pulse test in the 1960s in the Midkiff unit confirmed the northeast-southwest maximum permeability direction, but a pulse test conducted less than one mile away yielded a faster pulse transmissibility in the east-west direction (Schechter et al., 1996a). Data from the horizontal, Parker and Parsley 28 E. T. O'Daniel cores highlight variability in the Spraberry fracture characteristics that is present within reservoirs despite seemingly homogeneous lithologies and an absence of major structure, and that accounts for the local variations in permeability anisotropy.

Variability in the production potential of different zones across the play may be related to the different interconnectivity (intersecting or nonintersecting fractures) and conductivity (degree of mineralization) of the different fracture systems. Horizontal permeability anisotropy should be higher in zones that contain only the subparallel, northeast-southwest (set 1) fracture type. In contrast, reservoirs with weaker strata and the resulting intersecting fractures should have a less pronounced permeability anisotropy and better connectivity within the reservoir (e.g., Lorenz, 1997c). Thus, production rates from a conjugate Spraberry fracture system should be greater, both because of the better fracture interconnection and because of the insignificant mineralization. The lateral of the Parker and Parsley 28 E. T. O'Daniel well within the 1U reservoir, containing mineralized, subparallel, set 1 fractures, had an initial production (on 12/18/97) of 47 bbl of oil, 8 bbl of water, and 26 mcf of gas per day. Through the first half of 2001, the average daily production from this lateral was 8 bbl of oil, 45 bbl of water, and 3 mcf of gas (W. Knight, 2001, personal communication). Unfortunately, the lateral leg through the lower horizon, which contains the system of intersecting conjugate fractures, was lost before a comparison could be made between the production capabilities of the two fracture systems.

Such nonuniformity is exacerbated in the Spraberry Formation by low horizontal stress differentials that allow opening, closing, and extension of fracture systems. The in-situ stresses, and the related resistance of the Spraberry Formation to fracturing, are presently so low that mud weights and the piston action of tripping a core barrel into a hole full of drilling mud are commonly sufficient to cause hydraulic fractures in the formation. This results in Spraberry cores that are commonly intensely petal-fractured and/or split in one or more parallel planes along the core axis for much of the length of a core barrel. This below-the-bit, inadvertent hydraulic fracturing is probably common but undocumented in uncored Spraberry holes as well, because the hydraulic fracture gradient in the formation (0.40–0.045 psi/ft) (Baker et al., 2000) is about that of the weight of a column of water. So-called vacuum fracs, where the formation is broken down and stimulated by a hydraulic fracture created merely by the weight of a column of fluid in the wellbore, are a typical stimulation practice in the play.

Anisotropy ratios and orientations have also changed over time at a given Spraberry location, reflecting the dynamics of fracture apertures under conditions of changing in-situ stresses during production or injection (e.g., Lorenz, 1999b). Hydraulic fractures and low-pressure water injections for enhanced oil recovery in the Spraberry tend to follow the dominant natural fractures below a threshold injection pressure but are less constrained above this threshold because the low in-situ stress magnitudes and differential are easily overcome by injection pressures. Such stress changes cause existing, but previously ineffective, off-trend Spraberry fracture sets to open and become more permeable, leading to off-trend interwell communication. Humble's pulse test in the Midkiff unit demonstrated this phenomenon: water was injected into a pilot pattern over a period of six months, and communication was established between wells along the northeast-southwest trend early in the test. No communication was observed initially between the injection wells and production wells aligned perpendicular to this trend. Once injection water broke through to the off-trend wells, however, the volume of water recovered from those wells gradually increased as injection proceeded. A secondary, stress-sensitive fracture network was opened and exploited by the increased reservoir pressures created by continued water injection, decreasing the horizontal permeability anisotropy of the system.

Further evidence of stress-sensitive fractures was observed in 1993 during an 80 ac water-injection pilot in upper Spraberry reservoirs, also in the Midkiff unit (Schechter et al., 1996a). Production wells at this site, oriented northeast and southwest from an injection well, were monitored after initiation of water injection. None of the injected water was recovered from the nearest offset well for nearly 300 days. Once communication between the wells had been established, an injected radioactive tracer reached the production well within 24 hr. This change in conductivity of the reservoir system suggests that conductivity of the fracture system was enhanced as the fluid pressure in the fractures increased. Recent testing, however, has shown that enhanced fracture conductivity returns to near original values after an injection well is shut in, indicating reclosure of the fractures (Baker et al., 2000).

SUMMARY

Horizontal cores taken from two different levels of the Spraberry Formation show that significantly different systems of natural fractures can be present in otherwise similar, closely adjacent, sandstone-siltstone reservoirs. One fracture system consists of evenly spaced, mineralized, vertical, northeast-striking fractures. The other system, occurring in strata only 145 ft (44 m) deeper, consists of a less mineralized, vertical, intersecting fracture pair, the members of which strike north-northeast and east-northeast. Both fracture systems probably formed during the same Laramide tectonic event as a dynamically compatible system of fractures. Differences in the petrographic makeup of the two layers, primarily their clay content and the volume of quartz overgrowths, created important differences in yield strengths and an important mechanical stratigraphy. Subparallel extension fractures formed in the stronger layer, and intersecting conjugate shear or hybrid fractures formed in the weaker strata. The strikes of the former, as well as the trend of the present-day maximum horizontal compressive stress, are within the acute conjugate angle of the latter. This variability may be predictable to the extent that the subtleties in local diagenetic and depositional histories can be accurately reconstructed. Fracture characteristics, however, may vary significantly between different Spraberry reservoir units: the systems documented here, consisting of subparallel extension fractures in the upper zone with an intersecting conjugate fracture pattern in the lower unit, should not be extrapolated universally to the 1U and 5U Spraberry reservoirs across the Midland basin. The minimal differential between the present-day in-situ horizontal stresses, as well as the low in-situ stress magnitudes, provide poor constraints on the azimuths of hydraulic injections into the formation. Fluid injection causes temporary enhancement of fracture permeability, and fractures aligned in off-trend orientations may also be opened up under such higher pressure conditions.

APPENDIX: STATISTICAL ANALYSIS OF FRACTURE SPACING DATA

The spatial location data (spacing) of all three Spraberry fracture sets were evaluated statistically. Set 3 data were restricted to those fractures listed in Table 1 that are in the reservoir sandstone. Brief definitions of some less familiar statistics are given in the following paragraphs; a fuller discussion can be found in Davis (1986), Jensen et al. (2000), and other texts.

A summary of spacing sample statistics of all three fracture sets is shown in Table 3. Both the median and the average serve as simple measures of the typical spacing. Although there is some variation across the three sets, neither the medians nor the averages are statistically different at the 5% level. That is, the differences between the averages or medians of the three sets could be explained by the limited number of samples and the spacing variability.

In contrast, the variabilities (Table 3) assessed using the standard deviation, the interquartile range (IQR), or the linear L-scale (λ_2), do change markedly. All measures show set 3 spacings have

Table 3. Fracture Spacing Statistics*

	Set 1	Set 2	Set 3 (Sandstone only)
Number of spacings	19	24	13
Average, ft	2.9	2.4	4.4
Standard deviation, ft	1.2	1.9	3.9
C_v	0.4	0.8	0.9
Median, ft	2.8	2.7	3.5
IQR, ft	1.6	2.8	6.0
ℓ_2	0.7	1.1	2.2
t_3	0.05	0.15	0.24
t_4	0.15	0.04	0.08

*C_V = coefficient of variation = average/standard deviation; median = 50th percentile value; IQR = interquartile range = 75th minus 25th percentiles; ℓ_2 = L-scale; t_3 = L-skewness; and t_4 = L-kurtosis.

about twice the variability of set 2, whereas set 1 has only about two-thirds the variability of set 2. These results suggest that the spacings of the three sets are sufficiently dissimilar that sampling variation could not be the sole cause of the differences.

The large differences in variability indicate the sets come from different parent distributions, but they do not indicate the forms of those distributions. Several distribution forms have been observed for other fracture spacing populations (e.g., Dershowitz and Einstein, 1988); the exponential, power-law (or Pareto), and lognormal appear particularly common (Korvin, 1992, chapter 3). Plots for these and other distributions were used to test the Spraberry data sets (Figures 13, 14).

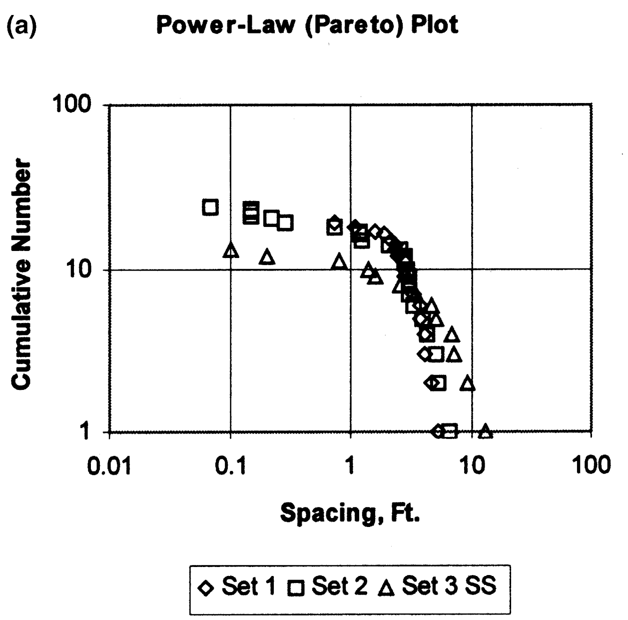
None of the Spraberry data sets exhibits power-law behavior (Figure 13a). A distinctive knee occurs for all sets in the region of about 2–4 ft. spacing. This suggests that fractal models are unsuitable for the fracture spacings cored in the Spraberry formation.

The relatively straight line formed by set 1 spacings could be considered as coming from a lognormal population (Figure 13b). Sets 2 and 3 do not, however, appear to be either lognormal (Figure 13b) or exponential (Figure 14a). Both plots of Figure 13 suggest that, for values in excess of about 2 ft, sets 1 and 2 have fracture spacings with similar distributions. For spacings smaller than 2 ft, however, set 2 has a considerable number of fractures that are much more closely spaced than set 1.

Probability plots can be useful for data diagnosis, as well as for defining distributions. Where data sets are small, however, probability plots may not give definitive results in determining the distribution a data set is likely to belong to (i.e., parent distribution). Thus, an alternative method was used to confirm the previous distribution observations by using analysis with L-moments (Hosking and Wallace, 1997). The L-moments give assessments similar to conventional statistics but are more robust. For example, the L-scale (λ_2) is a measure of variability, similar to the standard deviation, but is less subject to the extreme values in a data set. Combining the L-skewness and L-kurtosis measures, t_3 and t_4, (Figure 14b) has been found to give good results with small data sets for determining parent distributions (Hosking and Wallace, 1997, p. 40–41).

Figure 14b indicates that set 1 is approximately lognormal, in agreement with the assessment based on Figure 13b. Sets 2 and 3 appear to have generalized Pareto (GPA) distributions. Both sets plot on the GPA line and left of the point representing the exponential distribution. This implies that each set of spacings could come from a parent population with a distribution that is similar in form to an exponential distribution but that does not have as long a tail (Johnson et al., 1994, p. 614 ff). That is, the assumption that sets 2 and 3 are exponentially distributed would predict some spacings that are larger than the data indicate.

Fracture relationships were also investigated. None of the sets showed a statistically significant relationship between one spacing



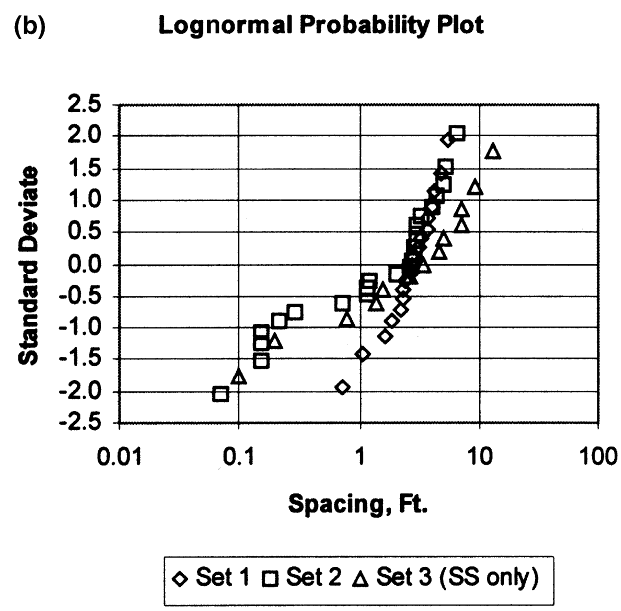


Figure 13. (a) Power-law (Pareto) and (b) lognormal probability plots for fracture spacing distributions. If the Spraberry data belonged to a distribution similar to that titled on the plot, the points should lie approximately on a straight line on that plot.

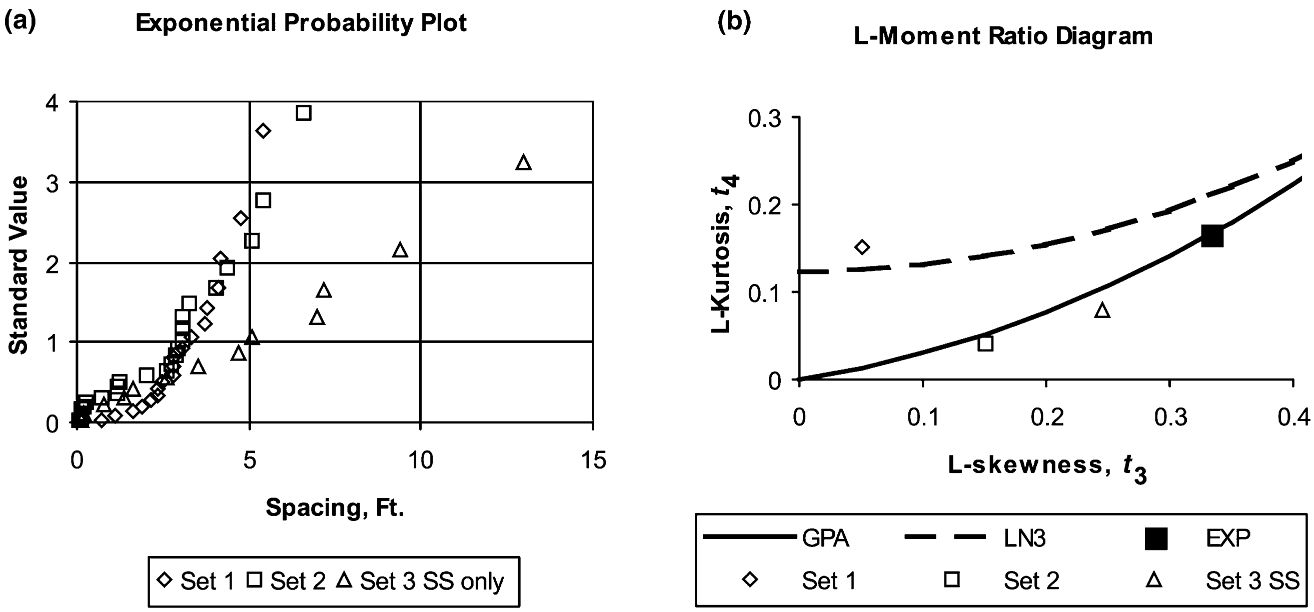


Figure 14. Further fracture spacing distribution plots: (a) exponential probability plot; (b) L-moment ratio diagram. GPA = generalized Pareto curve; LN3 = lognormal distribution curve; EXP = the point for the exponential distribution. The normal point is where the LN3 curve intersects the vertical axis.

and the spacing of adjacent fractures of the same set (Figure 15). This suggests that the fractures in each set do not show preferential bunching (e.g., swarming) or spreading.

The sequence of fractures in sets 2 and 3 was also tested. A chi-square (χ^2) test (Davis, 1986) was applied to determine if these fractures exhibited any systematic relationship. In particular, if one picked a set 2 fracture at random, what would be the probability that the next fracture also belongs to set 2. If there is no preferential relationship, the probability would be about 25/39 or 64%. A value much smaller than this would signify that set 3 fractures preferentially succeed set 2 members. A value much larger than 26/39 would suggest that set 2 fractures preferentially follow. The result, 14/25 or 56%, gives $\chi^2 = 1.4$ and is insignificant at the 20% level. Thus, both spacings and the set membership appear unrelated to neighboring spacing and membership.

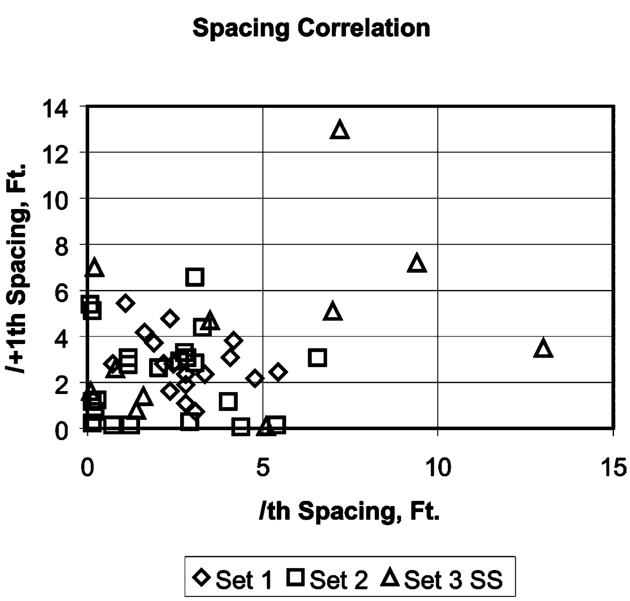


Figure 15. Comparison of the spacing of a pair of fractures of a given set (*x* axis) with the spacing of the neighboring pair (*y* axis).

REFERENCES CITED

Avasthi, J. M., R. C. Nolen-Hoeksema, and A. W. M. Rabaa, 1991, In-situ stress evaluation in the McElroy field, west Texas: Society of Petroleum Engineers Formation Evaluation, v. 6, p. 301–309.

Baker, R. O., R. A. Contreras, and D. Sztukowski, 2000, Characterization of the dynamic fracture transport properties in a naturally fractured reservoir: Society of Petroleum Engineers Permian Basin Oil and Gas Recovery Conference, SPE 59690, 15 p.

Calhoun, G. C., and R. E. Webster, 1983, Surface and subsurface expression of the Devils River uplift, Kinney and Val Verde counties, Texas, *in* E. C. Kettenbrink Jr., ed., Structure and stratigraphy of the Val Verde basin–Devils River uplift, Texas: West Texas Geological Society Publication 83-77, p. 101–118.

Cather, M., and J. C. Lorenz, 1998, Characterization of natural fractures in Spraberry trend area reservoirs, Permian basin, west Texas (abs.): AAPG Annual Convention, Program with Abstracts, v. 7, unpaginated.

Davis, J. C., 1986, Statistics and data analysis in geology, 2d ed.: New York, John Wiley and Sons, 656 p.

Dershowitz, W. S., and H. H. Einstein, 1988, Characterizing rock joint geometry with joint system models: Rock Mechanics and Rock Engineering, v. 21, p. 21–51.

Elkins, L. F., 1953, Reservoir performance and well spacing, Spraberry trend area field of west Texas: Petroleum Transactions of the American Institute of Mining Metallurgical and Petroleum Engineers, v. 198, p. 177–196.

Elkins, L. F., and A. M. Skov, 1960, Determination of fracture orientation from pressure interference: Petroleum Transactions of the American Institute of Mining Metallurgical and Petroleum Engineers, v. 219, p. 301–304.

Elkins, L. F., and A. M. Skov, 1963, Cyclic water flooding in the Spraberry utilizes "end effects" to increase oil production rate: Journal of Petroleum Technology, v. 15, p. 877–884.

Erdlac, R. J., 1993, Small-scale structures in the Guadalupe Mountains region: implication for Laramide stress trends in the Permian basin: New Mexico Geological Society Guidebook, 44th Field Conference, Carlsbad region, New Mexico and West Texas, p. 167–174.

Ewing, T. E., 1991, The tectonic framework of Texas: text to accompany the tectonic map of Texas: University of Texas at Austin, Bureau of Economic Geology, 36 p.

Griggs, D., and J. Handin, 1960, Observations on fracture and a hypothesis of earthquakes: Geological Society of America Memoir 79, p. 347–364.

Guevara, E. H., 1988, Geological characterization of Permian submarine fan reservoirs of the Driver waterflood unit, Spraberry trend, Midland basin, Texas: Bureau of Economic Geology Report of Investigations 172, 44 p.

Hancock, P. L., 1986, Joint spectra, *in* I. Nichol, and Rl. W. Nesbitt, eds., Geology in the real world—the Kingsley Dunham volume: London, Institution of Mining and Metallurgy, p. 155–164.

Hills, J. M., 1970, Late Paleozoic structural directions in southern Permian basin, west Texas and southeastern New Mexico: AAPG Bulletin, v. 54, p. 1809–1827.

Hosking, J. R. M., and J. R. Wallis, 1997, Regional frequency analysis: Cambridge, Cambridge University Press, 224 p.

Jensen, J. L., L. W. Lake, P. W. M. Corbett, and D. J. Goggin, 2000, Statistics for petroleum engineers and geoscientists, 2d ed.: Amsterdam, Elsevier, 356 p.

Johnson, N. L., S. Kotz, and N. Balakrishnan, 1994, Continuous univariate distributions, 2d ed.: New York, John Wiley and Sons, 756 p.

Korvin, G., 1992, Fractal models in the earth sciences: Amsterdam, Elsevier, 396 p.

Kulander, R., S. L. Dean, and B. J. Ward Jr., 1990, Fractured core analysis, interpretation, logging, and use of natural and induced fractures in core: AAPG Methods in Exploration Series 8, 88 p.

Laubach, S. E., 1997, A method to detect natural fracture strike in sandstones: AAPG Bulletin, v. 81, p. 604–623.

Lorenz, J. C., 1992, Well-bore geometries for optimum fracture characterization and drainage: West Texas Geological Society Bulletin, v. 32, p. 5–8.

Lorenz, J. C., 1995, Recognition and use of induced fractures and other features in core produced by the coring process (abs.): The Economic Integration of Geology and Formation Evaluation, Core Session of the First Joint Symposium of the Canadian Society of Petroleum Geologists and the Canadian Well Logging Society, unpaginated.

Lorenz, J. C., 1997a, Horizontal core fracture description: Spraberry Symposium at the University of Texas Permian Basin Center for Energy and Economic Diversification, section K, 22 p.

Lorenz, J. C., 1997b, Non-congruent natural fracture sets in adjacent beds at depth: data from horizontal cores from the Spraberry Formation, Midland basin, TX (abs.): AAPG Hedberg Research Conference on Reservoir Scale Deformation—Characterization and Prediction.

Lorenz, 1997c, Conjugate fracture zones: potential "sweet spot" reservoirs within regional parallel-fracture systems: Society of Petroleum Engineers Annual Technical Conference and Exhibition, SPE paper 38749, p. 481–484.

Lorenz, J. C., 1997d, Conjugate fracture pairs in the Molina Member of the Wasatch Formation, Piceance basin, Colorado: implications for fracture origins and hydrocarbon production/exploration, *in* J. C. Close and T. A. Casey, eds., Natural fracture systems in the southern Rockies: Farmington, Four Corners Geological Society, p. 97–104.

Lorenz, J. C., 1997e, Heartburn in predicting natural fractures: the effects of differential fracture susceptibility in heterogeneous lithologies, *in* T. E. Hoak, A. L. Klawitter, and P. K. Blomquist, eds., Fractured reservoirs: characterization and modeling: Rocky Mountain Association of Geologists 1997 Guidebook, p. 57–66.

Lorenz, J. C., 1999a, Fractures and features unique to deviated cores: the relative merits of horizontal and vertical cores for characterizing fractures and stresses (abs.): AAPG Hedberg Symposium, unpaginated.

Lorenz, J. C., 1999b, Stress-sensitive reservoirs: Journal of Petroleum Technology, v. 51, p. 61–63.

Lorenz, J. C., and R. E. Hill, 1992, Measurement and analysis of fractures in core, *in* J. W. Schmoker, E. B. Coalson, and C. A. Brown, eds., Geologic studies relevant to horizontal drilling: examples from western North America: Rocky Mountain Association of Geologists, p. 47–59.

McDonald, P., J. C. Lorenz, C. Sizemore, D. S. Schechter, and T. Sheffield, 1997, Fracture characterization based on oriented horizontal core from the Spraberry trend reservoir: a case study: Society of Petroleum Engineers Annual Technical Conference and Exhibition, SPE paper 38664, p. 231–239.

Montgomery, S. L., D. S. Schechter, and J. C. Lorenz, 2000, Advanced reservoir characterization to evaluate carbon dioxide flooding, Spraberry trend, Midland basin, Texas: AAPG Bulletin, v. 84, p. 1247–1273.

Nolen-Hoeksema, R. C., J. M. Avasthi, W. C. Pape, and A. W. M. El Rabaa, 1992, Waterflood improvement in the Permian basin: impact of in-situ stress evaluations: Society of Petroleum Engineers Annual Technical Conference and Exhibition, SPE paper 24873, p. 81–92.

Petit, J. P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: Journal of Structural Geology, v. 9, p. 597–608.

Pollard, D. D., and A. Aydin, 1988, Progress in understanding jointing over the past century: Geological Society of America Bulletin, v. 100, p. 1181–1204.

Price, J. G., and C. D. Henry, 1985, Summary of Tertiary stress orientations and tectonic history of trans-Pecos Texas, *in* T. W. Dickerson and W. R. Muehlberger, eds., Structure and tectonics of trans-Pecos Texas: West Texas Geological Society Field Conference, p. 149–151.

Schechter, D. S., P. McDonald, T. Sheffield, and R. O. Baker, 1996a, Reservoir characterization and CO_2 pilot design in the naturally fractured Spraberry trend area: Society of Petroleum Engineers Permian Basin Oil and Gas Recovery Conference, SPE 36469, p. 819–833.

Schechter, D. S., P. McDonald, T. Sheffield, and R. O. Baker, 1996b, Integration of laboratory and field data for development of a CO_2 pilot in the naturally fractured Spraberry trend: Society of Petroleum Engineers Annual Technical Conference and Exhibition, SPE paper 36657, p. 939–944.

Sterling, J. L., 2000, Fracture generation and fluids in the Spraberry Formation, Midland basin, Texas: Master's thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 92 p.

Tyler, N., and J. C. Gholston, 1988, Heterogeneous deep-sea fan reservoir, Shackelford and Preston waterflood units, Spraberry trend, west Texas: University of Texas at Austin, Bureau of Economic Geology, Report of Investigation 171, 38 p.

Wibberley, C. A. J., J. P. Petit, and T. Rives, 2000, Micromechanics of shear rupture and the control of normal stress: Journal of Structural Geology, v. 22, p. 411–427.
Wilkinson, W. M., 1953, Fracturing in Spraberry reservoir, west Texas: AAPG Bulletin, v. 37, p. 250–265.
Winfree, K. E., 1994, Post-Permian folding and fracturing of the Spraberry and San Andres formations within the Midland basin region of west Texas, *in* T. M. Laroche and J. J. Viveiros, eds., Structures and tectonics of the Big Bend and southern Permian basin, Texas: West Texas Geological Society Field Trip Guidebook, Publication 94-95, p. 189–212.
Winfree, K. E., 1995, Post-Permian folding and fracturing of the Spraberry and San Andres formations within the Midland basin region of west Texas: West Texas Geological Society Bulletin, v. 35, no. 3, p. 5–20.
Wu, H., and D. D. Pollard, 1995, An experimental study of the relationship between joint spacing and layer thickness: Journal of Structural Geology, v. 17, p. 887–905.