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SUBSURFACE FRACTURE SPACING: COMPARISON OF INFERENCES FROM SLANT/HORIZONTAL CORE AND VERTICAL CORE IN MESAVERDE RESERVOIRS

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ABSTRACT

Two hundred thirty-six (236) ft (71.9 m) of slant core and 115 ft (35.1 m) of horizontal core from the U.S. Department of Energy's Slant Hole Completion Test well (SHCT-1) in the Piceance basin, Colorado, show irregular, but remarkably close, spacings for 72 natural fractures cored in sandstone reservoirs of the Mesaverde Group. Over 4200 ft (1280 m) of vertical core (containing 275 fractures) from the vertical Multiwell Experiment wells at the same location provide valuable information on fracture orientation, termination, and height, but only data from the SHCT-1 core allow calculations of relative fracture spacing. Within the 162-ft (49-m) thick zone of overlapping core from the vertical and deviated wellbores, only one fracture is present in vertical core whereas 52 fractures occur in the equivalent SHCT-1 core. Measured fracture spacing in the deviated core varies from ≤0.1 ft to 17 ft (<0.03-5.2 m), and has a Weibull distribution that is strongly skewed toward the closer spacings. The relationship between bed thickness and fracture spacing is poor. The irregular distribution of regional-type fractures in these heterogeneous reservoirs suggests that measurements of "average fracture spacing" are of questionable value as direct input parameters into reservoir engineering models. Rather, deviated core provides data on the relative degree of fracturing, and confirms that cross fractures can be rare in the subsurface.

INTRODUCTION

This study was undertaken in order to document and analyze the unique set of data on subsurface fracture characteristics, especially spacing, provided by the U.S. Department of Energy's Slant Hole Completion Test well (SHCT-1). The SHCT-1 well is located at the Multiwell Experiment (MWX) site in northwestern Colorado. MWX was a field laboratory consisting of three closely spaced wells designed to characterize low-permeability sandstones, and to evaluate state-of-the-art and developing technology for production stimulation of these unconventional gas reservoirs.[1] Over 4200 ft (1280 m) of core were taken from the three wells during 1981-1983.

The SHCT project is designed to evaluate directional and horizontal drilling as an alternative development strategy for the tight, naturally fractured Mesaverde sandstones and coals. The SHCT-1 well reached total depth in August 1990. About 351 ft (107 m) of standard core, and 30 ft (9.1 m) of pressure core were collected from this well.

The SHCT-1 surface location is about 600 ft (185 m) south of the MWX site. The well was designed such that the deviated wellbore azimuth would trend as near as possible to perpendicular to the approximately west-northwest strike of the dominant subsurface natural fracture set, which had been measured in MWX core[1-5]. The as-built wellbore azimuth trends N2°W-N4°W through the cored intervals. The well was drilled to a depth of 6365 ft (1940 m) before being deviated to 60°. The well was then drilled at 60° for 1406 ft (429 m) before being kicked out to 85° (Fig. 1). The wellbore was never fully horizontal, although the 85° portion was drilled down the structural dip and is within a few degrees of parallel to bedding.

The four wells of this study are located in Garfield County, Colorado, about 9 miles (14 km) west of Rifle, in section 34, T6S, R94W. The wells test sandstone reservoirs of the Upper Cretaceous Mesaverde Group in the east-central part of the Piceance basin. The SHCT wellbore passes east of MWX-2 and MWX-3, and west of MWX-1 (Fig. 1). The slant core was taken through the MWX triad, and the lower, near-horizontal core was taken about 1200 ft (366 m) north of that location.

References and figures at end of paper.

Natural fractures have been proven to be an important production mechanism in the low-permeability Mesaverde reservoirs at the MWX site[2]. The local reservoir matrix-rock permeability is typically 0.1 to 2.0 microdarcies in restored-state laboratory measurements[3], whereas reservoir permeabilities calculated from well tests are two to three orders of magnitude higher due to the influence of the fracture system. Permeability is highly anisotropic at this site, due to the dominance of a single set of regional fractures in the subsurface.

DATA REVIEW AND METHODS

Types of Reservoirs

Core was taken from the SHCT-1 wellbore in three different types of sandstone reservoirs. The 60° interval was cored across a ripple-bedded, amorphous splay deposit (paludal zone 4) and a more heterogeneous, crossbedded, lenticular channel deposit (paludal zone 3) about 350 ft (110m) wide. These reservoirs occur within a coal-bearing lower delta plain facies. The 85° interval was cored within a much larger, relatively homogeneous, shoreline to shallow-marine blanket sandstone (the Cozzette Sandstone Member of the Iles Formation). All of these strata are part of the Upper Cretaceous Mesaverde Group in the Piceance basin. All reservoirs in this formation at this location are naturally fractured, as indicated by the extensive well tests and core from the MWX project[1].

Cored Intervals

The intervals cored in the SHCT well were also cored in part in the MWX wells (Fig. 2). The overlapping intervals allow for comparison of fracture frequency data gathered from slant/horizontal core with vertical core. The overlapping intervals are within correlated sedimentologic units, with core intervals correlated from the top of the unit rather than depth relative to sea level. The slant core interval of 7305-7581 ft (2227-2310 m) measured depth [7057-7194 ft (2151-2193 m) true vertical depth] has 72 ft (22 m) of vertical overlap with core from MWX-2, and 78 ft (24 m) of vertical overlap with core from MWX-3. In the horizontal core interval of 8990-9108 ft (2740-2776 m) measured depth [7938-7950 ft (2420-2423 m) true vertical depth], there is a 12 ft (3.7 m) vertical overlap with core from MWX-2. There is additional vertical Cozzette core from MWX-1, but the core interval in this well started just below the interval cored in SHCT-1.

MWX Fracture Data Base

Two hundred and seventy-five near-vertical, natural extension fractures were recorded in 4200 ft (1280 m) of vertical, 4-in (10-cm) diameter core taken from the three vertical MWX wells.[4,5] These fractures have a dominant west-northwest strike, and provide a data base for comparison with fractures in the deviated wellbore. Most of the fractures are single, isolated fractures, but en echelon fractures and closely spaced, multiply stranded fractures were counted as single fractures.

SHCT Fracture Data Base

Core from the SHCT-1 well includes 266 ft (81.1 m) of sandstone, mudstone and coal recovered from the 60° slant-hole section in the paludal zone, and 115 ft (35.1 m) recovered from the Cozzette sandstone where the wellbore is near horizontal. Natural fractures are abundant in the sandstone reservoir intervals in both zones, with 35 fractures recorded in paludal zones 3 and 4, and 37 fractures recorded in the Cozzette (Figs. 3 and 4). As in the MWX core, natural fractures are not present in the mudstones, although parallel to subparallel cleats occur in the coals. Only 16 of the paludal-zone fractures occur in core within the SHCT-MWX overlap zone. Unless fracture strands were seen to be connected, all fractures in the core from the inclined SHCT-1 wellbore were regarded as individual fractures regardless of how closely together they occur.

Fracture Orientation in SHCT-1

The core from SHCT was not oriented with multishot techniques. Rather, it was oriented by using bedding structures and data from the hole deviation survey. The method requires the core be fit together, with a master orientation line (MOL) marked across the top-dead-center of the core. All measurements are made relative to this line. In addition to fractures, bedding planes were measured in every continuous interval of core. Structural dip in the area is about 2 to 3 degrees to the northeast (insignificant relative to the hole inclinations of 60° to 85°), and thus, the apparent dip of bedding in core is in the general direction of the hole azimuth. Knowing that the in situ bedding is commonly horizontal, and that in deviated core it should therefore have an apparent dip in the hole azimuth direction, provides the means to orient the MOL. With the MOL oriented, all of the fracture strikes can be corrected to true orientation. The poles to the fractures were then plotted on a stereonet and rotated back to horizontal to get the true fracture orientations (Fig. 5). The mean strike and dip of measured fractures in the upper cored interval are N84°W and 89°S, respectively, and in the lower cored interval are N81°W, and 85°S. These average orientations were used to make the corrections for fracture spacing.

Fracture Widths

All natural fractures in the Mesaverde strata at this site are mineralized with quartz and/or calcite. Other, induced fractures are present in the core, but these can be recognized as induced on the basis of morphology and the absence of mineralization[5,6].

Measured fracture widths, including mineralization, range from 0.25 mm to 4 mm, averaging about 1 mm in SHCT core. Mineralization commonly fills half to two-thirds of this width, so that remnant (open) apertures range from 0 to 3 mm, averaging about 0.5 mm. The remnant apertures are irregular and have rough surfaces. Aperture may vary by 100% over a distance of several centimeters due to surface asperities and patchy mineralization. The mineralized surfaces commonly display an angular roughness caused by crystals which may be up to several millimeters in size. Where higher percentages of the fracture width are mineralized, crystals may extend across the fracture, leaving permeability pathways resembling clenched teeth. Vertical MWX core shows that an individual fracture may range from completely mineralized to having a remnant aperture of 1 cm along its length.

Other Fractures

Because the SHCT-1 wellbore azimuth (nearly north) was directed specifically such that it would trend as closely as possible to 90° to the dominant fracture trend, the number of west-northwest fractures intersected by the wellbore was maximized. However, three anomalous fractures were also encountered in the core. Two of these fractures strike northeast and occur within one foot (0.3 m) of each other in the upper half of paludal zone 4. The third fracture strikes northwest and occurs within the Cozzette. The first two are vertical extension fractures and are probably related to a minor population of northeast-striking fractures identified in MWX core. The vertical, northwest-striking fracture in the Cozzette is a right-lateral shear fracture that is unlike any fracture previously seen at this site.

Because of the 80° angular relationship between the SHCT-1 wellbore azimuth (N4°W) and the mean strike of the paludal-zone fracture set (N84°W), the wellbore hit about 98% of the fractures of the dominant set that it would have intersected had the wellbore been normal to the fracture trend (sine 80° = 0.98). Similarly, the wellbore is about 70% efficient in intersecting the northeast-trending fractures. If the two fracture sets had an equal frequency, the expected ratio of west-northwest fractures to northeast fractures present in the core would be 0.98/0.70 or 1.4/1, nearly equal. In fact, the actual measured frequency ratio is 70/2, or 35/1. This implies that the west-northwest fractures are about 25 times more numerous (35/1.4 = 25) than the northeast fractures (or that the northeast fractures comprise less than 4% of the total fracture population). In addition, this suggests that the cross fractures that are common in equivalent outcrops are primarily a surficial feature. For comparison, the northeast-trending fracture set in the vertical MWX core comprises three of 62 (less than 5%) of the fractures that were found in oriented core.[4,5]

Because they are rare, none of these anomalous fractures were included in the estimates of fracture spacing made below. However, they may be important in providing local communication between fractures of the dominant west-northwest set.

An isolated zone (4 ft [1.2 m] along the length of the core, or 3.4 ft [1.1m] of true reservoir width) in the upper half of paludal zone 3 contains approximately 28 unmineralized, planar and en echelon, vertical, west-northwest striking fractures. Study of these fractures is continuing, but their position and character is consistent with an interpretation that they are strands of a hydraulic fracture from one of the MWX stimulation experiments. They will not be considered further in this paper.

FRACTURE SPACING

Vertical MWX Wells

Estimating vertical-fracture spacing from vertical core is not a rewarding exercise. In the simplest case (where only one fracture set is present, where spacing is regular, and where each fracture extends the full thickness of the reservoir interval), the probability of encountering a fracture is the ratio of the width of investigation (core or wellbore diameter) to the fracture spacing. For multiple sets of fractures, a more complex Monte Carlo method of estimating intersection probability must be used[7]. However, meaningful estimates of fracture spacing are difficult to derive from the one-dimensional vertical data provided from a conventionally drilled wellbore, especially if (1) fractures with a different strike are present but cannot be distinguished in all cases from the first set, or (2) if en echelon fractures are irregularly distributed throughout the reservoir because of the influence of sedimentary heterogeneities (as is commonly the case).

Given enough vertical core, some estimates of relative fracture density can be made. At the MWX site, for instance, where 275 vertical extension fractures were encountered in 4200 ft (1280 m) of core, a ratio exists of approximately one fracture for every 15 ft (4.6 m) of core[4]. However, all but three percent of these fractures occur in sandstone (69%) or siltstone (28%), the high-modulus rocks that comprise less than half of the section. The most complete data set, which will be used for discussion here, comes from the 2000-ft (610-m) thick section containing heterogeneous fluvial sandstones, where 219 fractures were found within the 900 ft (275 m) of sandstone and siltstone cored. Fracture heights of up to 6 ft (1.8 m) were measured, but most of the fractures are less than 1 ft (0.3 m) high, even in sandstone beds with gross thicknesses of more than 10 ft (3 m) (Fig. 6). The tendency of slightly-less-than-vertical fractures to drift out of the core is a contributing factor to the prevalence of small measured fracture heights, but this phenomena is due primarily to the internal sedimentary heterogeneity of the reservoir sandstones. Fractures are commonly contained within the boundaries of the numerous thinner sedimentary/mechanical layers that comprise the total reservoir thickness.

The importance of fracture height being consistently less than bedding thickness is that it renders the significance of later calculations of "average fracture spacing" ambiguous. For example, in the population of 219 fractures in the fluvial zone, each with a top and bottom termination, there are 438 terminations. Of these, only 312 terminate within the core. (The rest extend beyond the lateral limits of the core due to the sub-parallel relationship between fracture plane and core axis.) Forty-eight percent of the 312 known terminations are at the mudstone contact marking the boundary of a sandstone. This percentage is relatively high because most of the fractures are found in relatively thin sandstones (Fig. 6). Thirty-four percent terminate for no apparent reason within the sandstone, and 18% terminate at an obvious sedimentary heterogeneity (See Fig. 6 of Reference 2). Therefore, over half of the fractures terminate <u>within</u> a sandstone bed, and over a third of <u>those</u> fractures terminate at an obvious lithologic discontinuity within the bed.

Thus, fractures are irregularly distributed in the vertical plane, and those fractures intersected by a horizontal transect (or wellbore) across the reservoir will be indicative of a relative fracture frequency, not the absolute spacing of some fracture set that extends from the top to the base of the reservoir. For this reason, the calculations of fracture spacing from deviated core that follow are relative measurements of lateral fracture frequency rather than absolute fracture spacings. This caution holds for all regional-type fractures in heterogeneous reservoirs.

The ratio of fractures to length of sandstone core in the fluvial interval in vertical MWX core is about one fracture per 4 linear ft (1.2 m) of core. However, only 47 of the 219 fractures (21%) occur in sandstones that are more than 10 ft (3 m) thick (approaching reservoir scale). Therefore, despite numerous fractures seen in the MWX core, most of the reservoirs themselves would have been considered to be unfractured had only 30 or 60 ft of core been acquired from one or two reservoirs of interest. To illustrate this, consider that within the confines of the paludal zone 3, the paludal zone 4, and the Cozzette reservoirs proper -- reservoirs where the deviated core shows extensive fracturing -- only one fracture was encountered in the 162 ft (49 m) of vertical core taken from sections in the three MWX wells which overlap the SHCT cored interval. Even if the entire 175 ft (53 m) of vertical core available from these reservoirs proper is examined, no more fractures are observed. Fractures were more common in the thin-bedded sandstones and siltstones underlying and overlying these reservoirs, but the reservoirs themselves were only inferred to be fractured. This inference was based on the presence of associated fractures and from the indications of anomalously high permeabilities calculated during well testing, not from abundant fractures cored in the reservoirs.

There is no reliable way to turn the vertical fracture frequency described above into a lateral fracture spacing when the fracture distribution is so irregular. For the sake of argument, one could take the average fracture spacing of 2.2 ft (67 cm) from the inclined paludal core (described more fully below), and the relationship that the probability of intersecting a fracture is the ratio of the diameter of the circular area investigated to the fracture spacing, and calculate that the probability of hitting a fracture with vertical 4-in (10-cm) diameter core would be about 15%. However, the value of this number is ambiguous where the fracture population consists of numerous fractures with heights of 5-25% of the reservoir thickness, and where fractures are irregularly distributed (see Figures 1 and 10 of Reference 2). Moreover, the estimate of 15% cannot be tested when only one 4-ft (1.3-m) high fracture was encountered in the 90 ft (27 m) of reservoir rock cored across the two 25-30 ft (7.6-9.1 m) thick paludal sandstones.

Deviated SHCT Well

Despite the questionable value of such a number, a raw "average fracture spacing" for the deviated SHCT core can be obtained for comparative purposes by dividing the length of sandstone core recovered (minus the length above and below the first and last fractures in each reservoir, and corrected to true horizontal distance) by one less than the number of fractures in each reservoir. Fracture spacing is measured perpendicular to the fracture planes, and in this study, corrections are required for both hole inclination and hole direction relative to the average fracture planes. In the slant core interval, the exact hole inclination was 58°, and the measured spacing is multiplied by the sine of 59° (the intersection angle of the hole with the average fracture dip) and by the cosine of 10° (the correction for the intersection of hole direction, N4°W, with mean fracture strike, N84°W) in order to get true horizontal spacing (a correction factor of 0.84). Therefore, a 10-ft spacing measured in core would yield a true spacing of 8.4 ft. The same method was applied to the 85° cored interval, but results in a correction factor of only 0.98.

The calculations yield average spacing of 2.2 ft (0.67 m) in the paludal zone, and 3 ft (1 m) in the Cozzette. In both cases, the minimum spacing is less than 0.1 ft (0.03 m). The maximum spacing is 6 ft (3 m) in paludal core and 17.5 ft (5.3 m) in the Cozzette core (Fig. 7). Most of the fracture spacings are less than 2 ft (0.61 m). The histograms suggest that if a fracture has been intersected by a vertical wellbore, there is a more than 60% chance that a parallel fracture lies less than 2 ft (0.61 m) away. Even for the more closely spaced fractures, the spacing distribution is skewed (Fig. 8).

Cumulative probability plots of the data (Fig. 9) show an initially similar distribution of fracture spacings within the paludal and Cozzette reservoirs. These plots also show changes in slope within each population plotted, suggesting that there may be two or more sub-populations of fractures within each data set: one with a spacing of 1 ft (0.3 m) or less, and another with a greater-than-1-ft (0.3 m) spacing. The more closely spaced populations probably correspond to those fractures occurring within the swarms apparent on Figures 3 and 4, whereas the larger spacings correspond to the variability in spacing of isolated fractures and swarms of fractures.

The fractures of the widely spaced population fit a Weibull distribution rather than a normal distribution (Fig. 10), consistent with other authors' measurements of the distributions of other types of fracture parameters[8]. The average spacing measured for fracture swarms is about 4.8 ft (1.5 m) and 6 ft (1.8 m) for the paludal and Cozzette respectively, although there is considerable variability in these spacings as well, ranging from 2.5 ft (0.8 m) to 17.6 ft (5.4 m) in both zones.

Fracture Spacing and Bed Thickness

A general oil-field rule of thumb has been that fracture spacing is on the order of bed thickness. This relationship is not apparent in data from the SHCT-1 well. Even the relatively homogeneous Cozzette Sandstone, which is 60 ft (18 m) thick at this site, displays an "average fracture spacing" of about 3 ft (1 m), nearly equivalent to spacing in the paludal sandstones which are only half as thick.

These fractures are not the result of flexure of the strata: "structure" in the area consists primarily of a 2° dip to the northeast and possibly a broad north-northwest trending anticlinal nose. Rather, the fractures are the result of deep burial, high pore pressure, and horizontal tectonic compression[10,11]. Spacing of such fractures apparently bears little relationship to bed thicknesses. Other authors have noted that fracture spacing is commonly only proportional to bed thickness for beds less than 4.6 ft (1.4 m) thick,[12] and that fracture spacing is relatively constant above this bed thickness.

The truncation of the upper end of the spacing trend for the paludal cumulative probability plot (Fig. 9) may be a function of either the smaller bed thickness or possibly the limited size of the paludal reservoirs. Whereas the Cozzette sandstone is effectively unlimited laterally (scale of miles) and has no apparent limit to the maximum fracture spacing (at least on the scale of 115 ft (35.1 m) of core available), the paludal reservoirs are generally less than 500 ft (152 m) wide[9].

Fracture Spacing in Outcrop

Fracture spacings were measured in outcrops of paludal and Cozzette sandstones along the Grand Hogback about 12 mi (20 km) distant from the MWX site.[2] Although the strata as a whole have been structurally deformed and now dip up to 90° in outcrop, much of the deformation has apparently been accommodated within the interbedded ductile mudstones. Average fracture spacing in the Cozzette is about 3.4 ft (1.1 m), and has a cumulative probability distribution remarkably similar to that derived from subsurface data (Figs. 10, 11). Similar patterns of irregularly spaced regional fractures, commonly occurring as swarms, have been documented in outcrops of less deformed strata elsewhere in the Rocky Mountain region.[13]

The fractures in outcrop display very little remnant mineralization and have been obviously altered by weathering, but the dominant set of fractures in the Cozzette has apparently not been enhanced by structural uplift. Fractures in the paludal outcrops, farther from the relatively ductile Mancos Shale, may have been enhanced (both extended lengthwise and increased in number). Average fracture spacing measured in a paludal lens is on the order of 1.4 ft (0.43 m), roughly half of that found in the subsurface.

Cross fractures, commonly created by stress release during erosion and exposure, and therefore well-developed in outcrops of both strata, are uncommon in the subsurface.

CONCLUSIONS

1. Vertical core that was taken through the sections that overlap the slant core intervals encountered one natural fracture. In this same 162-ft (49.4-m) thick overlap interval, the slant core contains 16 fractures in the paludal sandstones (150 ft/45.7 m vertical section), and 36 fractures in the Cozzette sandstone (12 ft/3.7 m vertical section).

2. Vertical core provides valuable information on fracture height (if fractures are intersected), and on fracture relationships to lithology and bedding, whereas core from deviated wellbores provides information on relative fracture spacing and frequency.

3. Methods for predicting fracture spacing from vertical wells are inadequate for subsurface regional fractures in heterogeneous reservoirs.

4. Measurements of "average fracture spacing" for regional-type fractures are of questionable value for direct input into reservoir engineering models.

5. Excellent measurements of relative lateral fracture frequency can, however, be derived from core from deviated wellbores for comparative purposes.

6. Fracture spacing in the SHCT-1 core has a Weibull distribution that is strongly skewed toward closer spacings.

7. Measured fracture spacings in SHCT-1 core suggest that multiple, closely spaced fractures are a population separate from the more widely spaced fractures, and may represent fracture swarms and the spacings of swarms respectively.

8. In the slant-hole core examined, average fracture frequency is not related to bed thickness, although the widest observed fracture spacings occur in the thicker, more homogeneous, and more widespread sandstones.

9. Fractures of the dominant west-northwest regional set at the MWX site are at least 25 times more numerous than any other fractures encountered in the subsurface.

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Figure Captions

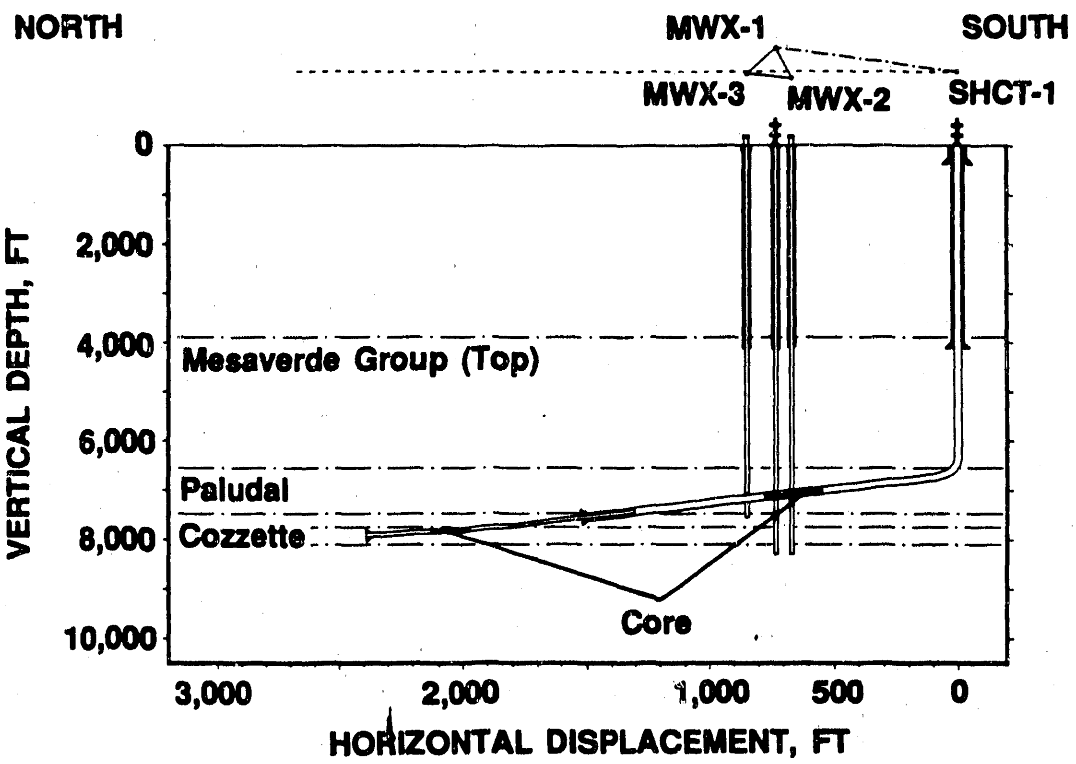

Fig. 1. Spatial Arrangement of MWX and SHCT Wells

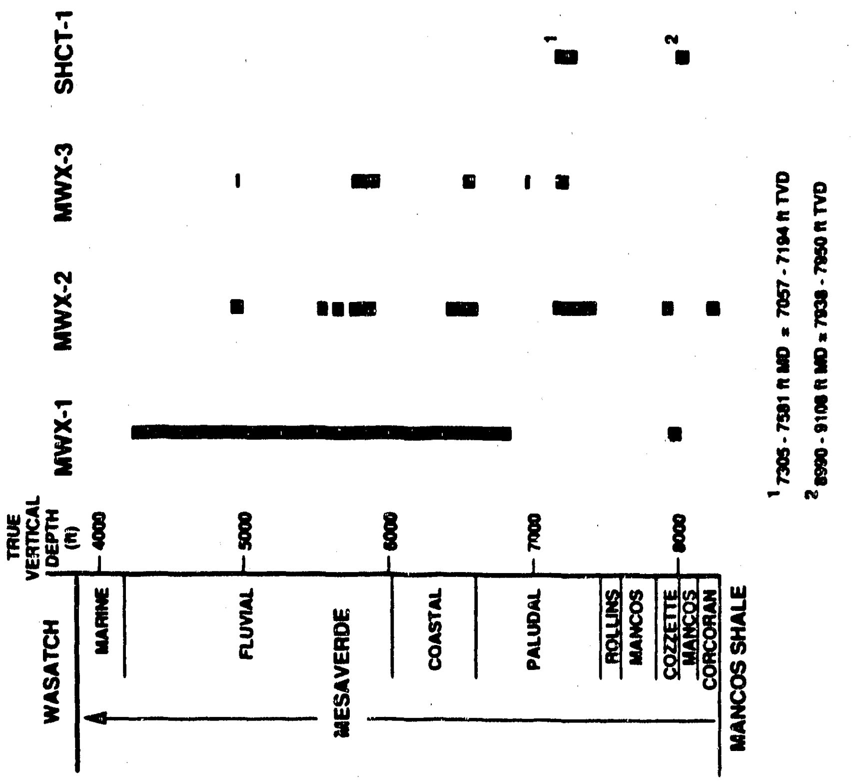

Fig. 2. Cored Intervals in MWX and SHCT Wells

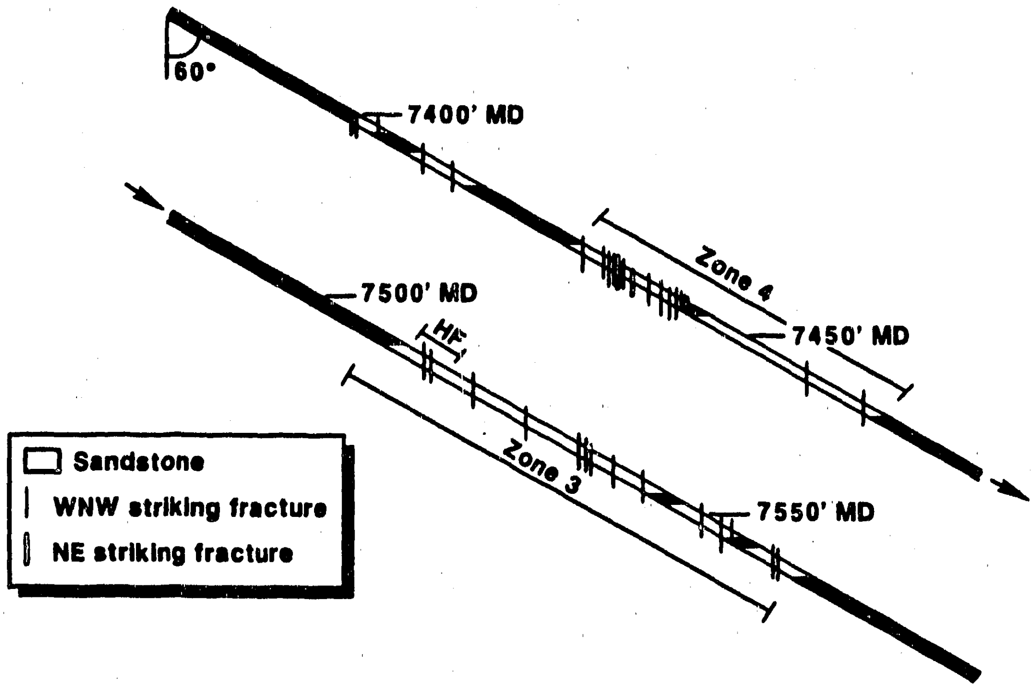

Fig. 3. Fractures in Paludal Core, SHCT-1

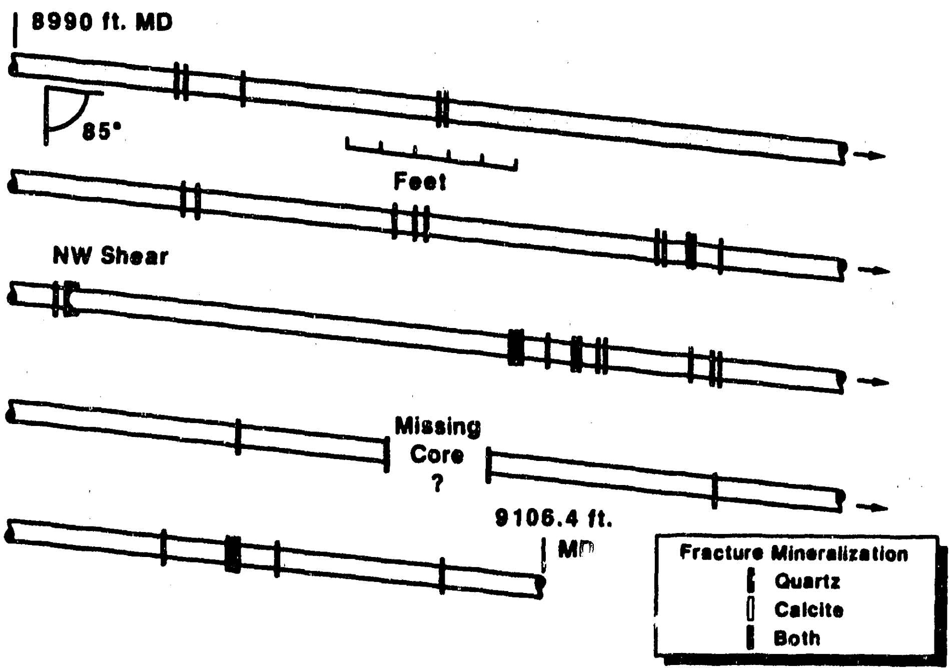

Fig. 4. Fractures in Cozzette Core, SHCT-1

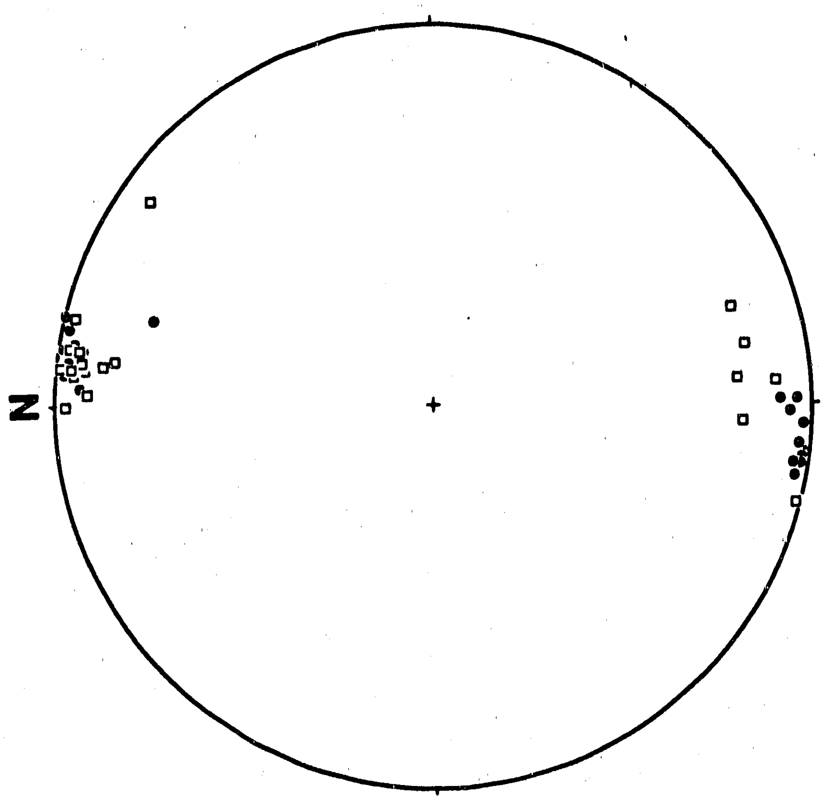

Fig. 5. Stereonet of Poles to Planes of Fractures In SHCT Core: Circles = 23 Paludal Fractures, Squares = 19 Cozzette Fractures

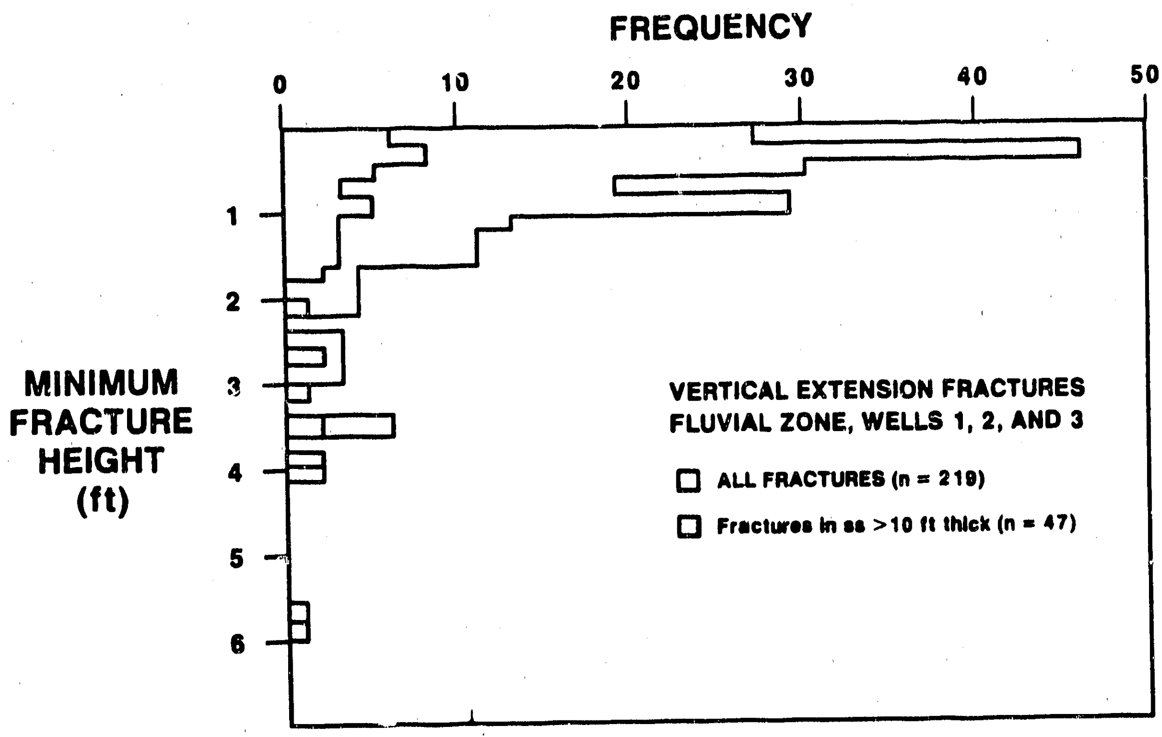

Fig. 6. Frequency vs Height of Fractures, MWX core

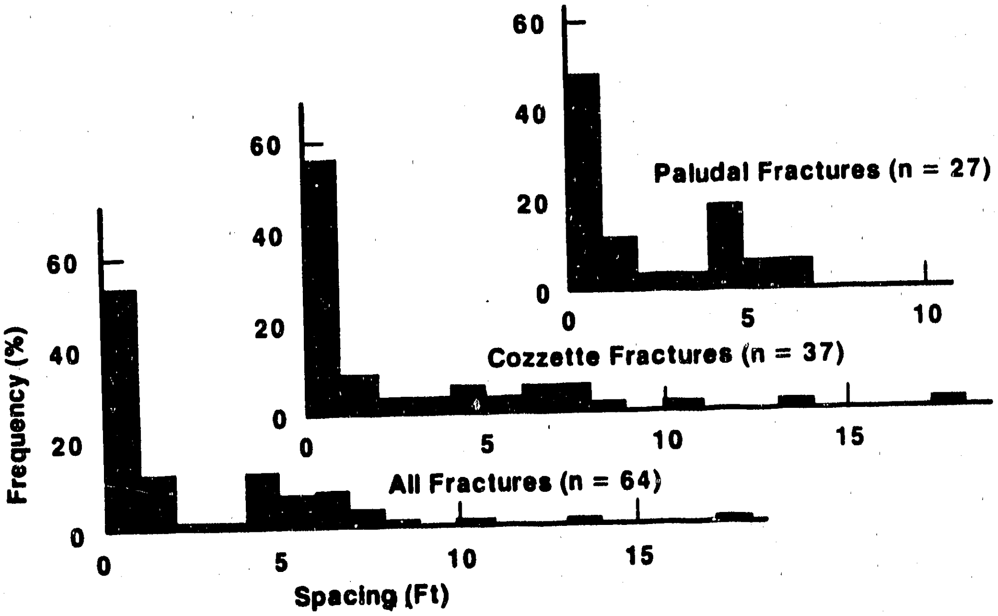

Fig. 7. Fracture Spacing Histogram, SHCT-1

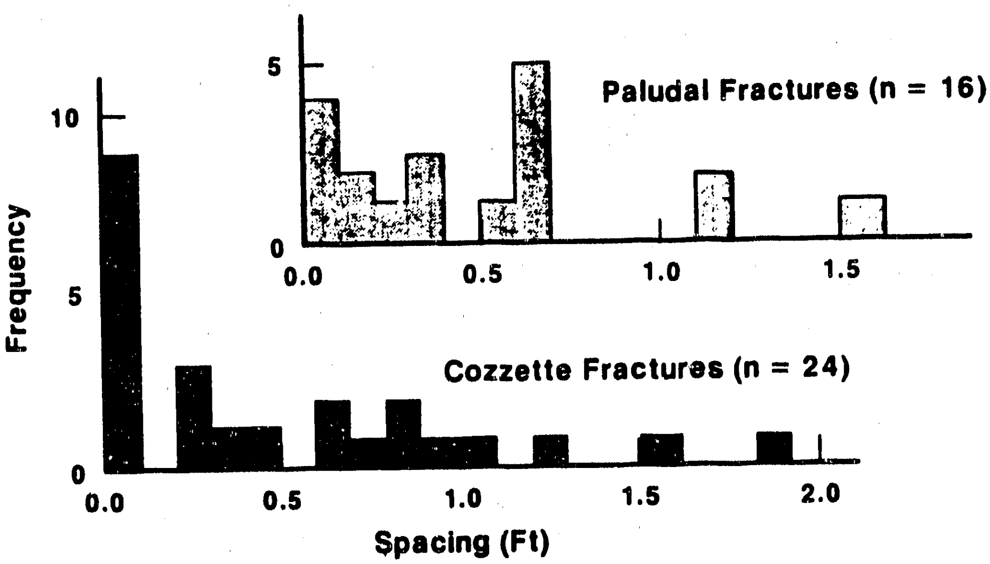

Fig. 8. Closely Spaced Fractures, SHCT-1

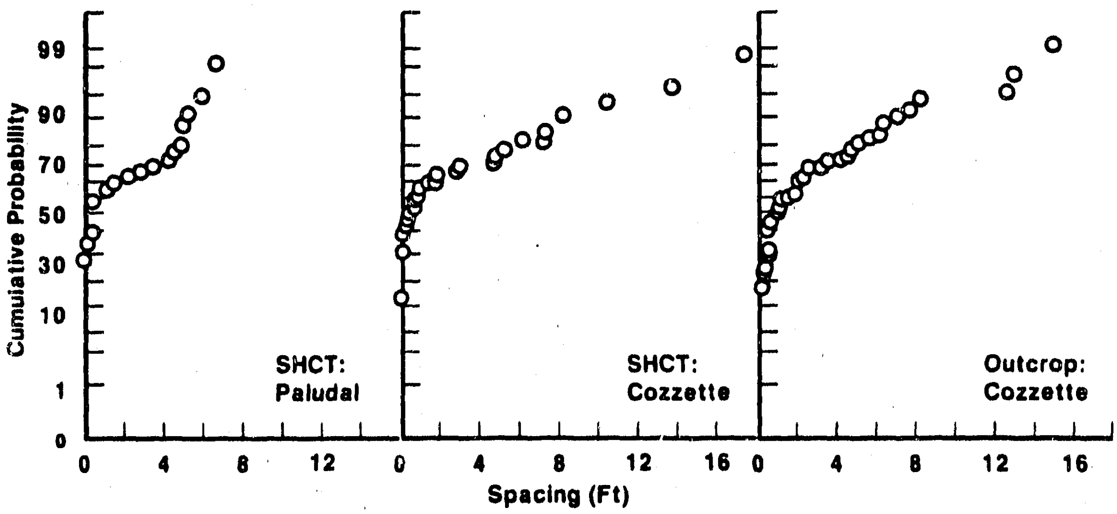

Fig. 9. Cumulative Percent Probability Plots of Fracture Spacing

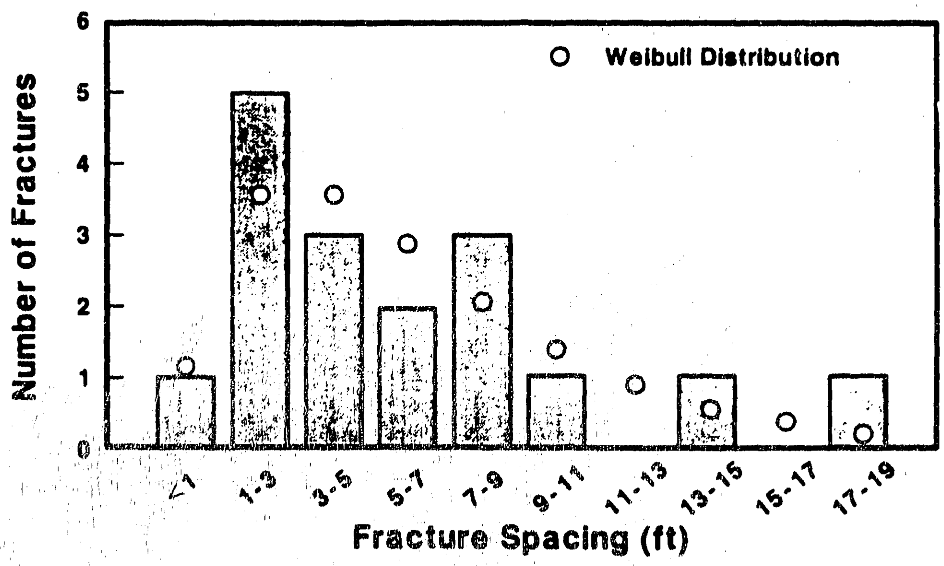

Fig. 10. Weibull Distribution of Widely Spaced Fractures, Cozzette, SHCT-1

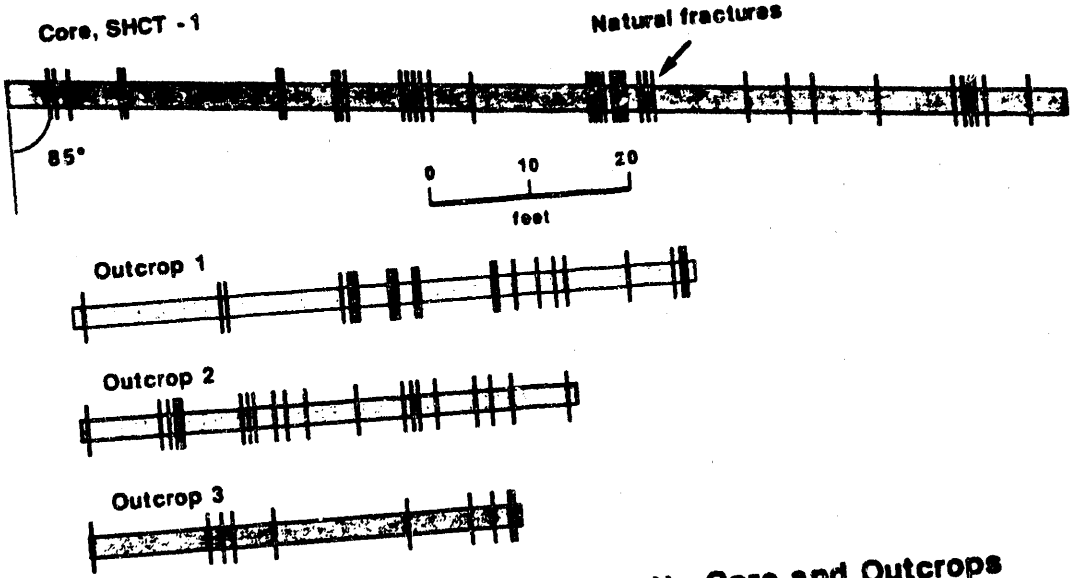

Fig. 11. Fracture Spacing, Cozzette Core and Outcrops

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