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Vertical and Lateral Variations in Fracture Spacing in Folded Carbonate Sections and its Relation to Locating Horizontal Wells

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Abstract

Optimum drilling direction and attitude in fractured reservoirs are a function of the width and orientation of the natural fractures present, and the 3-D variation in their fracture intensity or spacing. To make these drilling determinations in fractured carbonate reservoirs, we are faced with determining the relative effect of lithology and structural position on subsurface fracture intensity. Work on several North American folded carbonate sections indicates that weakly deformed or lower curvature portions of the folds display an overall greater stratigraphic variation in fracture intensity than hinge zones or areas of higher curvature. In addition, lithologies exhibiting low fracture intensity off-hinge display larger increases when entering the hinge than those with higher initial off-hinge intensity.

The data further indicate that while average fracture intensity is better in hinge zones, flank positions contain layers of optimal properties that have fracture intensities as good if not greater than average intensities in the forelimb or hinge zone. The conclusion is made that proper deviated or horizontal completions in optimum lithologic layers in flank positions (backlimb or forelimb) could give flow rates as high or higher than average hinge zone completions. Also indicated is a structural style or mode of structural development control on fracture intensity with leading-edge folds containing nearly an order of magnitude more fractures than foreland folds in the same stratigraphic package. In terms of drilling directions, results indicate that backlimb wells should follow optimum stratigraphic horizons, possibly a strike direction; while hinge wells should cross-cut multiple horizons, possibly in a general dip direction.

Introduction

The porosity and permeability of natural subsurface fracture systems are a function of fracture spacing or intensity (how many fractures) and fracture aperture available for fluid flow (how wide they are). Horizontal wells can be used to optimize the contribution of both parameters in fractured reservoirs (Figure 1). Since we can do little in early exploration to actively high-grade fracture aperture, much of our exploration activity in these reservoirs involves high-grading fracture intensity.

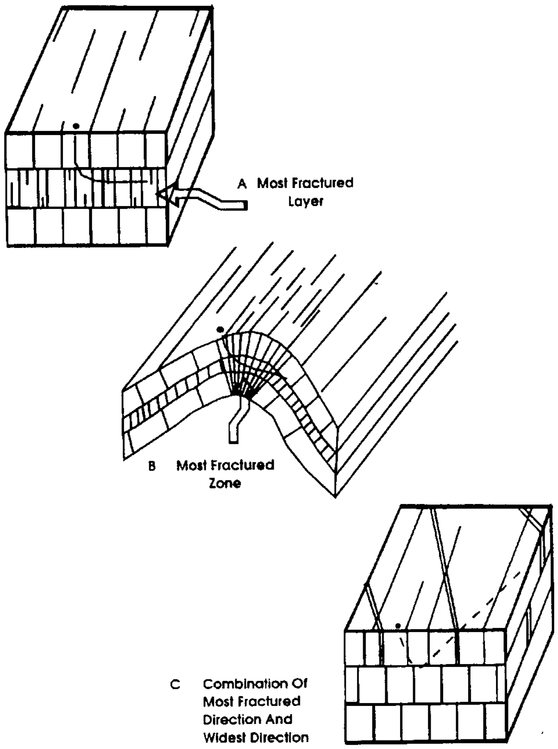


FIGURE 1: Schematic diagrams of the three general approaches to utilizing horizontal wells in fractured reservoirs; (a) parallel to bedding in the most fractured horizon and perpendicular to the fracture trend, (b) crossing a fold hinge in an optimally fractured layer, and (c) tracking the optimum trade-off direction between multiple fracture sets of varying spacing and aperture (due to variations in horizontal in situ stress).

Fracture intensity can be defined and predicted by a combination of material property variations (a function of mineral composition, porosity, grain size, and mechanical bed thickness), in situ conditions (depth, pore pressure, temperature, and rate of deformation), and strain distribution within the section (structural position)(1). Because we are mostly interested in determining fracture intensity distributions in individual structures, the environmental parameters at fracturing are usually assumed to have been constant over the vertical and horizontal limits of the field, thus having little effect on relative fracture intensity variations. This leaves us with lithology and structural position as the prime factors to work with in picking optimum well locations, borehole trajectories, and completion zones.

Past experiences with fractured carbonate reservoirs have led

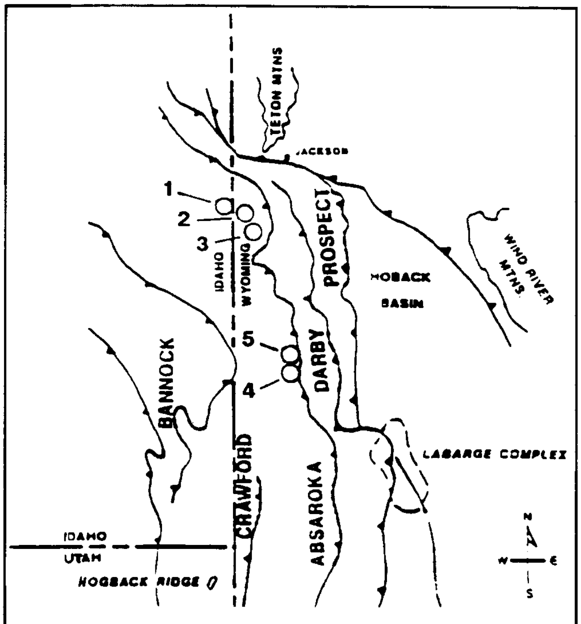


FIGURE 2: Location map of the Western Wyoming Thrust Belt depicting the five outcrop localities shown in Figures 3-7. The map is modified from a previous publication(8).

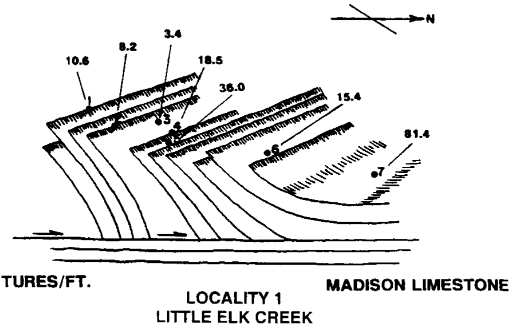


FIGURE 3: Outcrop sketch of field Locality 1 with average fracture intensity (fractures/ft. = fractures/0.3048 m); measurements per station are shown. The view represents about 50 ft. (15.24 m) of outcrop.

us to conclude that, in many cases, lithologic variations have a somewhat larger effect on fracture intensity than does structural position. This conclusion will be detailed with the use of four carbonate rock sections of similar age and composition in the remainder of this manuscript.

Discussion

Fracture Intensity

Outcrop observations from one section in the Western Wyoming Thrust Belt were used to detail fracture intensity variations in the Lower Paleozoic carbonates. This interval is typical of productive fractured reservoirs throughout the western U.S. and Canada. To accomplish this, measurements were made at five localities (Figure 2), four of which involved the Mississippian Madison limestone. The remaining locality contained both the Devonian Bighorn dolomite and the overlying Devonian Darby calcareous siltstone. At each field locality, several fracture-measurement stations were selected where fracture spacing was recorded. These stations were selected to gain an understanding of both the vertical and lateral variation in fracture intensity within the folded section.

At each station, the following information was recorded: strike and dip of fractured bed, bed thickness, and the number of fractures encountered along two measurement lines. For exposed bedding surfaces, measurement lines three feet long (0.984 m) were laid out parallel to bed strike and parallel to bed dip. For measurements in cross section or cliff faces, measurements were taken parallel and perpendicular to bedding along the outcrop face.

At each station, the two fracture intensity numbers (fractures/ft.) were averaged and plotted on perspective outcrop sketches (Figures 3-7). These figures depict both vertical and lateral variations in fracture intensity in deformed geometries similar to those producing in the subsurface in this area, for example, Whitney Canyon Field(2).

They show variations of both a primarily stratigraphic nature (such as in Figures 3 and 4) and of a primarily structural nature (such as in Figure 6). While it is true that fracture intensities in surface outcrops are often somewhat higher than equivalent situations in the subsurface due to the combined processes of weathering and unloading, it is assumed that these processes affect individual outcrops equally(1). Thus, while intensities in outcrop may not be identical to those of equivalent situations in the subsurface (usually higher at the surface), the relative intensities among layers and within one layer as it crosses the structure are probably similar if not constant. As such, while absolute values may not be accurate, these fracture intensity variation maps can be compared with either laboratory measurements or predictions of hydraulic fracture aperture to estimate subsurface fracture porosity and fracture permeability variations likely to be encountered in the subsurface(1).

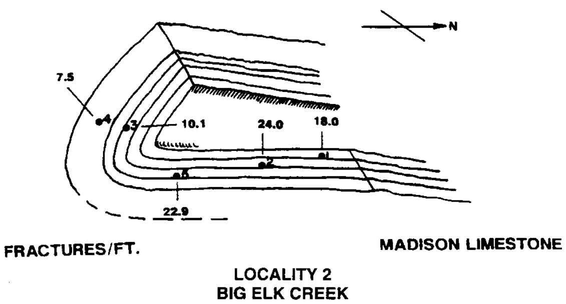


FIGURE 4: Outcrop sketch of field Locality 2 with average fracture intensity (fractures/ft. = fractures/0.3048 m); measurements per station are shown. The view represents about 50 ft. (15.24 m) of outcrop.

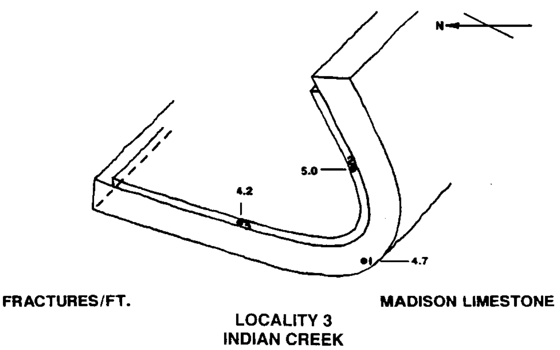


FIGURE 5: Outcrop sketch of field Locality 3 with average fracture intensity (fractures/ft. = fractures/0.3048 m); measurements per station are shown. The view represents about 50 ft. (15.24 m) of outcrop.

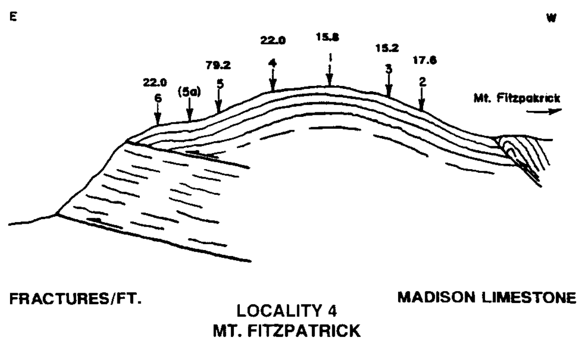


FIGURE 6: Outcrop sketch of field Locality 4 with average fracture intensity (fractures/ft. = fractures/0.3048 m); measurements per station are shown. The view represents about 100 ft. (30.48 m) of outcrop.

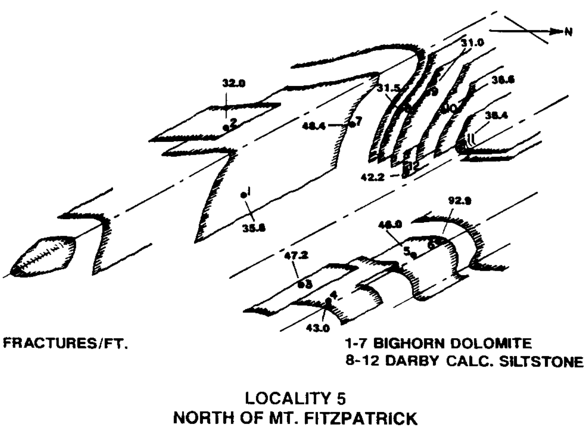


FIGURE 7: Outcrop sketch of field Locality 5 with average fracture intensity (fractures/ft. = fractures/0.3048 m); measurements per station are shown. The view represents about 100 ft. (30.48 m) of outcrop.

An alternate way of viewing these data is by use of frequency diagrams of the combined data. A histogram of all Wyoming Thrust Belt field measurements taken is displayed by rock type in Figure 8. Such distribution diagrams are standard for most reservoir engineering approaches when assigning average properties to reservoir models.

This distribution compares favourably with data collected in a similar manner from three equivalent Madison and Darby sections at

1. Sheep Mountain,
2. a Rocky Mountain foreland structure in the Bighorn Basin (Figures 9 and 10), and,
3. from a Mississippian carbonate section from leading edge anticlines in the Rundle Group in the Canadian Thrust Belt near Grande Cache, Alberta (Figure 11). These three fracture intensity distributions display data from similar rock packages but are from different locations involving various structural styles, field observers, and sizes of dataset. For example, the Sheep Mountain dataset is from a basement cored foreland 'drapefold,' has the lowest overall fracture intensity, and contains the greatest number of observations: N=197 (Figures 9 and 10). The remaining two (Figures 8 and 11) are from higher overall intensity 'leading edge' anticlines in Laramide thrust belts, but contain fewer overall observations: N=51 for the two combined.

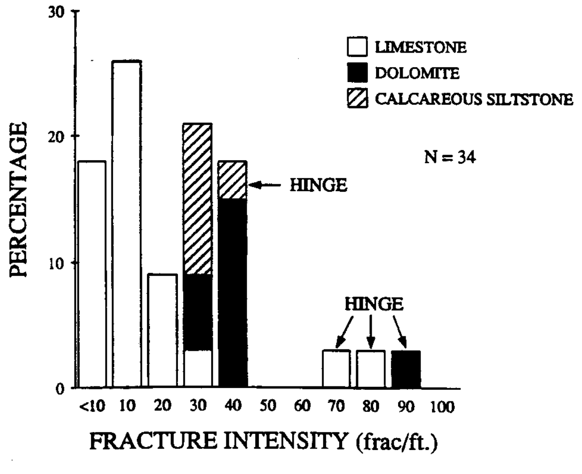


FIGURE 8: Outcrop-based fracture intensity (fractures/ft. = fractures/0.3048 m) frequency diagram for the lower Paleozoic carbonates of the Western Wyoming Thrust Belt shown in Figures 2-7. Frequency is expressed as percentage of total population (N) at that station.

The Wyoming Thrust Belt observations (Figure 8) show that for measurement stations outside of fold hinges, lithology controls fracture intensity, with the dolomites most fractured and the limestones the least fractured. The calcareous siltstones are intermediate in fracture intensity, but have only slightly less fracture intensities than the dolomites. This distribution is logical and predictable(1,3,4). The lithologic control within the limestones, as determined by outcrop observation, is nicely displayed in Figure 3, exclusive of the synclinal hinge at station 7. The general composition relationship for non-hinge sections is also shown in the Sheep Mountain backlimb dataset in Figure 9, where the higher fracture intensity observations are dominantly from dolomites. Unfortunately, the Rundle Group and Sheep Mountain forelimb datasets were not generally collected by lithology, making a parallel lithologic comparison impossible. However, at one station outside of a hinge on a fold in the Rundle Group, adjacent limestone and dolomite measurements were taken. There, the dolomite had 3.4 times the fracture intensity of the limestone (limestone = 8,

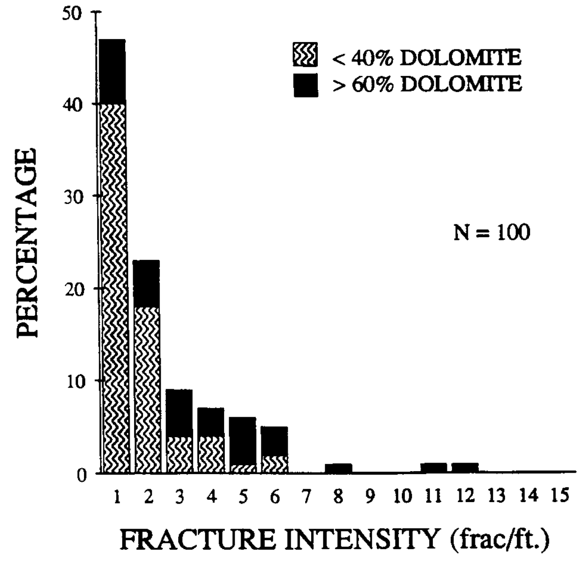


FIGURE 9: Outcrop-based fracture intensity (fractures/ft. = fractures/0.3048 m) frequency diagram for Madison limestone in the backlimb of Sheep Mountain, a foreland fold in the Bighorn Basin of Wyoming. Frequency is expressed as percentage of total population (N) at that station.

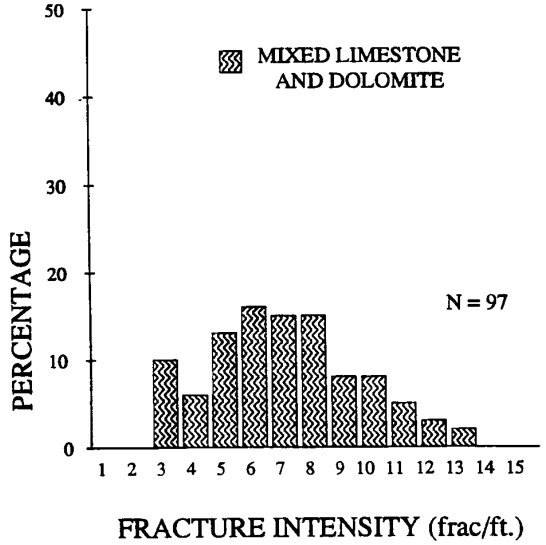


FIGURE 10: Outcrop-based fracture intensity (fractures/ft. = fractures/0.3048 m) frequency diagram for Madison limestone in the forelimb of Sheep Mountain, a foreland fold in the Bighorn Basin of Wyoming. Frequency is expressed as percentage of total population (N) at that station.

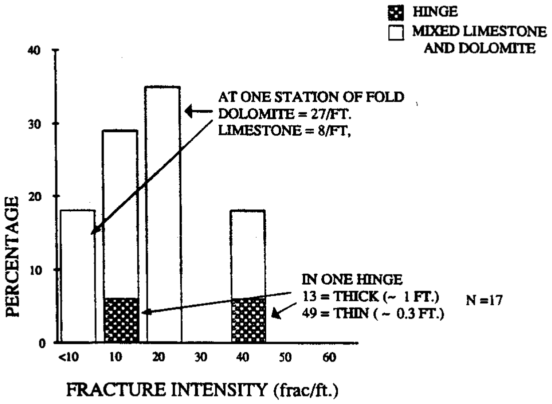


FIGURE 11: Outcrop-based fracture intensity (fractures/ft. = fractures/0.3048 m) frequency diagram for carbonates of the lower Paleozoic Rundle Group from leading edge anticlines in the Western Canadian Thrust Belt, Alberta. Frequency is expressed as percentage of total population (N) at that station.

dolomite = 27/ft. or 27/0.3048 m), thus generally substantiating the lithologic control in this dataset as well.

Hinge or forelimb deformation increased fracture intensity in all three datasets. However, the increase is variable and heavily influenced by rock type and bed thickness. For example, the Wyoming Thrust Belt dataset in Figure 8 shows an increase in fracture intensity in all three lithologies in hinge zones, with the multiplier varying by rock type. The less brittle limestones, while lower in non-hinge fracture intensity, increased six to eight times within hinges; while the more brittle dolomites increased only a factor of 2.2. Such changes have also been seen and reported for the equivalent section in the Sawtooth Range of western Montana(5). Calcareous siltstones increased only 1.3 times, giving an intermediate fracture intensity response, but were relatively under-sampled at 15% of the data, as evidenced by Figure 8. This is supported by the Madison Limestone map in Figure 6, where a 4 to five timnes increase in intensity is related to a gentle synclinal hinge, and in Figure 7, stations three through six, where dolomite fracture intensity increased only two times due to hinge strain.

Comparison of the Sheep Mountain backlimb and forelimb data (Figures 9 and 10, respectively) shows an increase in average intensity in the high strain forelimb (roughly from 2 to 7 fractures/ft., /0.3048 m, geometric average). However, the range in the forelimb population is slightly smaller (10 versus 11 for the backlimb), while the highest intensity only increased one fracture/ft. over the backlimb. The major change is in the shape of the two distributions, from a very skewed distribution for the backlimb to a more symmetric one for the forelimb. As in the Wyoming Thrust Belt data, the higher intensity backlimb or non-hinge lithologies increased in the equivalent section in the forelimb less than the lower baseline lithologies.

Because of different sampling procedures, the Rundle data (Figure 11) does not depict rock type or relatively significant numbers of hinge measurements, but does depict another important controlling parameter, bed thickness(1). The two hinge measurements shown in this figure are from two lithologically similar beds in the same hinge, but with different bed thicknesses. Here, a decrease in bed thickness from 1.0 to 0.3 ft. (0.3048 to 0.1016 m) increases the fracture intensity 3.8 times (from 13 to 49 fractures/ft., or fractures /0.3048 m).

Analysis of these three above-mentioned datasets shows several interesting common characteristics including:

1. backlimb or non-hinge intensity distributions are wider or more variable than forelimb or hinge distributions (especially shown in Figures 9 and 10);
2. brittle rocks such as dolomites have the highest fracture intensities in backlimb or non-hinge areas and in forelimb areas,but their increase within the hinge is less than that of the less brittle limestones possessing lower base level backlimb intensities (Figures 8-10);
3. restricted areas of non-hinge rock can exhibit as high or nearly as high fracture intensities as equivalent rock in hinge areas; and
4. the leading-edge folds are nearly an order of magnitude higher in fracture intensity than the foreland folds.

The observation that rocks with a lower fracture intensity have a greater percentage increase in hinges than rocks with higher base-level intensities is also shown in a subsurface dataset for equivalent Madison limestone at Lost Soldier and Wertz Fields (foreland structures) in the Bighorn Basin of Wyoming as measured by Holy Harrison and Joan Tilden, formerly of Amoco. Figure 12 plots their data for fracture intensity as a function of 2nd derivative, a form of curvature or tightness of hinge assumed to be proportional to strain. The lower base-level intensity Tensleep sandstone increased six times in intensity when going from a 2nd derivative of 14 to 55, while the higher base-level intensity Madison increased only three times when going through a similar range from 17 to 55. Overall, these intensity numbers are similar to the Sheep Mountain data, also from a foreland structure, and significantly lower than the two leading edge thrust-related folds.

Well Trajectory

Assuming that the above observations hold in general for folded carbonate sections, several strategies can be invoked to optimize well trajectories or well paths in the exploration and exploitation phases for such reservoirs. These strategies consider relative fracture spacing variations among rock layers and how they range from backlimb to hinge to forelimb, as well as the dominant azimuth of fractures in these same fold domains. Optimum wellbore azimuth can be calculated when various sets of fractures exist with different spacings and stress-dependent widths(6). Such an approach is used in this discussion, except that the azimuthal variation of the in situ stress is considered small to negligible.

A hierarchy of optimized well paths for a typical asymmetric carbonate fold is given in Figure 13. The highest predicted production rates occur along wellpath A on Figure 13. At A, the well

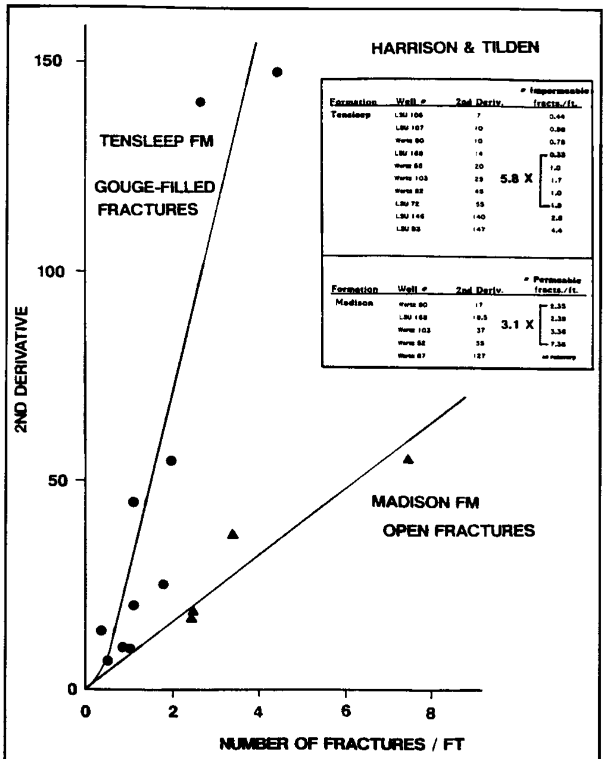
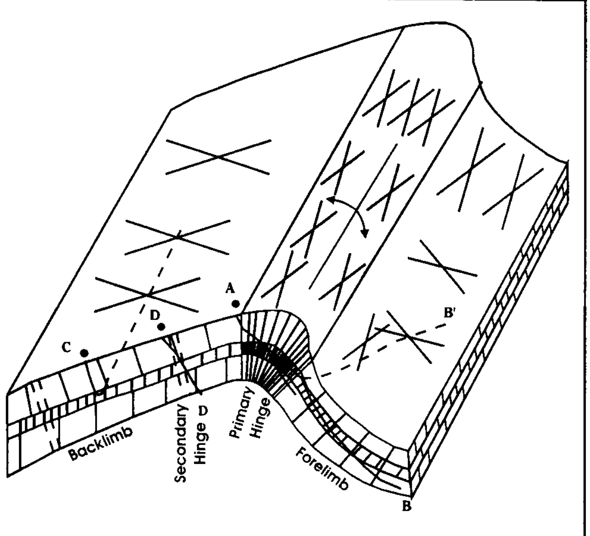


FIGURE 12: Core-based fracture intensity (fractures/ft. = fractures/0.3048 m) versus second derivative (strain?) plot for two formations in Lost Soldier and Wertz Fields, Bighorn Basin, Wyoming.

should encounter high intensity (low spacing) Type II fractures subparallel to the fold axis(4) (Type II fractures are perpendicular to bedding and are subparallel to the bedding strike). The fracture intensity of all layers will increase when entering the hinge (assuming all are brittle and deform by fracture) with the difference in intensity among layers subdued in the hinge(s) compared to the flanks. As a result, the wellpath should intersect as many layers as possible in an azimuth perpendicular to the Type II fractures, or in the dip direction (well trajectory A on Figure 13).

Depending on the level of strain in the forelimb of the fold, wellbore A could be deepened to develop the steep limb of the structure, shown as wellbores B and B′ on Figure 13. Wellbore B continues in the dip direction and would be optimum for intersecting Type II fractures from the limb that has experienced a 'migrating hinge' during fold development. Path B′ (bisecting dip and strike directions) attempts to intersect both Type I (perpendicular to bedding and subparallel to dip direction) and Type II fractures as might be expected in a 'fixed hinge' development of the fold(4). The optimum azimuth of B′ would be dependent on the relative abundances of Types I and II fractures. Once determined or predicted, published monographs could be used to obtain this azimuth(6). Caution should be observed in booking reserves in the forelimb of such structures, however, until a well has tested the flank. Some folds have experienced high strain, high mean stress conditions in the forelimb, causing the limb to deform ductilly or in a compactive manner rather than by dilation involving fractures.

Well path C on Figure 13 is the next best predicted producer. It attempts to cross-cut Type I fracture sets in the backlimb of the fold. These are less abundant than the Type II fractures in the hinge, but tend to be larger and interconnect greater vertical and lateral dimensions in the fold. The result on production is that C may have lower flow rates than A, B, and B′ but may eventually communicate greater reserves per well. Rates are lower because all layers will have lower fracture intensity than the hinge. However, certain optimum layers will have fracture spacings almost as good as that of the average of the hinge. The key to wellbore C then is to select the optimum layer(s) and to have the horizontal portion of the wellbore run parallel to its boundaries and completely within it (wellbore C, Figure 13).



A - Oblique Across Hinge In Dip Direction
B - As With "A" But In Forelimb
B' - Alternate to "B" Oblique To Strike & Dip
C - Parallel To Strike In Backlimb In Most Fractured Layer (s)
D - Oblique To Both Secondary Hinge and Layering

FIGURE 13: Schematic diagram of a typical fractured asymmetric fold with highgraded optimum well paths (A is best) for a brittle carbonate. Well path rankings will vary with rock type.

Another possible target in such a fold is shown as wellbore D on Figure 13. This trajectory attempts to develop more minor secondary hinges with relatively small dip inflections that sometimes occur on the backlimb of folds. These contain small swarms of Type II fractures that cut multiple layers within the fold. The optimum well path would cross the hinge and cross the layering in an oblique manner. Rates and reserves for these completions should be quite variable.

Conclusions

Several unique datasets of outcrop-derived fracture intensity in carbonate rocks depict the relative importance of lithologic and structural control on fracture distribution. It has been shown through various views of the data that lithology is a dominant control on fracture intensity especially in non-hinge areas of folds and that it also controls the relative increase in intensity within hinge zones to a lesser extent. Further, it appears that these characteristics predict fractured reservoir potential in restricted, optimum zones in backlimb or non-hinge fold areas that are as good as average hinge zone properties.

Several rules of thumb could be used to predict hinge zone fracture intensity. Limestone backlimb fracture intensities could increase four to eight times within hinge zones, whereas dolomites might increase only two to three times.

Overall, these four datasets in equivalent carbonate sections indicate that the fracture intensities of leading-edge thrust-related anticlines (Wyoming Thrust Belt and Rundle Group datasets) are nearly an order of magnitude higher than those of foreland anticlines (Sheep Mountain and Lost Soldier/Wertz Field datasets). This is logical as the leading edge folds were probably folded and unfolded more than once as the section passed through thrust ramps during emplacements, whereas the foreland folds experienced folding only once.

In terms of drilling directions, results indicate that backlimb wells should follow optimum stratigraphic layers, possibly in the strike direction; while hinge wells should cross-cut multiple horizons, possibly in a general dip direction. Optimum forelimb well tracks are dependent on rock type and the history of migrated or fixed hinges. Tracks cross-cutting layers and varying in azimuth from dip-parallel to 45° to dip azimuth are possible.

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