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An Analysis of Joint Development in Thick Sandstone Beds of the Elk Basin Anticline, Montana-Wyoming

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ABSTRACT

Prominent outcrops of Campanian sandstones within the Elk Basin Anticline, a basement-cored Laramide structure on the Wyoming-Montana border, display both joints and shear fractures. Of 72 outcrops sampled within Elk Basin sandstone beds 67 are cut by one or more systematic joint sets. Systematic strike joints are far more common than dip joints. In some outcrops two joint sets develop with dihedral angles of 10° to 25°, particularly on the north end of the Elk Basin Anticline. This behavior is indicative of a clockwise reorientation of the bedding-parallel stress axes during fold development. Bedding thicknesses range from a few centimeters to over 10 m, a range that provides an excellent opportunity to examine joint development as a function of bed thickness. Joint spacing is indicative of joint development. A linear joint spacing-bedding thickness relationship is found within the Elk Basin sandstones by fitting a line, called a fracture spacing index (FSI), to thickness-spacing data from various structural positions. The FSI is 0.79 for strike joints in sandstone beds of the backlimb and 0.96 for strike joints in the forelimb. The coefficient of determination (r^2) is 0.84 for the backlimb FSI and 0.67 for forelimb FSI. Scatter about a linear fit is attributed to variation in bed thickness, lack of accuracy in measuring bed thickness, and variation in elastic properties of beds. A student's t-statistic shows that in the forelimb the mean fracture spacing ratio (FSR) which is mean bed thickness divided by median joint spacing is statistically larger than the backlimb. The distribution of fracture spacing at Elk Basin Anticline is consistent with greater forelimb extension, a characteristic of other basement-cored folds in the Rocky Mountains. Assuming that Elk Basin is a typical basement-cored structure, the implication of this study for industry is that forelimbs will have a higher fracture porosity where the porosity is largely in the form of strike joints. However, fracture porosity may also depend on other parameters such as bed thickness with fractures more closely spaced in thinner beds.

INTRODUCTION

A linear correlation between joint spacing and bedding thickness for specific suites of sedimentary rocks is well documented for beds less than one meter thick (Bogdonov, 1947, Price, 1966, Huang and Angelier, 1989). Such a relationship permits the prediction of joint spacing in other beds in the immediate vicinity using the fracture spacing index (FSI). An FSI is the slope of the best fit line for a plot of bed thickness versus median joint spacing where bed thickness is the independent parameter (Narr and Suppe, 1991). On theoretical grounds (i.e., Hobbs, 1967; Gross et al., 1995) this correlation between spacing and thickness should also hold in thicker beds. Yet, data in the literature suggest that the dependence of spacing on bed thickness might breakdown in beds with thicknesses exceeding two meters (McQuillan, 1973; Ladeira and Price, 1981).

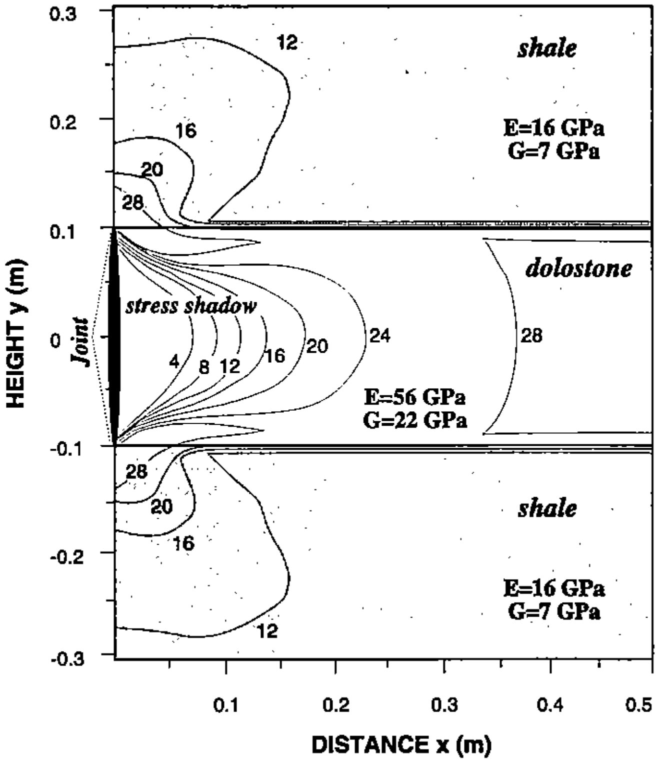

FIGURE 1. Contour diagram showing a model of the 2-D distribution of joint-normal tensile stress (σ_{xx}) in MPa for a section of interlayered dolostone and shale (adapted from Fischer, 1994). Stress is symmetrical about the joint in the dolostone so only half of the model is shown. The model is subjected to a strain of 5 x 10^{-4}.

The phenomenon leading to the dependence of joint spacing on bed thickness is a zone of reduced tensile stress adjacent to existing joints (Fig. 1). This zone is a stress reduction shadow arising because joints act as free surfaces that do not permit the transmission of a joint-normal tensile stress (Pollard and Segall, 1987). Tensile stress is zero at the joint face and increases to the remote tensile stress at a joint-normal distance proportional to joint height. In the absence of the full remote tensile stress, conditions for the initiation of subsequent joints are less favorable within stress reduction shadows. If in layered rocks, joints are prevented from further vertical growth at the interface between beds, there is a relationship between stress shadow width and bed thickness of about one to one (Hobbs, 1967; Narr and Suppe, 1991). Joint sets in layered rocks often develop through a process of sequential infilling, in which new joints propagate between existing joints as strain increases (Hobbs, 1967). When infilling joints develop a spacing equivalent to stress-shadow width, (i.e., a spacing-thickness ratio of about one), their overlapping stress shadows inhibit further infilling of joints. At this point large increments of strain are necessary in order to favor the initiation of more infilling joints (Gross, 1993; Becker and Gross, 1996). In addition to bed thickness, a number of other factors may control the size of the stress reduction shadow and, hence, joint spacing in layered rocks, including elastic properties (Gross et al., 1995), strain arising from structural position (Becker and Gross, 1996), and distribution plus size of initiating flaws (Narr and Suppe, 1991).

The primary objective of our study in the Cretaceous sandstones of the Elk Basin Anticline, Montana-Wyoming, was to find a geological setting in which the linear correlation between joint spacing and bedding thickness holds for beds approaching ten meters thick as predicted by stress shadow theory. Secondary objectives included an analysis of: 1) joint development as a function of structural position; 2) joint spacing as a function of joint orientation; 3) joint spacing as a function of sandstone porosity; and 4) the contrast in joint development between basement-involved folds and folds associated with décollement tectonics. Ultimately, the data from each of these analyses will aid in the interpretation of borehole imaging logs and constrain models for fracture porosity within fractured reservoirs.

GEOLOGICAL SETTING

Elk Basin is a breached anticline, typical of Laramide (i.e., late Cretaceous through Eocene) basement-involved folds in the northern portion of the Big Horn Basin, Montana-Wyoming (McCabe, 1948). Other basement-involved folds have been called drape folds (Stearns, 1971), forced folds (Stearns, 1978), fault-propagation folds (Woodward et al., 1985), and basement-involved thrust-generated folds or thrust folds (Stone, 1991). Structural relief on the Elk Basin Anticline is about 1500 m (Fig. 2). The surface morphology of the NNW striking structure is characterized by an elliptical bowl of several concentric ridges exposing a 400 m section of Campanian clastic rocks. Deep seismic sections show a basement thrust to the ENE, causing an asymmetric drape of cover rocks with a forelimb dip in excess of 30° to the ENE, and the backlimb dipping roughly 23° to the WSW (Bally, 1983, Stone, 1993). The anticline is cut by a number of NE-trending cross-fold faults of the scissors and oblique-slip nature. Sandstone bluffs are sliced by regularly spaced joints that are the focus of this study.

The geological history of the Elk Basin Anticline extends from late Cretaceous sedimentation through Paleocene to Eocene basement thrusting. Late Cretaceous sedimentation was linked to thrust-belt tectonics centered west of the Big Horn Basin where thrust sheets of the Sevier Orogeny shed clastic sediments eastward into the Cretaceous Interior Seaway. During the Campanian, the Absaroka Thrust Sheet was active to the southwest of Elk Basin (Wiltschko and Dorr, 1983). At this time, the area surrounding Elk Basin was a muddy shelf east of a region subject to occasional tectonic loading by thrust sheets (Swift and Rice, 1984). Rapid sedimentation accompanying thrust loading produced a

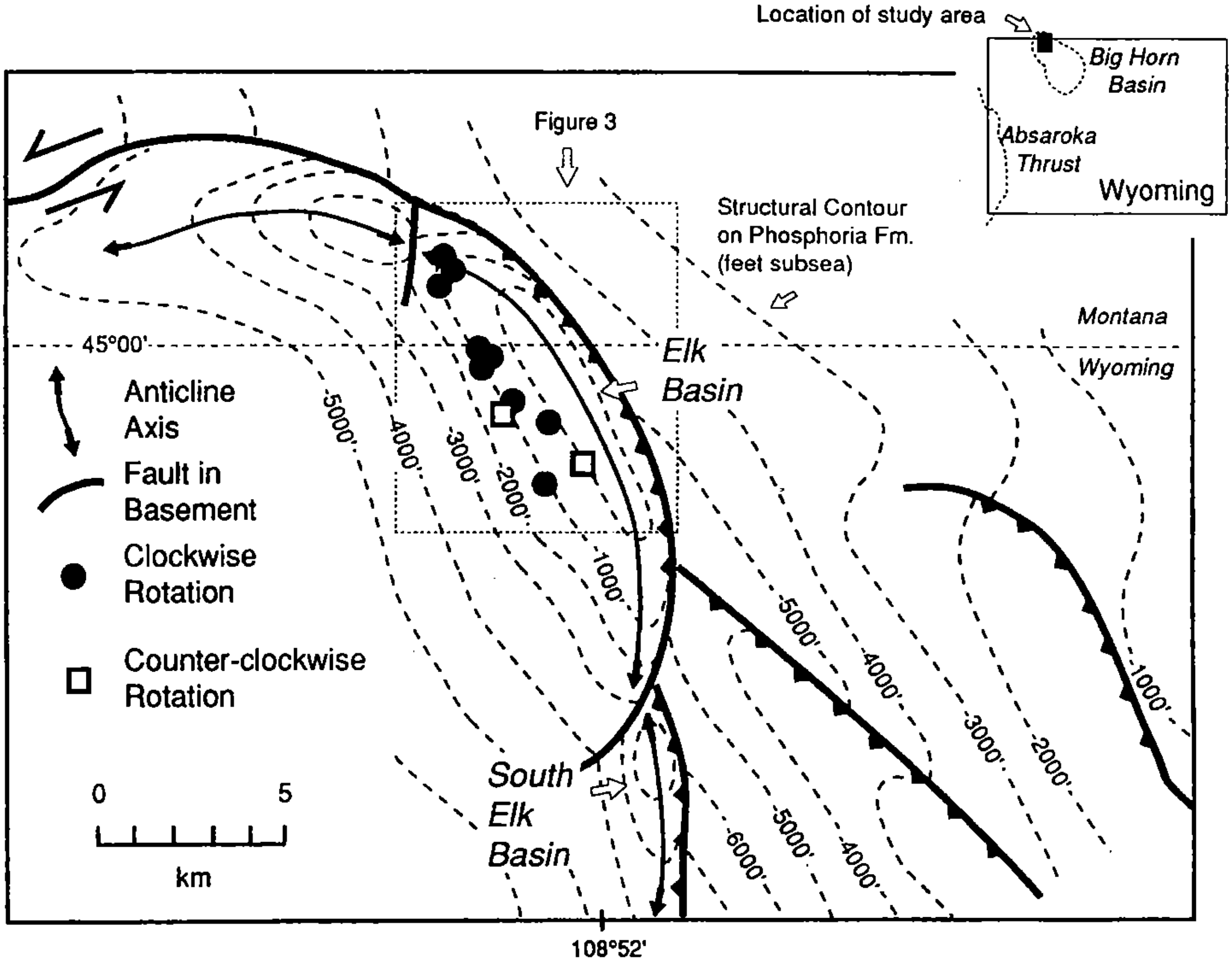

Figure 2. Elk Basin Anticline and South Elk Basin Anticline, northern Big Horn Basin (adapted from Stone, 1993). Structural contour map on Phosphoria Formation given in feet below sea level (adapted from Stone, 1983). Data points mark the surface location of outcrops where joint sets abut to give a sense of rotation of the minimum horizontal stress (S_h) during folding of cover rocks.

progradational shelf sequence. Times of quiescence brought thick blankets of marine shale as a consequence of subsidence exceeding sedimentation. The physiographic ridges of Elk Basin reflect this cyclic sedimentation. Recessive marine shales of the Cody, Claggett, and Bear Paw Formations interrupt the ridge forming delta platform sands of the Telegraph Creek Formation, the fluvial channel sands of the Eagle Formation, and the delta front sands of the Judith River Formation (Fig. 3). It is the channel and deltaic sands of the Eagle and Judith River Formations that are the focus of our study on joint development in thick-bedded clastic rocks.

Individual formations consist of many beds with sandstone layers ranging in thickness from a few cm to more than 10 m. Beds are separated by shale or poorly cemented mudstone a few cm thick. One appealing aspect of working in the Campanian section in Elk Basin is that it provides a range of bed thicknesses that extend over more than three orders of magnitude. Sandstone beds of interest include the five fluvial sand layers in the Eagle Formation known from bottom to top as the Eagle A through E, the Parkman Member of the Claggett Formation and the deltaic sand beds of the Judith River Formation. The thickest bed is the Virgille Member of the Eagle Formation which is without shaly interlayers for more than 10 m.

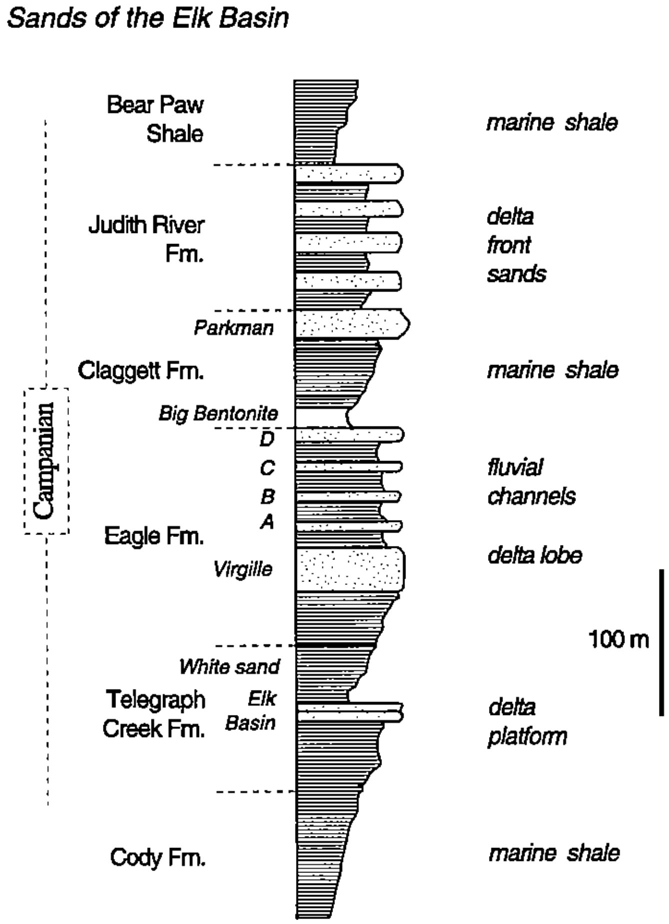

FIGURE 3. Schematic of the Campanian stratigraphic section within the Elk Basin. Scale is approximate.

FIELD OBSERVATIONS

Fracture Types

Sandstone outcrops of the Elk Basin display two types of fracture: deformation bands and joints. Deformation bands originate as shear fractures (i.e., small faults) in sandstone whose cataclastic zone becomes well cemented so that they are more resistive to weathering relative to the host sandstone (Aydin and Johnson, 1978). Other names for these features include braided shear fractures (Engelder, 1974) and tabular compaction zones (Kulander et al., 1991). Such bands of cataclastic sandstone are common within five forelimb outcrops (#1-3, 13, 19) of the Virgille Member of the Eagle Formation where beds can exceed 10 m thick. These small faults are usually within 10° of vertical but cut through the Virgille in so many orientations that a preferred strike is not apparent. Deformation bands are far less common in the backlimb panel of the Virgille Member (outcrop #36) and are not seen in other formations of the basin. Deformation bands form adjacent to major vertical faults cross cutting the Elk Basin Anticline. In the Virgille Member, deformation bands are found up to 100 meters from the nearest cross fault where spacing is on the order of a meter or two.

Joints are cracks in rocks exhibiting opening displacement and no shear offset. The Elk Basin Member of the Telegraph Creek Formation, the Virgille Member plus the five thick sands of the upper Eagle Formation, the Parkman Member of the Claggett Formation, and the sand bodies of the Judith River Formation all contain joints that are regularly spaced and, for the most part, normal to bedding. Joints invariably propagated to but not beyond bed boundaries which are defined by shale partings. A distinctive surface morphology is not common, but when present in thicker beds (> 4 m), it consists of radiating plumes normal to rib marks. It was not possible to observe the effect of bed boundaries on the development of joint surface morphology. When beds except the Virgille Member are cut by shear fractures, these fractures are within a couple meters of major cross-strike faults, particularly common on the forelimb of the Elk Basin Anticline (Fig. 4).

The Trend of Systematic Joints

The most common systematic joint set within Elk Basin is subparallel to the fold axis (Fig. 5). We call these strike joints following Sheldon's (1912) terminology. Two observations pertain to strike joint sets throughout the Elk Basin Anticline. First, the northern end of the plunging anticline trends more westerly relative to the central portion of the anticline. While the trend of strike joints at a few outcrops in the northern portion of the field area also mimic the change in trend of the plunging northern nose of the anticline, many outcrops have strike joints that follow the general trend of the central portion of the Elk Basin Anticline. The implication is that the same strike joint set carries through the nose of the anticline where it is no longer in the true 'strike' joint orientation. Second, the backlimb carries uniformly oriented strike joints over a region of several km^2. Here, it is noteworthy that the strike joints are often misaligned a few degrees clockwise from the strike of bedding. In contrast to the backlimb, strike joints on the forelimb vary more in orientation from one outcrop to the next as if disrupted by local faulting.

Systematic joints trending ENE-WSW, normal to strike of the fold axis, are considerably less common than strike joints. These joints are called "cross-fold joints" by Engelder and Geiser (1980) and "strike-perpendicular joints" by Gross (1993), but we shall revert to Sheldon's (1912) terminology and call these dip joints. Dip joints fall into two main categories: systematic dip joints that typically extend greater than several meters in trace length, and non-systematic cross joints that are confined to and abut against pre-existing strike joints. Systematic dip joints were found in only 12% of our outcrops within Elk Basin and in most of these outcrops the

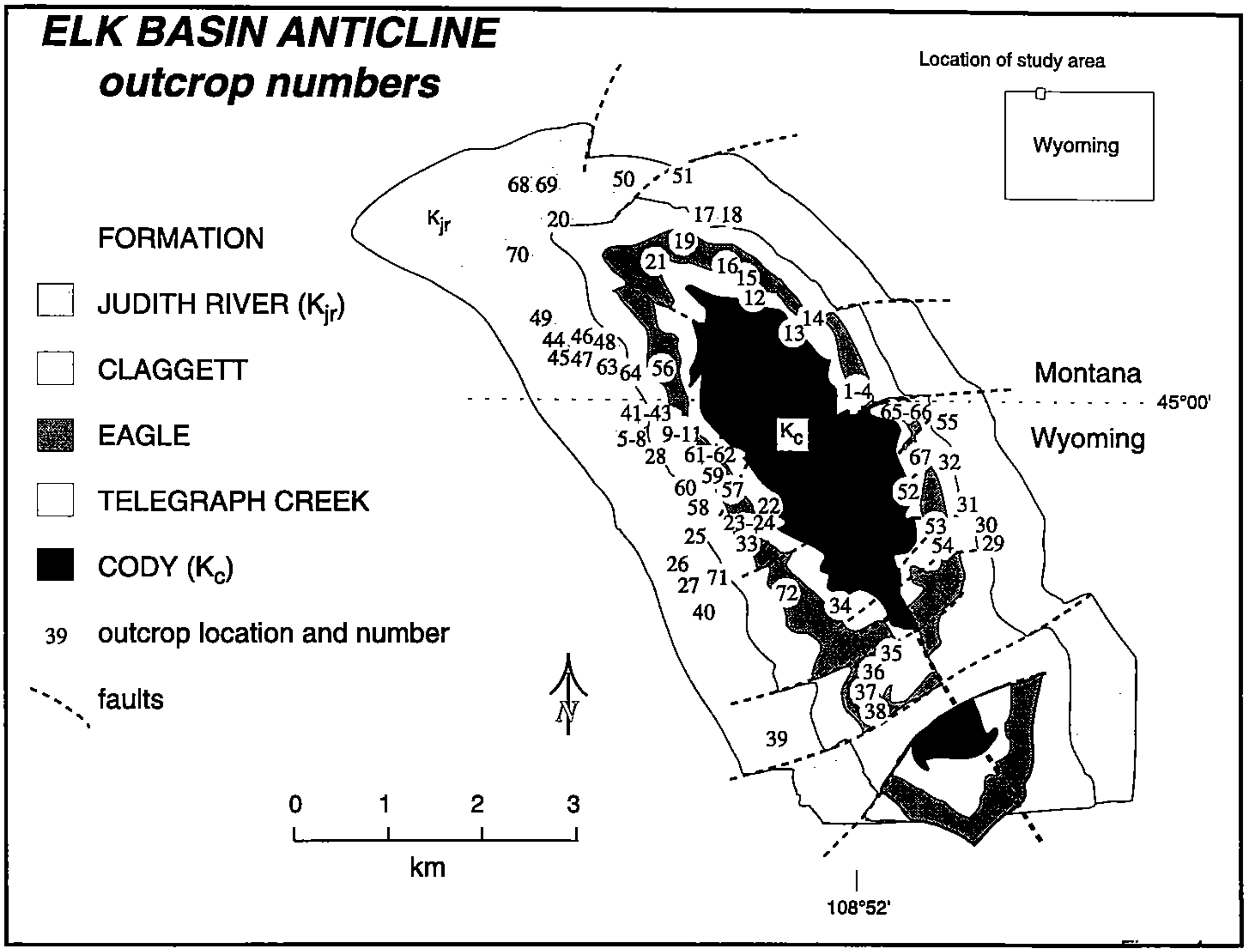

FIGURE 4. Map of the Campanian section within the Elk Basin Anticline showing locations of outcrops labeled by number where brittle fractures were sampled. Outcrop locations correspond to those listed in Appendix 1.

cross joints in the strike orientation abut dip joints. Cross joints in the dip joint orientation are far more common to the Elk Basin Anticline than systematic dip joints. The growth of late cross joints is consistent with the interpretation that strike joints and dip joints did not grow simultaneously but this does not address the question of when the systematic dip joint sets propagated relative to the strike joint sets.

Some outcrops contain strike joints from two joint sets with their trends misaligned between 10° and 25° from each other. Although two misaligned joint sets are more common in outcrops with strike joints, two outcrops were found to contain two sets of misaligned dip joints. When two joint sets are present, members of the later joint set abut members of the first joint by curving perpendicular in a manner described by Dyer (1988) for joints within sandstones of Arches National Park. An abutting relationship in ten outcrops indicates a clockwise rotation of the joint-controlling stress (i.e., S_h) whereas in two outcrops an abutting relationship indicates a counterclockwise rotation (Fig. 6). The clockwise rotation of the later strike joint set is most characteristic of the northern end of the Elk Basin Anticline where the trace of the basement thrust becomes a tear fault with left lateral displacement (Fig. 2).

Joint Spacing - Bed Thickness Relations

Our analysis of joint development focused on the correlation between joint spacing and bed thickness. Beds of uniform thickness are ideal for an analysis of joint spacing. Such beds must be well enough exposed to allow the scan of several dozen joints. Joint spacing was measured using scan line techniques that followed standard practices in the geological literature (Narr and Lerche, 1984). A 100 m measuring tape was laid on the outcrop, sometimes on a

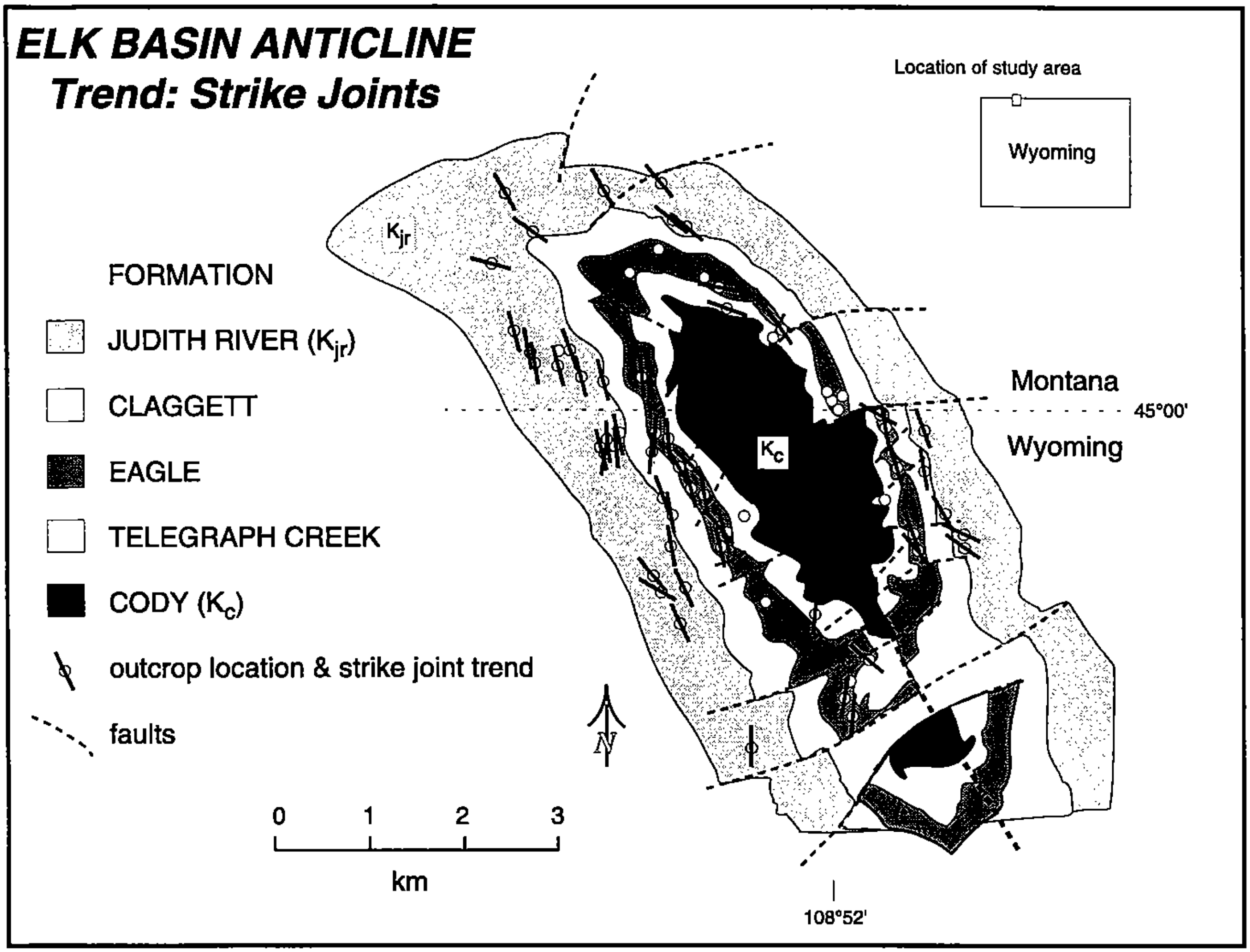

FIGURE 5. Map of the Campanian section within the Elk Basin Anticline showing locations of outcrops where fractures were sampled and the orientation of strike joints.

pavement and sometimes beneath an outcrop face. We measured the orientation of all joints whose outcrop trace intersects our tape and then noted the position of this intersection along the tape. Data on fractures were recorded at 72 outcrops throughout Elk Basin (Fig. 4; Appendix 1).

Our study was less than ideal because the clastic section at Elk Basin contains many beds of varying thickness and irregular surfaces. Furthermore, because most data were collected on bedding plane surfaces, the boundaries marking the top of many measured beds were not present. In the case of the thickest beds (≈10 m), an outcrop giving 100 to 200 linear meters of joint-normal exposure was required. Three dimensional (i.e., pavement and face) exposures were best because dip and strike measurements were taken to avoid making the assumption that all joints were bedding normal. This check was particularly critical because scan lines were taken within an anticline with limb dips of as much as 30°. For the most part joints were bedding normal to within the accuracy of geological measurement techniques.

Of the 72 stations where fracture data were recorded, 49 yielded data useful for an analysis of the relation between bed thickness and joint spacing. Five outcrops contained deformation bands rather than joints. Others yielded good data on joint orientation and spacing, but a reliable measure of bed thickness was not possible because of burial (i.e., pavement outcrops) or because bed thickness varied so much that a single datum based on the average bed thickness was meaningless. As a general rule, beds with a thickness variation of greater than 10% were left out of our analysis. High quality outcrops for our analysis were more common on the backlimb of the Elk Basin Anticline.

Fracture spacing index (FSI) is the slope of the best fit line for a plot of mean bed thickness versus median joint spacing for a particular set of beds or outcrops (Narr and

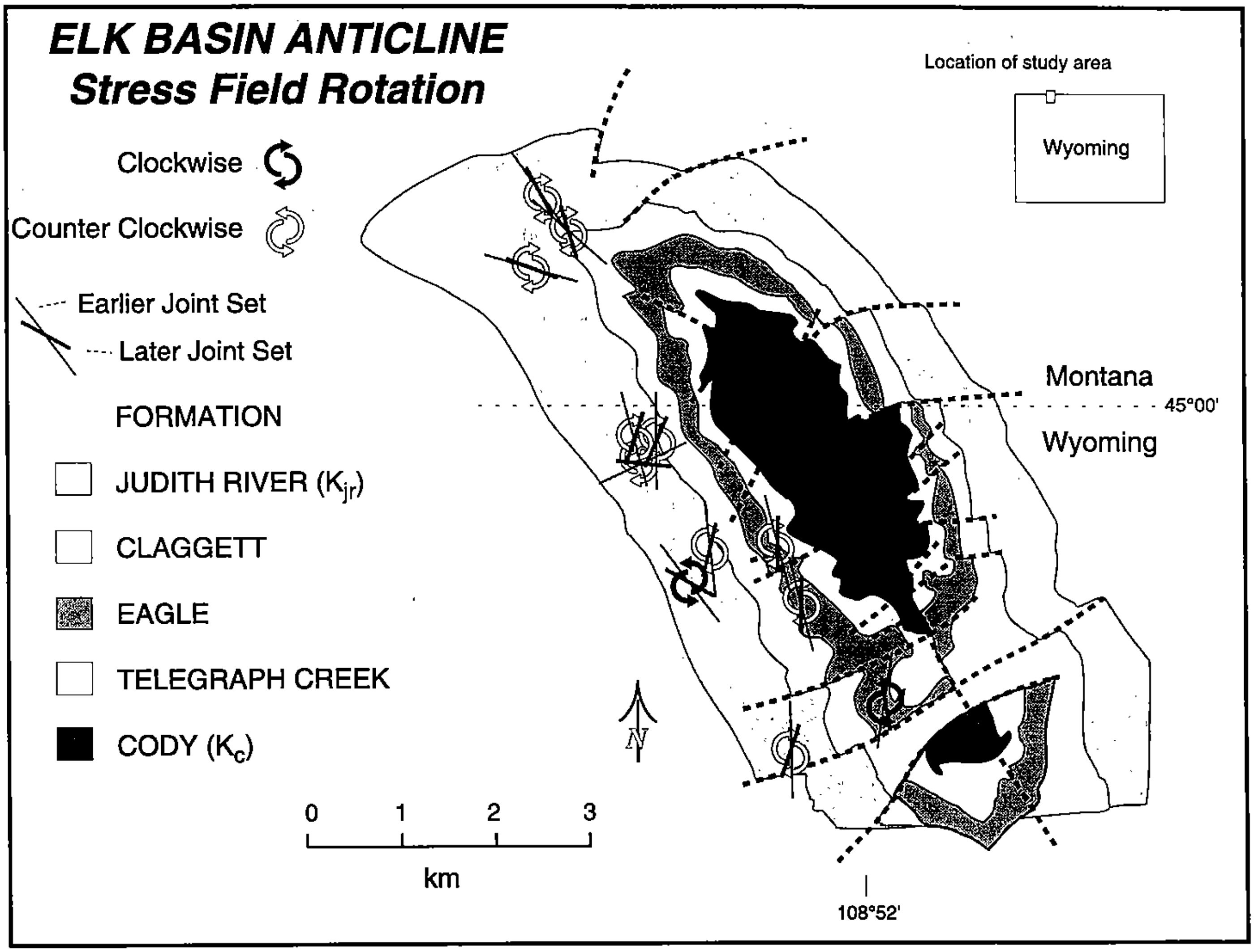

FIGURE 6. Map of the Campanian section within the Elk Basin Anticline showing locations of outcrops where two joint sets abut at low angles to give a sense of rotation of the bedding-parallel stress field (the joints parallel S_H) as the Elk Basin Anticline evolved. Sense of rotation is given along with an indication of the strike of the earlier (lighter line) and later (heavier line) joint sets. Refer to Figure 2 for the position of these outcrops relative to structural contours on the Phosphoria Formation. Some outcrops shown in this diagram are not listed in Appendix 1 because an FSR could not be obtained.

Suppe, 1991). Although plotted on the abscissa, joint spacing is the dependent variable. This convention is used so that a larger FSI indicates a better developed, more closely spaced joint set. An FSI plot for backlimb strike joints includes data from the Judith River Formation, the Parkman Member of the Claggett Formation and the Eagle sands plus the Virgille Member of the Eagle Formation (Fig. 7a). A positive correlation exists between bed thickness and joint spacing for beds up to 10 m in thickness. Considering joint development in all sandstone units of the backlimb, the composite FSI is 0.79. Joint development in the forelimb leads to a composite FSI of 0.96 (Fig. 7b). This result suggests that the development of strike joints is a function of structural position, at least when comparing forelimb data with backlimb data. To test the statistical significance of this conclusion a student's t-statistic was applied to fracture spacing ratio data.

The fracture spacing ratio (FSR) is the mean bed thickness divided by median joint spacing for a given bed (Gross, 1993). FSR data are sorted by strike and dip joint sets in the forelimb and backlimb as well as by lithological units (i.e., the Judith River Formation including the Parkman Member, the Eagle sands, and the Virgille Member of the Eagle Formation) (Fig. 8). A student's t-statistic was used to test the null hypothesis that population means were equal. When comparing the mean FSR for dip joints in the backlimb with mean FSR for strike joints in the backlimb, the null hypothesis was rejected for both one- and two-tailed tests at a confidence level of 95%. From this analysis, a statistically significant difference is found between the mean FSR the dip

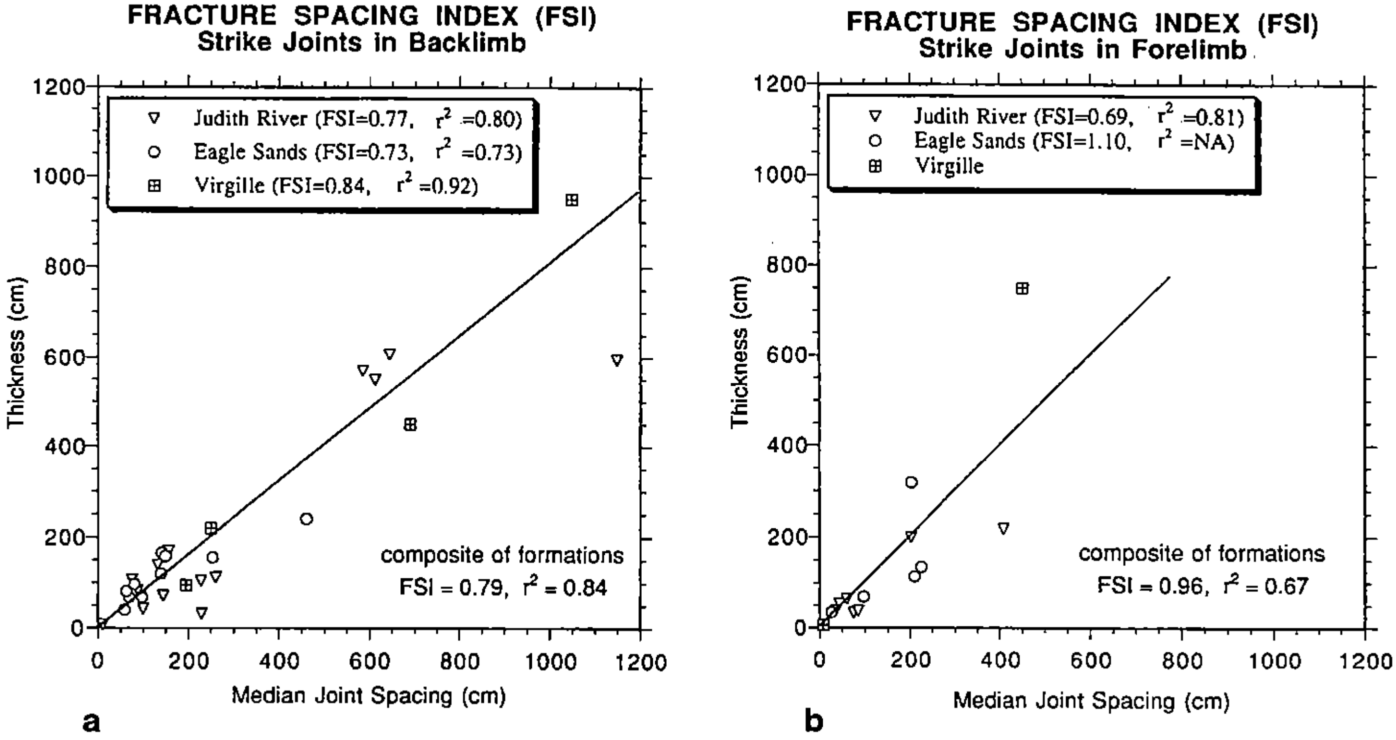

FIGURE 7. a.) A fracture spacing index plot for strike joints from the backlimb of the Elk Basin Anticline. b.) A fracture spacing index plot for strike joints from the forelimb of the Elk Basin Anticline. In both plots data given for the Virgille Member of the Eagle Formation, the upper sands of the Eagle Formation, the Parkman Member of the Claggett Formation, and the delta front sands of the Judith River Formation. Data from the Parkman Member of the Claggett Formation have been included with the data from the Judith River Formation. Critical outcrop numbers are indicated next to data points.

and strike joints. When testing the hypothesis that the mean of FSR for strike joints on the forelimb (0.95) is equal to the mean from the backlimb (0.75), the hypothesis is rejected for a one-tailed test in favor of the alternative hypothesis that the forelimb mean for strike joints is larger than the backlimb mean. This result is consistent with our FSI data showing more closely spaced joints on the forelimb. The development of strike joints is a function of structural position, the same conclusion reached using the FSI data.

Applying the same analysis to compare dip joint development on the forelimb and backlimb, there is no statistical difference for mean FSR for dip joints on the two limbs. This result is based on a very small sample population. If true, the dip joints develop independently of structural position on the Elk Basin Anticline. When the backlimb data are divided according to formation unit, there is no statistical difference among the mean FSR from the Judith River Formation, the upper sands of the Eagle Formation, and the Virgille member of the Eagle Formation.

THIN-SECTION PETROGRAPHY

Porosity

Commonly, stiffer beds carry more closely spaced joints (Gross et al., 1995). Experiments have shown that elastic compliance correlates with sandstone porosity (Bell, 1978). If this elastic-modulus-porosity relationship applies to sandstones of Elk Basin, it is possible to gain some sense of the distribution in elastic properties of rocks at Elk Basin by measuring sandstone porosity. Open (i.e., not cement-filled) porosity was measured by point counting 15 blue-stained thin sections. 600 points were measured within each thin section that included grains of quartz, feldspar, carbonate, lithic fragments, accessory minerals, cement, and pore space.

Samples from the Judith River Formation have a porosity as high as 17% whereas other Judith River sands, an Eagle sand and a sample of the Parkman Member had a porosity as low as 0.2% (Fig. 9). Two of the low porosity samples (#5 and #17) come from beds in which dip joints constitute the systematic set. The FSR versus porosity data cluster in two groups: the samples with low porosity come from beds with higher average FSR than samples with a high porosity.

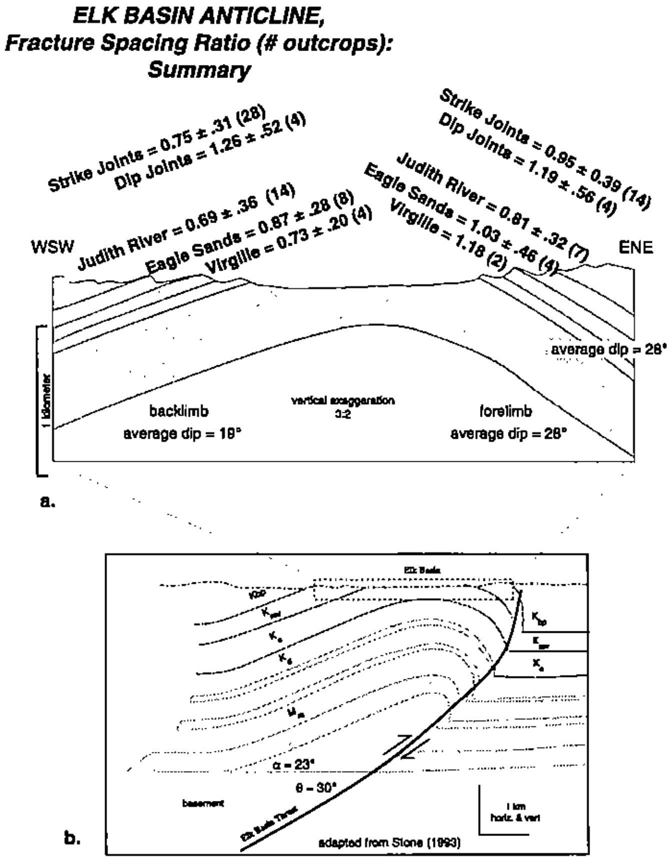

Figure 8. a.) A schematic cross section through the Cretaceous section of the Elk Basin Anticline. Fracture spacing ratio (FSR) data are averaged for both structural orientation (strike and dip) and lithology (Judith River, Eagle, Virgille). The number of outcrops for each data set is given. The structural orientation averages include data from the Elk Basin Member. The lithology averages consist of strike data only. b.) Structural cross section of Elk Basin based on a time-migrated, interpreted seismic profile (adapted from Stone, 1993).

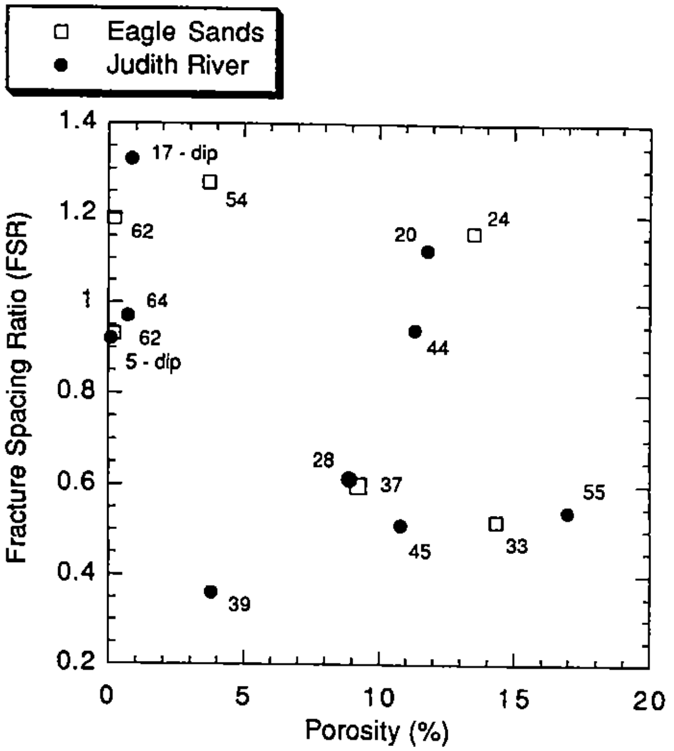

Figure 9. Porosity versus fracture spacing ratio (FSR) for beds of the Judith River Formation, the Parkman Formation and the upper sands of the Eagle Formation. Samples are indicated by outcrop as listed in Appendix 1.

Cataclastic Grains

Quartz grains within sandstones of the Elk Basin Anticline contain two microscopic deformation mechanisms, one brittle and one ductile. Throughout the anticline, beds contain some quartz grains that are shattered as if those sandstones are an incipient cataclastic rock. Shattering occurs when unsupported grains are point-loaded by adjacent grains (Gallagher et al., 1974). Cataclasis in grains is most prevalent in sandstone beds with porosity in excess of 9% (Fig. 10). In sandstone above 9% porosity, there is no correlation between porosity and the number of grains carrying evidence of cataclasis. The incipient cataclasis described here is not associated with the deformation bands of the Virgille.

DISCUSSION

At Elk Basin spacing of strike joints correlates with thickness for beds up to 10 m (Fig. 7), in marked contrast to results reported by McQuillan (1974) and Ladeira and Price (1981) who show that spacing is independent of thickness for beds thicker than 2 m. At present the geological conditions favoring either behavior in thick beds are unknown.

Joint Spacing-Bed Thickness Statistics

The correlation joint spacing and bed thickness at Elk Basin ($0.67 < r^2 < 0.92$) is somewhat weaker than correlation based on data collected in the Monterey Formation of California (e.g., $r^2 > 0.95$; see Narr and Suppe, 1991; Gross, 1993). Because of this poorer correlation at Elk Basin no obvious differences in joint spacing appear among various rock formations. Some of the scatter in Figure 7a is attributed to a variability in the thickness of individual beds due to cross bedding and interfingering shale facies. In contrast, beds of

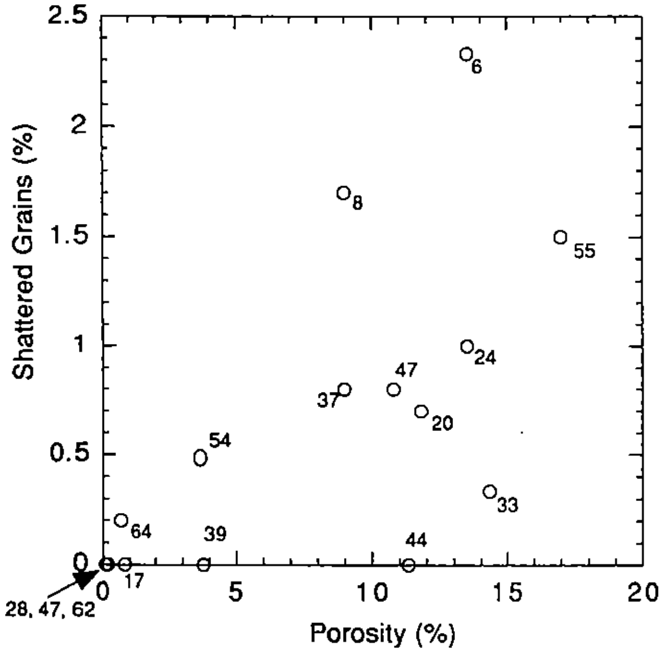

FIGURE 10. A plot of percentage of cataclastic quartz grains versus sandstone porosity. Cataclastic grains are those grains separated into two or more pieces by edge-to-edge microfractures. These samples come from both the Judith River Formation, the Parkman Formation, and the upper sands of the Eagle Formation. Samples are indicated by outcrop as listed in Appendix 1.

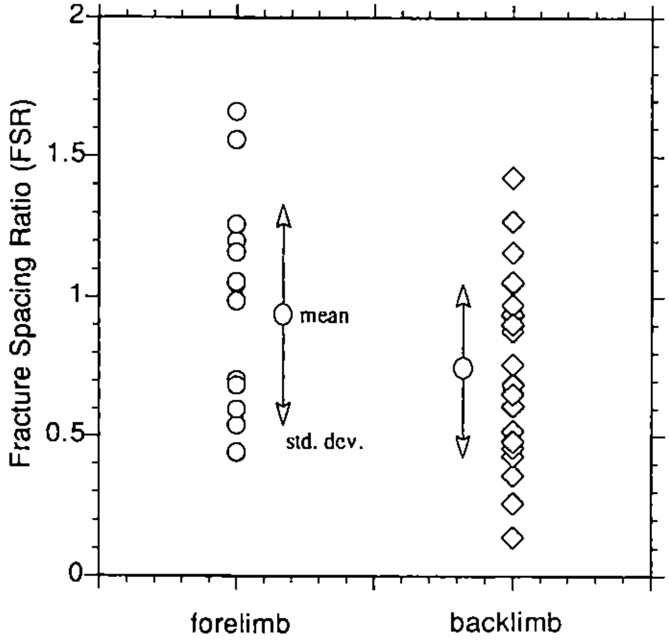

FIGURE 11. A comparison of fracture spacing ratio data from the forelimb and backlimb of the Elk Basin Anticline. Each data point on the diagram represents the FSR for one outcrop as listed in Appendix 1.

the Monterey Formation were remarkably uniform in thickness. There was also a scatter in joint spacing data that could not be attributed to variation in bed thickness. An example of this scatter can be seen in the three Judith River beds approximately 1 m thick, whose median joint spacings differ by more than a factor of three.

The FSI calculated for the combined Judith River and Eagle Sands beds is 0.79, nearly the same as that found in Devonian siltstones of the Catskill Delta Complex, Appalachian Plateau, New York (0.76 as reported in Lowey, 1995). However, this FSI is considerably less than the ~ 1.3 values measured in the Monterey Formation of California (Narr and Suppe, 1991; Gross, 1993).

Joint Development as a Function of Structural Position

Statistical analysis of strike joints at Elk Basin demonstrate that the mean FSR of 0.95 on the forelimb is significantly greater than the mean FSR of 0.75 on the backlimb. There is considerable overlap in FSR values for strike joints from the forelimb and backlimb (Fig. 11). Assuming that this difference is geologically significant, then according to the fracture spacing ratio, the forelimb was subjected to slightly higher strain than the backlimb. The small difference in FSR (20%) does not represent a complete fracture infilling event as is the case for the Gerofit Formation, Israel (Becker and Gross, 1996). Rather, only partial infilling occurred in the forelimb in response to larger strain in that structural position. Possible mechanisms for slightly greater extension in the forelimb include structural thinning in order to accommodate mismatch between dip of basement faulting and backlimb rotation of the Elk Basin Anticline (Stone, 1993), and drag associated with displacement along the Elk Basin thrust.

The geographic distribution of FSR data is also intriguing. A plot of FSR data for strike joints in the Judith River Formation and the Parkman Member of the Claggett Formation shows that FSR values tend to be higher throughout the northern half of the Elk Basin Anticline (Fig. 12). There is limited evidence that suggests the backlimb consists of two joint domains that might further add to scatter in the data used to generate a single FSI for the backlimb. A similar plot of FSR data for strike joints in the Eagle sands shows somewhat higher FSR values (Fig. 13). FSR data for the Eagle sands comes from the region of the backlimb panel where FSR values were low for the Judith River Formation.

The difference in FSR between systematic dip and strike joints (46% in the backlimb) is greater than the difference for strike joints between fold limbs, although once again sample populations are small. Unlike strike joints, dip joints are not pervasive throughout the Elk Basin structure, and thus probably did not form in response to a uniformly distributed layer-parallel extension. Furthermore, consistently higher

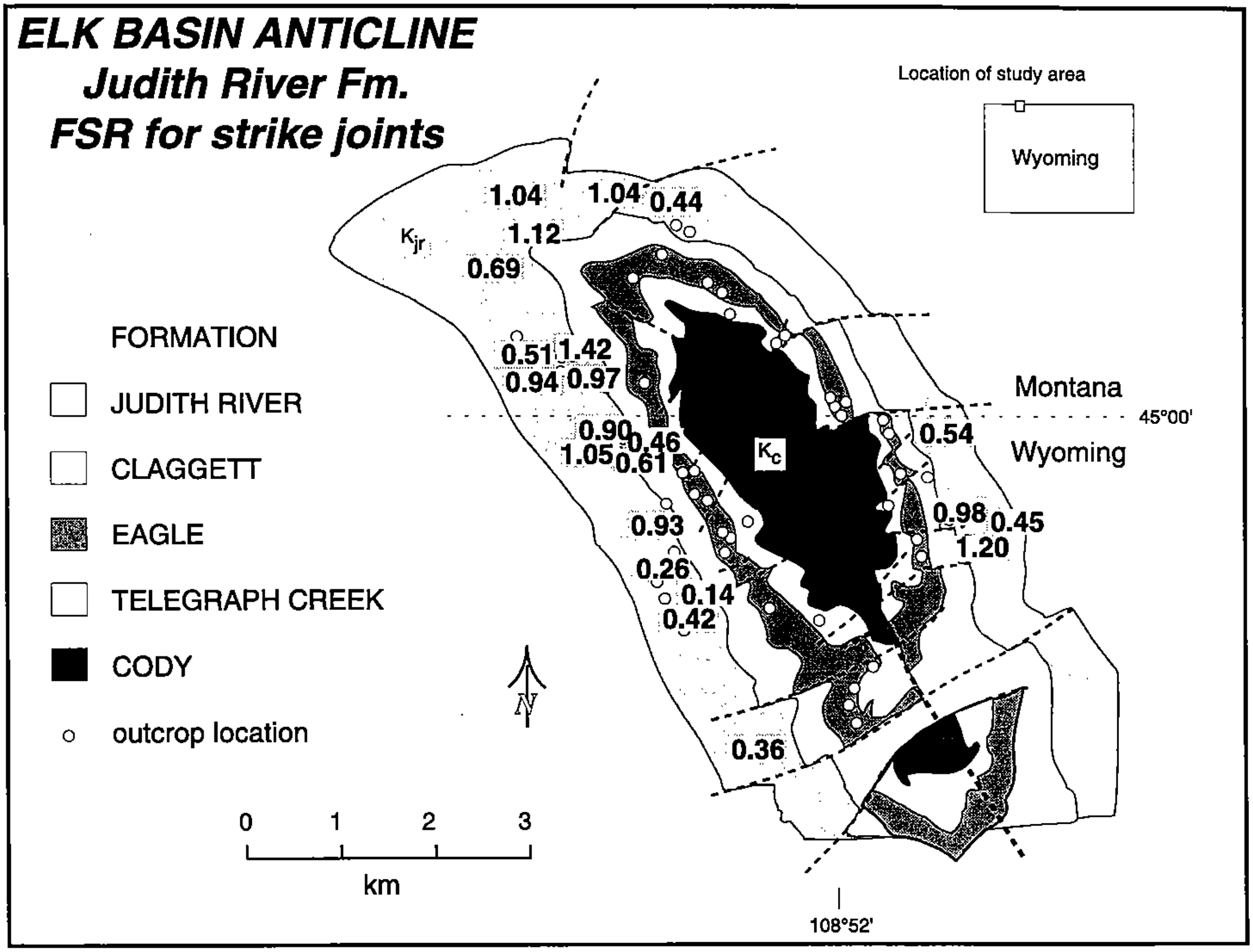

Figure 12. A plot of FSR data for strike joints within the Judith River Formation and the Parkman Member of the Claggett Formation. The data appear on a map of the Campanian section within the Elk Basin Anticline showing locations of outcrops where brittle fractures were sampled.

FSRs imply that dip joints reflect local areas of high extensional strain parallel to the fold axis, perhaps in direct association with surficial and/or underlying NE-SW trending normal faults.

Joint Development as a Function of Porosity

As shown by the distribution of data in Figure 7a, there is scatter about the least-squares fit line representing an FSI in the backlimb of Elk Basin. Aside from scatter arising from irregular bed thickness, a variation in elastic properties from bed to bed will increase scatter on the FSI plot. Elastic modulus of the bed affects the width of the stress shadow so that stiffer beds have wider stress shadows (Gross et al., 1995). Yet, higher modulus beds tend to have more closely spaced joints. Gross et al. (1995) explain this latter observation by pointing out that when layers of different moduli are all subject to uniform layer-parallel stretching, the stiffer beds reach their tensile strength at lower strains. As strain continues, infilling of joints in stiff beds is more complete so that these beds have a larger FSR. Beds with lower open porosity within the Elk Basin Anticline show a tendency to have a higher mean FSR. This conclusion is based on a linear fit to the data on Figure 9 with a low coefficient of determination ($r^2 = 0.17$). If this correlation between porosity and FSR is valid, however weak, and if the correlation between compliance and porosity holds, stiffer sandstone beds (i.e., low porosity rocks) in the Elk Basin Anticline contain more closely spaced joints.

On FSI diagrams, beds with high porosity tend to plot on the low FSR side of the best-fit line whose slope gives the FSI for the forelimb and backlimb (Figure 7). This effect is

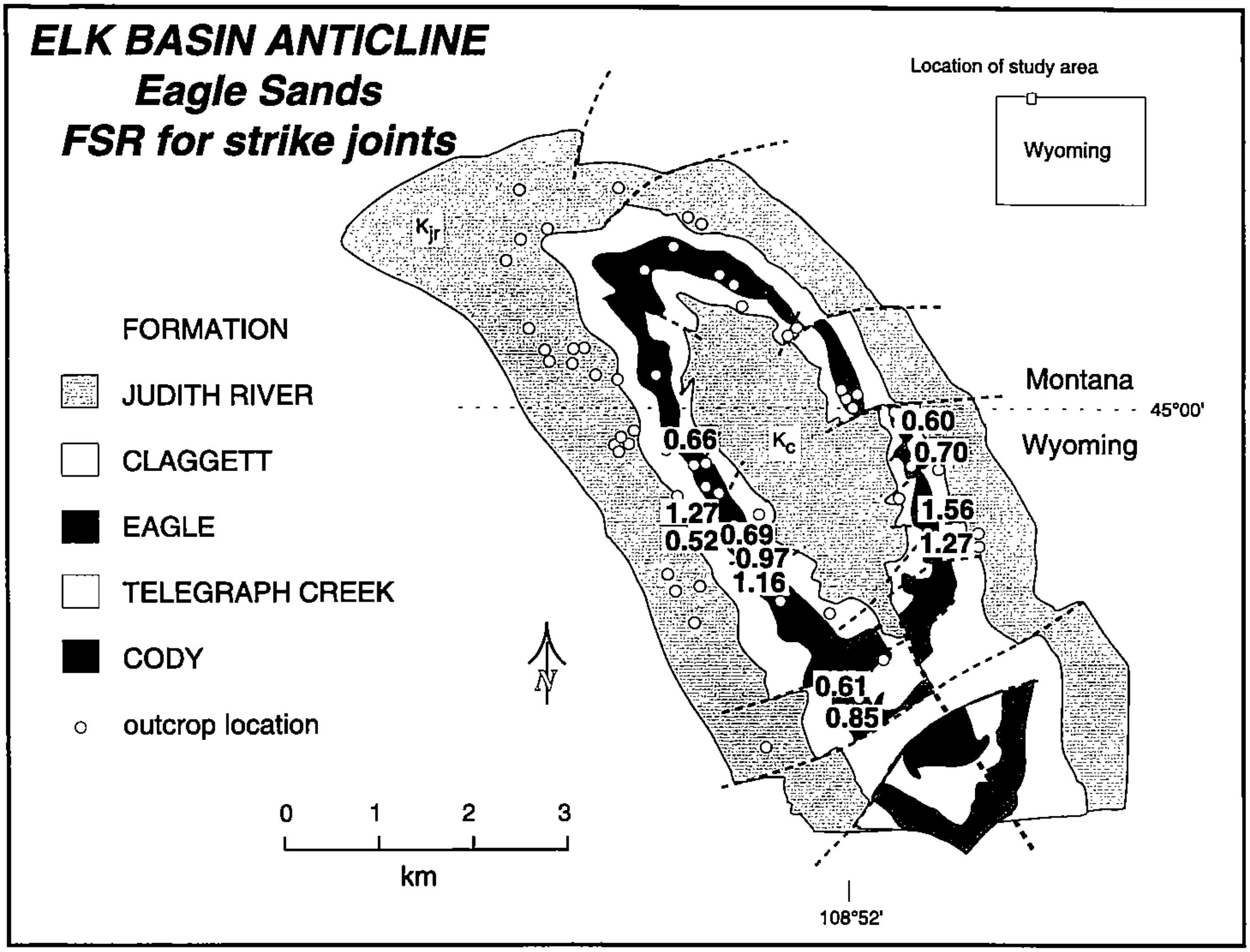

FIGURE 13. A plot of FSR data for strike joints within the Eagle sands of the Eagle Formation. The data appear on a map of the Campanian section within the Elk Basin Anticline showing locations of outcrops where brittle fractures were sampled.

particularly strong for thicker beds where samples from outcrop #55 in the forelimb and outcrops #33, #37, and #45 in the backlimb have a porosity in excess of 9%. The thickest bed with low porosity is found at outcrop #64 and this sample plots on the high FSR side of the best-fit line (Figure 7a). One exception to the general rule is the high porosity sample from outcrop #8 which plots on the high FSR side of the best-fit line for backlimb data.

Mean FSRs for both strike and dip joints are consistently lower than the ~ 1.3 values observed in carbonates and porcellanites of the Monterey Formation (Narr and Suppe, 1991). One explanation for low FSR values at Elk Basin is that rocks were subjected to less strain than in other fold belts. This hypothesis is difficult to test due to lack of strain markers. An alternative explanation is that sandstones at Elk Basin have lower elastic moduli, and hence display wider joint spacings, than rocks in those other settings. These sandstones are very friable, a characteristic consistent with low moduli rocks.

Structural Development of the Elk Basin Anticline

Observations concerning brittle structures of the Elk Basin Anticline may help shed light on the structural development of Laramide basement-related thrusts and related hydrocarbon reservoirs. Important observations include the fact that strike joints are the most pervasive set present. In the northwestern plunging nose of the Elk Basin Anticline, strike joints are independent of local fold axis but rather follow the trend of strike joints further to the SE. Dip joints are found locally but where present reveal a higher FSR than strike joints. In the majority of cases, strike joints form prior to dip joints so that dip joints are commonly 'cross joints'. Macroscopic brittle fractures along with the microscopic deformation mechanism, cataclasis, are considered pervasive deformation mechanisms on the scale of the Elk Basin Anticline, because spacing on such fractures is more than three orders of magnitude less than the scale of the overall structure.

The nature and sequence of brittle deformation at Elk Basin differs markedly from the brittle evolution of thin-skinned foreland fold and thrust belts, where dip joints are the most pervasive set (Nickelsen, 1979; Engelder and Geiser, 1980; Srivastava and Engelder, 1990). At many places in both the Appalachian Plateau and Valley and Ridge dip joint sets developed prior to substantial folding (Nickelsen, 1979; Engelder and Geiser, 1980; Kulander and Dean, 1986). In other places such as parts of the Appalachian Valley and Ridge, and the western Transverse Ranges of California, dip joints propagate during folding as a manifestation of strike (fold axis) parallel extension in response to regional layer-parallel shortening (Engelder and Engelder 1977; Gross and Engelder, 1995). At Elk Basin the most pervasive joint set is oriented roughly parallel to strike, and dip joints are found only in 8 out of 72 stations. Thus, it appears that rocks exposed at Elk Basin did not experience an episode of substantial strike-parallel extension required for early dip joint development.

Studies of the kinematic history of Laramide structures assume that basement was competent relative to the cover so that its brittle deformation controlled the kinematic evolution of the cover (Stearns, 1971; Matthews, 1986). As applied to the Elk Basin, basement would have shortened and then yielded by thrust faulting during Paleocene-age Laramide compression. During this early phase, cover rode passively on top of basement. The dip angle of thrusting in basement was between 25° and 35° (cf. Stone, 1993) which is consistent with brittle fracture in the laboratory (Handin and Hager, 1957). The attitude of the basement fault is unknown at greater depths. Seismic surveys suggest that basement below Elk Basin Anticline faulted at a dip of 30°, whereas the backlimb angle as indicated by seismic interpretation is only 23° (cf. Stone, 1993). In a kinematic analysis the backlimb dip angle is taken as a measure of backlimb rotation as basement cuts up into cover rock. The backlimb rotation is accomplished by motion along a listric fault that steepens where basement overthrusts cover rock. However, to maintain balance during later rotation, extension by cataclastic strain must occur within the basement and the forelimb nose of cover rock (cf. Figure 34 in Stone, 1993). Such cataclasis is the mechanism for marked extension in the forelimb of cover rock as most vividly displayed in outcrops of the Wingate Formation on the northern side of the Uncompahgre Uplift at Kodel's Canyon, Colorado (Jamison and Stearns, 1982).

In brief, three types of deformation affected the passive cover rocks of the Elk Basin Anticline: 1) an early layer-parallel compression that led to basement faulting; 2) backlimb rotation, and fold-normal extension, particularly in the forelimb; and 3) local axis-parallel stretching. This deformational history includes a contractional phase and a later extensional phase. The extensional phase is partitioned between an early axis-normal extension in folding over the basement thrust and later axis-parallel stretching to accommodate the doubly plunging anticline. This view of early contractional and later extension is consistent with Narr and Suppe's (1994) kinematic analysis of basement-involved contractional structures.

Early Contraction

Did the northeast-directed shortening that led to faulting in basement rock affect the cover rock of Elk Basin? The development of shattered grains is restricted to the more porous and evidently weaker members of the stratigraphy (Fig. 10). Unlike the deformation bands adjacent to major faults cutting the Virgille Member, incipient cataclasis within porous sandstone beds is equally common within both limbs. During early faulting of basement the stress state in basement was $S_H > S_h > S_v$. This stress state produces the highest differential stresses to affect the basement at Elk Basin, a condition favoring the development of incipient but pervasive cataclasis in the cover rock. For this latter reason, we speculate that cataclasis of porous sandstone beds, particularly in the backlimb, is the only manifestation of an early basin-wide compression that triggered faulting in basement rock. If so, any well-developed cataclasis associated with forelimb extension is hidden from view in the subsurface but may be of importance to hydrocarbon exploration in such structures.

Later Extension

During the first stage of anticlinal growth, sedimentary strata were draped over a fold above a basement reverse fault (Fig. 8). Draping of over basement led to a condition of tangential longitudinal strain (e.g., Ramsay and Huber, 1987) which is a stretching parallel to layering and normal to the anticlinal axis. Stretching causes a pervasive joint set throughout Elk Basin oriented sub-parallel to strike of the anticlinal drape axis and underlying fault (Fig. 5). Lemiszki et al. (1994) refer to this systematic joint set as "hinge-parallel extension fractures". As a consequence of northeast vergence of the basement thrust, the overlying fold of cover rock is asymmetric with a steeper NE limb. Thus, the forelimb may have experienced a greater amount of stretching than the backlimb during this phase. The higher FSI in beds of the forelimb is consistent with greater forelimb stretching.

Seismic sections show drag in both hanging wall and foot wall of the Elk Basin thrust, thus providing an additional mechanism for layer parallel extension (strike joints) in the forelimb. The final structural geometry observed on the surface is controlled by along-strike variations in thrust geometry found within the sedimentary cover rocks. Because most "strike" joints formed prior to this later deformation phase, they remain approximately parallel to the general trend of the anticline, rather than parallel to local strike around plunging fold noses.

Rotation of the Bedding-Parallel Stresses During Development of Elk Basin Anticline

When more than one joint set is present, abutting relationships give some indication of the relative timing of propagation of each joint set and the orientation of the bedding-parallel stress field at the time of propagation. Timing is apparent if joints of a later set curve to abut joints of an earlier set or curve to propagate parallel to the earlier set (Dyer, 1988). A number of outcrops carry two strike joint sets with the later set developed at a small angle to an earlier joint set (Fig. 6). As the later set propagated, it followed a curved path perpendicular to the earlier set. These later joints are not cross joints largely because their orientation is not consistent with common cross joint behavior with propagation and growth at a high angle to the existing joint set. These two strike joint sets suggest that during the Laramide Orogeny local bedding-parallel principal stresses in sandstone beds of the Elk Basin Anticline rotated relative to a coordinate system fixed to crystalline basement. A clockwise rotation is indicated by double joint sets in a number of the outcrops found on the northern end of the Elk Basin Anticline.

There is more than one possible cause for the propagation of two strike joint sets on the backlimb at Elk Basin. First, beds on the northern end of the basin may have been dragged during the development of the left-lateral tear fault in basement. Such drag could have reoriented the beds by a few degrees counter clockwise. If a second episode of extension had the same orientation as the first, further fold growth would have resulted in later joints that are misoriented in a clockwise direction from earlier joints. It is tempting to speculate that the higher FSR values in the northern half of the Elk Basin Anticline are a consequence of this drag. This is not as far-fetched as it may seem because all FSR data were calculated from the first strike joint set. The data in Appendix 1 show that the FSR calculated from a composite of the two strike joint sets is quite large relative to the FSR at outcrops with just one joint set.

A second possibility involves initial fold growth with an axis convex toward the northeastern direction of vergence. The initial strike joint pattern would have curved around the northern plunging nose of the fold. As the fold growth continued, the anticlinal axis may have become relatively straight with the extension direction rotating in a clockwise sense to remain parallel to the fold axis. Within the present coordinate system for measuring joint orientation, these models can not be distinguished. In brief, jointing indicates that fold development was complex with 'rotating' axes of bedding-parallel principal stresses.

CONCLUSIONS

Strike joints constitute the most common systematic set in sandstones of the Elk Basin Anticline. In the anticline, joint spacing correlates with bed thickness for sandstone beds to at least 10 m thick. Scatter in this correlation is attributed to variation in bed thickness, lack of accuracy in measuring bed thickness, and variation in elastic properties of beds. Although McQuillan's (1974) data set on joint spacing versus bed thickness breaks down for beds thicker than two meters, the Elk Basin data shows that there are geological environments in which a linear relationship extends beyond beds of 2 m thick. Forelimb sandstones have an FSI of 0.96 compared with an FSI of 0.79 in backlimb sandstone. The mean of the forelimb joint spacing data (i.e., FSR) is statistically greater than the mean of the backlimb data reflecting a greater amount of extension in the forelimb. Such forelimb extension is common in other basement-cored anticlines within the Rocky Mountains.

The lack of a pervasive regional dip joint set at Elk Basin suggests this tectonic setting is quite different from the foreland décollement environment where of tectonic shortening and transport are large and dip joints are well developed. In the thick-skinned basement-involved thrust environment at Elk Basin the dominant strike-parallel systematic joint set most likely developed due to tangential longitudinal stretching of draped strata above a basement fault. Tightening of the fold and propagation of the thrust into overlying strata led to later hanging wall transport and layer-parallel contraction, resulting in localized axis-parallel extension and the local development of later dip joints.

Assuming the Elk Basin Anticline is typical of basement-cored anticlines, this study has a number of implications for exploration and development of fractured anticlinal reservoirs in other Laramide structures. If fracture porosity correlates with joint spacing, beds of the forelimb will have a higher fracture porosity. The greatest number of fractures will be encountered drilling normal to the axis of the anticlinal structure. Thinner beds will contain more bedding-normal fractures than thicker beds. However, absolute fracture porosity will also depend on parameters such as fracture aperture, parameters that we were unable to assess in this study.

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APPENDIX 1

Station #	Rock Unit	Bed Thickness (cm)	Joint Type	Orientation (Early set) (listed first)	# Sets	Median Spacing (cm)	Fracture Spacing Ratio (FSR)	# Spacing Data	Porosity %
5	Judith River	20-25	dip	245/89	1	25	0.92	32	0.1
5	Judith River	20-25	dip	276/80	both	20	1.15	36	
6	Judith River	163-179	strike	345/85	1	126	1.34*	6	
6	Judith River	163-179	strike	019/70	both	157	1.08	10	
7	Judith River	140	strike	359/75	1	133.5	1.05	20	
7	Judith River	140	strike	024/77	both	71	1.97	33	
8	Judith River	500-600	strike	020/82	1	612.5	0.9	8	
9	Virgille	95	strike	001/74	1	196	0.48	19	
10	Virgille	400-500	strike	358/76	1	690	0.65	8	
11	Eagle A	36-43	strike	006/79	1	60	0.66	38	
12	Elk Basin	67-77	strike	111/76	1	61	1.16	15	
14	Virgille	700-800	strike	147/68	1	750	1.66	7	
15	Virgille	5-6	strike	098/77	1	8.3	0.69	14	
17	Judith River	30-35	dip	041/86	1	25	1.32	29	0.8
18	Judith River	36-41	dip	045/87	1	20.5	1.88	40	
20	Judith River	37-52	strike	129/85	1	40	1.12**	39	11.8
20	Judith River	37-52	strike	163/89	both	36	1.25	47	
22	Elk Basin	30-34	dip	041/86	1	42	0.76	29	
23	Virgille	210-230	strike	351/78	1	250	0.88	9	
24	Eagle A	159-171	strike	323/69	1	143	1.16	17	13.5
25	Judith River	75-88	strike	359/70	1	89	0.93	23	
26	Judith River	38-48	strike	323/78	1	156	0.26	14	
26	Judith River	38-48	strike	299/74	both	101	0.41	24	
28	Judith River	7-8	strike	353/74	1	12	0.61	23	9
29	Judith River	51-58	strike	308/88	1	45	1.2	31	
30	Parkman	28-38	strike	112/83	1	74	0.45	16	
31	Parkman	200	strike	156/79	1	203	0.98	12	
32	Judith River	16-29	dip	232/86	1	20	1.03	34	
33	Eagle D	230-250	strike	353/80	1	462	0.52	7	14.3
34	Elk Basin	47-75	strike	006/79	1	69	0.88	25	
35	Virgille	900-1000	strike	300/74	1	1049	0.91	4	
37	Eagle A	145-165	strike	009/80	1	255	0.61	11	9
37	Eagle A	145-165	strike	351/83	both	116	1.34	34	
38	Eagle D	120-400	strike	006/84	1	141	0.30-0.85*	11	4.5
39	Judith River	64-92	strike	019/86	1	197	0.36	12	
39	Judith River	64-92	strike	019/86	both	146	0.49	17	3.8
40	Judith River	104-128	strike	331/71	1	261	0.42	10	
42	Parkman	100-110	strike	347/75	1	229	0.46	11	
43	Judith River	17-21	dip	244/89	1	10	1.88	37	
44	Judith River	595-620	strike	350/77	1	645	0.94	10	11.3
45	Judith River	590-600	strike	351/76	1	1149	0.51	6	10.8
46	Judith River	655	dip	055/88	1	443	1.48	7	
48	Judith River	106-109	strike	344/75	1	75	1.42	15	

Appendix 1 continued

Station #	Rock Unit	Bed Thickness (cm)	Joint Type	Orientation (Early set) (listed first)	# Sets	Median Spacing (cm)	Fracture Spacing Ratio (FSR)	# Spacing Data	Porosity %
50	Judith River	57-70	strike	151/76	1	61	1.04	16	
51	Judith River	16-61	strike	153/74	1	86	0.44	8	
53	Eagle D	114-115	dip	210/76	1	212	0.54	10	
54	Eagle C	26-42	strike	139/82	1	27	1.27	34	3.7
55	Judith River	188-248	strike	162/69	1	401	0.54	7	17
57	Eagle C	47-89	strike	348/83	1	70	0.97	6	
59	Eagle C	48-90	strike	339/77	1	99	0.69	9	
60	Claggett	13-18	strike	339/69	1	34	0.48	17	
61a	Eagle A	62-98	strike	316/73	1	64	1.27	26	
61b	Eagle C	126-210	strike	311/71	1	150	1.05	15	
62	Eagle E	55-161	strike	324/73	1	83	0.93-1.19*	31	0.2
64	Parkman	570	strike	353/74	1	586	0.97	12	0.7
65	Eagle C	120-155	strike	179/73	1	226	0.6	6	
66	Eagle C	68-70	strike	126/76	1	98	0.7	6	
67	Eagle C	175-490	strike	167/81	1	204	1.56	16	
69	Judith River	36-40	strike	141/75	1	36	1.04	10	
70	Judith River	58-76	strike	283/82	1	102	0.69	6	
71	Parkman	28-35	strike	341/78	1	229	0.14	14	

* - Poor data not incorporated in calculation of averages in Figure 8

** - Data from the axial plane region not incorporated in calculation of averages in Figure 8

REFERENCES

Aydin, A., and Johnson, A.M., 1978, Development of faults as zones of deformation bands and as slip surfaces in sandstone: Pure and Applied Geophysics, v. 116, p. 931-942.

Bally, A.W., 1983, Seismic expression of structural styles: American Association of Petroleum Geologists: Studies in Geology, Series 15.

Becker, A., and Gross, M.R., 1996, Joint set development in mechanically layered rocks: an example from southern Israel: Tectonophysics, v. 257, p. 223-237.

Bell, F.G., 1978, The physical and mechanical properties of the Fell sandstones, Northumberland, England, Engineering Geology, v. 12, p. 1-29.

Bogdonov, A.A., 1947, The intensity of cleavage as related to the thickness of beds: Soviet Geology, v. 16 (in Russian).

Dyer, R., 1988, Using joint interactions to estimate paleostress ratios: Journal of Structural Geology, v. 10, p. 685-699.

Engelder, T., 1974, Cataclasis and the generation of fault gouge: Geological Society of America Bulletin, v. 85, p. 1515-1522.

Engelder, T. and Engelder, R., 1977, Fossil distortion and decollement tectonics of the Appalachian Plateau: Geology, v. 5, p. 457-460.

Engelder, T., and Geiser, P.A., 1980, On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York: Journal of Geophysical Research, v. 85, p. 6319-6341.

Fischer, M., 1994, Applications of Linear Elastic Fracture Mechanics to some problems of fracture and fault propagation: Ph.D. Thesis, The Pennsylvania State University, University Park PA, 180 p.

Gallagher, J.J., Friedman, M., Handin, J., and Sowers, G., 1974, Experimental studies relating to microfracture in sandstone, Tectonophysics, v. 21, p. 203-247.

Gross, M.R., 1993, The origin and spacing of cross joints: Examples from the Monterey Formation, Santa Barbara coastline, California, Journal of Structural Geology: v. 15. p. 737-751.

Gross, M.R., 1995, Fracture partitioning: Failure mode as a function of lithology in the Monterey Formation of coastal California: Geological Society of America Bulletin, v. 107, p. 779-792.

Gross, M.R., and Engelder, T., 1995, Strain accommodated by brittle failure in adjacent units of the Monterey Formation, U.S.A.: Scale effects and evidence for uniform displacement boundary conditions: Journal of Structural Geology, v. 17, p. 1303-1318.

Gross, M.R., Fischer, M.P., Engelder, T., and Greenfield, R.J., 1995, Factors controlling joint spacing in interbedded sedimentary rocks: Integrating numerical models with field observations from the Monterey Formation, USA: In Ameen, M.S., ed., Fractography: fracture topography as a tool in fracture mechanics and stress analysis: Geological Society Special Publication No. 92, p. 215-233.

Handin, J., and Hager R.V., 1957, Experimental deformation of sedimentary rocks under confining pressure: Tests at room temperature on dry samples: Bulletin American Association Petroleum Geologists, v. 41, p. 1-50.

Hobbs, D. W., 1967, The formation of tension joints in sedimentary rocks: an explanation: Geological Magazine,. v. 104, 550-556.

Huang, Q. and Angelier, J., 1989, Fracture spacing and its relation to bed thickness: Geological Magazine, v. 126, p. 355-362.

Jamison, W.R., and Stearns, D.W., 1982, Tectonic Deformation of Wingate Sandstone, Colorado National Monument: American Association of Petroleum Geologists Bulletin: v. 66, p. 2584-2608.

Kulander, B.R., and Dean, S.L., 1986, Structure and tectonics of central and southern Appalachian Valley and Ridge and Plateau Provinces, West Virginia and Virginia, American Association of Petroleum Geologists Bulletin, v. 70, p. 1674-1684.

Kulander, B.R., Dean, S.L., and Ward, B.J., 1991, Fractured Core Analysis: Interpretation, Logging, and Use of Natural and Induced Fractures in Core: AAPG Methods in Exploration Series, No. 8, American Association of Petroleum Geologists, Tulsa, Oklahoma, 88 p.

Ladeira, F.L., and Price, N.J., 1981, Relationship between fracture spacing and bed thickness, Journal of Structural Geology, v. 3, p. 179-183.

Lemiszki. P.T., Landers, J.D., and Hatcher, R.D., 1994, Controls on hinge-parallel extension fracturing in single-layer tangential-longitudinal strain folds: Journal of Geophysical Research, v. 99, p. 22,027-22,041.

Lowey, S. L., 1995,The post-Alleghanian tectonic history of the Appalachian Basin based on joint patterns in Devonian black shales: M.S. Thesis, The Pennsylvania State University, University Park PA, 179 p.

Matthews, V., III, 1986,A case for brittle deformation of basement during the Laramide revolution in the Rocky Mountain foreland province: The Mountain Geologist, v. 23, p. 1-5.

McCabe. W.S., 1948,Elk Basin Anticline, Park County, Wyoming, and Carbon County, Montana: American Association of Petroleum Geologists Bulletin, v. 32, p. 52-67.

McQuillan, H., 1973, Small-scale fracture density in Asmari Formation of southwest Iran and its relation to bed thickness and structural setting: American Association of Petroleum Geologists Bulletin, v. 57, p. 2367-2385.

Narr, W., and Lerche, I., 1984, A method for estimating subsurface fracture density in core: American Association of Petroleum Geologists Bulletin, v. 68, p. 637-648.

Narr, W. and Suppe, J., 1991, Joint spacing in sedimentary rocks: Journal of Structural Geology, v. 13, p. 1037-1048.

Narr, W. and Suppe, J., 1994, Kinematics of basement-involved compressive structures: American Journal of Science, v. 294, p. 802-860.

Nickelsen, R.P., 1979, Sequence of structural stages of the Allegheny orogeny at the Bear Valley Strip Mine, Shamokin, Pennsylvania, American Journal of Science, v. 279, p. 225-271.

Price, N.J., 1966, Fault and Joint Development in Brittle and Semi-brittle Rock, Pergamon Press, London, 176 p.

Pollard, D.D., and Segall, P., 1987, Theoretical displacements and stresses near fractures in rock: with applications to faults, joints, veins, dikes, and solution surfaces, in Atkinson, B., ed., Fracture Mechanics of Rock, Academic Press, Orlando, p.227-350.

Ramsay, J.G., and Huber, M.I., 1987, The techniques of modern structural geology: Volume 2: Folds and Fractures: Academic Press, Inc, Orlando, 307 p.

Sheldon, P., 1912, Some observations and experiments on joint planes, Journal of Geology, v. 20, p. 53-70.

Srivastava, D., and Engelder, T., 1990, Crack-propagation sequence and pore-fluid conditions during fault-bend folding in the Appalachian Valley and Ridge, Geological Society of America, v. 102, p.116-128.

Stearns., D.S., 1971, Mechanisms of drape folding in Wyoming province, In Renfro, A.R., ed., Symposium on Wyoming tectonics and their economic significance: Casper, Wyoming Geological Association, p. 125-143.

Stearns., D.S., 1978, Faulting and forced folding in Rocky Mountains foreland, in Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1-37.

Stone, D.S., 1983, The Greybull Sandstone pool (Lower Cretaceous) on the Elk Basin thrust-fold complex, Wyoming and Montana, in Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver Colorado, Rocky Mountain Association of Geologists, p. 345-356.

Stone, D.S., 1991, Wilson Creek field - U.S.A., Piceance Basin, northern Colorado: American Association of Petroleum Geologists Bulletin, v. 75, p. 1-45.

Stone, D.S., 1993, Basement-involved thrust -generated folds as seismically imaged in the subsurface of the central Rocky Mountain foreland: in Schmidt, C.J., Chase, R.B., and Erslev, E.A., eds., Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States, Geological Society of America Special Paper 280, p. 271-318.

Swift, D.J.P. and Rice, D.D., 1984, Sand bodies on muddy shelves: A model for sedimentation in the western interior Cretaceous seaway, North America: in Tillman, R.W., and Siemers, C.T., eds., Siliciclastic shelf sediments: Society of Economic Paleontologists and Mineralogists: Special Publication 34, p. 43-62.

Wiltschko, D.V., and Dorr, J.A., 1983, Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah, American Association of Petroleum Geologists Bulletin, v. 67, p. 1304-1322.

Woodward, N.B., Boyer, S.E., and Suppe, J., 1985, An outline of balanced cross sections (Studies in Geology II, second edition): Knoxville, University of Tennessee, Department of Geological Sciences, 170 p.